VIRGINIA WATER RESOURCES RESEARCH CENTER

Virginia's Stormwater Impact Evaluation: Developing an Optimization Tool for Improved Site Development, Selection and Placement of Stormwater Runoff BMPs

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Since the early 1970's, the most common approach to stormwater management in the United States has been to drain runoff from a developed site as quickly and efficiently as possible, and then detain this runoff and release it to a downstream receiving channel at a controlled rate. Without question, the most popular means by which this management approach occurs is through the use of dry detention basins. In 2007, The Congressional Research Service reported that up to 50 percent of water pollution problems in the United States are attributed to urban stormwater runoff (CRS, 2007). Pollutants washed off of roads, parking lots, and other surfaces include nutrients, hydrocarbons, pesticides, heavy metals, bacteria, as well as larger debris. Stormwater runoff entering a conventional dry detention basin typically does not experience a hydraulic residence time of adequate duration to provide significant gravitational settling of suspended pollutants.

In 1987, the Clean Water Act (CWA) was amended to include Section 319. Section 319 of the CWA expanded upon previously unsuccessful efforts to control non-point source (NPS) discharges. The amendment required States to identify impaired water bodies whose water quality could not be improved without controlling NPS discharges. Furthermore, upon their identification, States were required to develop management programs and standards to improve these impaired waters. Fundamental to most NPS management programs is the use of best management practices or BMPs.

A stormwater BMP is a device or strategy for removing targeted pollutants from stormwater runoff, thus preventing their introduction to receiving waters. A BMP performs beyond the scope of conventional stormwater management practices, such as dry detention basins, by not only mitigating the peak rate of runoff from a given site, but by also attempting to improve the quality of the runoff. Presently, there are approximately 15 different structural BMPs in wide-spread usage throughout the United States, each with its own intrinsic performance capabilities and limitations.

Historically, to supplement personal experience and professional judgment, many in the engineering community have relied on various BMP selection matrices and flow charts to select an appropriate BMP for a particular application. One of the earliest collections of these BMP selection matrices is found in the Federal Highway Administration's 1996 publication titled Evaluation and Management of Highway Runoff Water Quality (FHWA, 1996). In many states, BMP selection matrices (or other, similar forms of guidance) are developed and published by the state's stormwater control program.

Extending beyond traditional selection approaches, engineers are increasingly expected to examine more and more criteria when choosing a BMP for a particular application. Included among these criteria are physical site characteristics; local, state, and federal pollution control ordinances; and implementation and long-term maintenance costs. Introducing what is essentially an unlimited number of influential selection criteria to such a wide array of available BMP options make the selection of a single BMP for a particular application a daunting task.

The BMP selection matrices (and other methods of BMP selection) available today are subject to personal bias and subjectivity despite their great value to engineers and planners. Consequently, stormwater management solutions too often default to the traditional “drain and detain” stormwater management approach with little or no consideration given to alternative design strategies and BMP options. An unfortunate reality is that, while effective for providing runoff rate attenuation, dry detention facilities are often not the best BMP option in terms of water quality improvement and cost.

This report documents the application of the Analytic Hierarchy Process (AHP) decision support algorithm to the stormwater BMP selection process. “The analytic hierarchy process (AHP) provides the objective mathematics to process the inescapably subjective and personal preferences of an individual or a group in making a decision” (Schmoldt, 2001, p. 15). Fundamentally, the AHP works by developing comparisons among competing alternatives (in this application, individual BMP types) as well as the criteria used to judge the alternatives. The AHP permits mathematical comparison when the influential criteria exhibit vastly different scales (units) as is the case with the broad spectrum of factors influencing the BMP selection process.

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Chapter 1. Introduction and Background

1.1 Traditional (Rate Control) Approach to Stormwater Management

Since the early 1970's, the most common approach to stormwater management in the United States has been to drain runoff from a developed site as quickly and efficiently as possible, and then detain this runoff and release it to a downstream receiving channel at a controlled rate. Often the design release rate is established as the pre-development runoff rate to the discharge point corresponding to the return frequency storm(s) of interest. Without question, the most popular means by which this management approach occurs is through the use of dry detention basins. Dry detention basins are earthen structures constructed either through the impoundment of a natural depression or by the excavation of existing soil. Many dry detention basins are equipped with multi-stage riser outlets which provide peak runoff rate attenuation for multiple return frequency storms such as the 2, 5, 10, 25, and 100 year runoff producing events. Historically the emphasis has been placed exclusively on peak runoff rate reduction when implementing a dry detention basin. However, due to gravitational settling of the large particulate fraction of suspended solids in stormwater runoff, some minimal water quality benefit has always been observed in these types of impounding facilities.

Dry detention basins are applied throughout the United States in residential, commercial, industrial, and highway stormwater management scenarios. However, despite such widespread acceptance, numerous shortcomings do exist with their implementation. Perhaps the most notable shortcoming lies in the significant, often irreversible manner in which this stormwater management approach alters a site's naturally occurring hydrologic balance. By rapidly conveying runoff to a detention basin through curb and gutter systems and storm sewer networks, a site's post-development time of concentration is typically reduced to a fraction of the pre-development time. This decreased flow time greatly diminishes the opportunities for infiltration, evaporation, and evapotranspiration of runoff. The reduced infiltration opportunity is of particular concern because of the extent to which it denies naturally occurring groundwater recharge. Further compounding the groundwater recharge deficiency are the standards to which detention basins are typically designed when they are constructed on well-drained soils, such as Hydrologic Soil Groups (HSG) A and B. Such basins are often equipped with a clay and/or synthetic liner to minimize infiltration losses through the basin floor and embankments. On sites with a high percentage of impervious land cover, the collection, conveyance, and detention approach to stormwater management can essentially eliminate the critical groundwater recharge link entirely from the hydrologic cycle.

Another issue of concern with the "drain and detain" approach to stormwater management is the increased volume of runoff generated from developed sites. Runoff can be effectively captured and released from a detention facility at a controlled rate equal to or less than that of pre-development conditions. However, the overall volume of runoff from a developed site is almost always greater than that generated from its pre-development state. A significant issue created by increase in runoff volume is the frequency and duration with which downstream receiving channels experience bank-full flows. These bank-full conditions are a significant contributor to bank erosion, scour, and sediment transport.

The acreage required for the construction of a dry detention basin is also often considered an inherent deficiency with the traditional approach to stormwater management. The storage volume required to reduce the rate of runoff from multiple return frequency storms, sometimes including up to the 100-year runoff producing event, often results in detention basin area requirements comprising a significant fraction of an overall site's land area. Therefore, particularly on smaller sites, achieving adequate runoff management through the use of a dry detention basin is often economically unattractive if not entirely unfeasible.

Another notable shortcoming observed in the application of detention facilities for the management of runoff from developed sites is the minimal water quality benefit that these impoundments provide. The Congressional Research Service reported in 2007 that up to 50 percent of water pollution problems in the United States are attributed to urban stormwater runoff (CRS, 2007). Pollutants washed off of roads, parking lots, and other surfaces include nutrients, hydrocarbons, pesticides, heavy metals, bacteria, as well as larger debris. Stormwater runoff entering a conventional dry detention basin typically does not experience a hydraulic residence time of adequate duration to provide significant gravitational settling of suspended pollutants. Furthermore, because the minimal water quality benefits that are provided by a detention basin occur primarily through gravitational settling, the removal of soluble contaminants such as phosphorus and nitrogen is essentially nonexistent.

1.2 Increased Pollutant Runoff Arising from Land Use Conversion

The runoff from urbanized areas carries a variety of soluble and particulate pollutants, typically at levels much greater than those observed in the runoff from undisturbed, natural spaces. Many of these pollutants pose significant threats to the aquatic ecosystems to which they are introduced. The increased pollutant load found in the runoff from developed areas is a combined function of altered hydrologic patterns and elevated pollutant buildup rates. Land use intensification, in the form of increased impervious cover, alters a site's naturally occurring hydrologic balance in a number of different ways. First, there is an inevitable loss in evapotranspiration capacity as vegetation is replaced with impervious surface. Second, the natural storage capacity of the site is typically reduced as loose, permeable soils are replaced with pavement, structures, and managed lawns comprised of highly compacted soils. Urbanization also increases pollutant generation rates as impervious surfaces collect and accumulate pollutants more readily than undisturbed soils. Even runoff from those urbanized areas categorized as "pervious" has the potential to carry high pollutant loads arising from the application of fertilizers and pesticides. The combined result of altered runoff patterns and increased pollutant accumulation rates is the potential for surface runoff containing harmful levels of nutrients, suspended sediment, hydrocarbons, and other pollutants.

The state of Virginia defines phosphorus as its “keystone pollutant.” This designation came initially from the Chesapeake Bay Local Assistance Department (CBLAD) in an early attempt to evaluate pollutant export from developed sites (Virginia DCR, 1999). Phosphorus was selected because of the unique manner in which it exhibits characteristics of both soluble and particulate pollutants. Phosphorus and other nutrients such as nitrogen are of concern because of their potential to cause eutrophication of the water bodies to which they are introduced. As eutrophication occurs in an aquatic ecosystem, plant species such as algae often experience explosive growth rates. As these algal blooms restrict the sunlight available to bottom dwelling species (both plant an animal) there is a steady decrease in the levels of dissolved oxygen in the water. When dissolved oxygen decreases to hypoxic levels, fish and other aquatic species must migrate to other locations or suffocate.

Notable levels of suspended sediment are often found in the runoff generated from impervious surfaces, managed lawns, and sites whose surfaces have been denuded through construction processes. Natural channels are able to convey a baseline sediment load and, in fact, some sediment load is necessary to preserve the stream’s natural state of morphological equilibrium. However, elevated sediment loading such as that generated from urbanized land areas has significantly adverse effects on a number of aquatic species. Streams subjected to perpetually elevated sediment loading will eventually exhibit sediment deposition levels that smother benthic habitat (Virginia DCR, 1999).

Another pollutant type often found in urban runoff is petroleum hydrocarbons. Hydrocarbons may exist as pure compounds comprised entirely of carbon and hydrogen or in an impure state with the hydrocarbon chemically bound to impurities such as sulfur or nitrogen. These pollutants are often introduced to the land surface through the leaking of automobile lubricants and spills at fueling and service stations. When deposited onto impervious surfaces such as asphalt, hydrocarbons accumulate until a rainfall event washes them off. The introduction of hydrocarbons to natural waterways, even in very small amounts, can have devastating, long-lasting impacts on aquatic animal and plant species.

Numerous other pollutants are found in stormwater runoff from urbanized lands. These include bacteria and metals such as cadmium, copper, lead, and zinc. The organic matter sometimes found in surface runoff can accumulate in receiving waters and result in increased biochemical oxygen demand (BOD). The degree to which these pollutants pose a risk depends on the levels at which they are present, as well as the natural characteristics of the water body to which they are introduced.

1.3 Best Management Practices (BMPs) as a Runoff Control Strategy

The primary legislative means by which the nation's waterways are protected is the Clean Water Act (CWA). The CWA places joint responsibility on States and the U.S. Environmental Protection Agency (EPA) for regulating both point and nonpoint sources (NPS) of pollution. Since its ratification in 1977, the CWA has evolved such that point sources of pollution are managed by a permitting system while NPS pollution is typically addressed through State-level runoff management strategies.

The CWA defines a point source discharge as "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or floating craft, from which pollutants are or may be discharged" (33 U.S.C. § 1362(14)). Amended section 402 of the CWA created a permitting system by which point source discharges could be regulated. This permitting program is called the National Pollutant Discharge Elimination System (NPDES). Issuance of a NPDES permit requires that the permittee comply with pollutant discharge limits that are based on the "best available technology." Permit issuance and renewal may also be contingent on the permittee monitoring and reporting the point source discharge. For municipalities operating Municipal Separate Storm Sewer Systems (MS4s), the EPA or a delegated State body may issue a system-wide permit.

In 1987, the CWA was amended to include Section 319. Section 319 of the CWA expanded upon previously unsuccessful efforts to control NPS discharges. The amendment required States to identify impaired water bodies whose water quality could not be improved without controlling NPS discharges. Furthermore, upon their identification, States were required to develop management programs and standards to improve these impaired waters. Analogous to the NPDES permitting program for point source discharges, Section 319 of the CWA enabled States to establish water quality programs and standards for NPS discharges. Fundamental to most NPS management programs is the inclusion of best management practices or BMPs. A stormwater BMP is a device, practice, or method for removing, reducing, retarding, or preventing targeted stormwater runoff constituents, pollutants, and contaminants from reaching receiving waters. A BMP performs beyond the scope of conventional stormwater management practices, such as dry detention basins, by not only mitigating the peak rate of runoff from a given site, but also attempting to improve the quality of the runoff.

1.4 Non-Structural Best Management Practices

BMPs can be broadly categorized as structural or non-structural. Non-structural BMPs, also referred to as "source control" practices, function by attempting to minimize the accumulation of pollutants, thus reducing their initial concentrations in stormwater runoff. Street sweeping and fertilizer application controls are examples of source control BMPs. Another class of BMP includes those practices, sometimes termed Low Impact Development (LID), that seek to maintain a site's pre-development hydrology in its developed state. The term LID is broad-reaching, and encompasses both structural BMPs such as vegetated roofs and rainwater capture devices as well as non-structural design strategies frequently termed "Minimum Disturbance / Minimum Maintenance."

Minimum Disturbance / Minimum Maintenance (MD/MM) is an approach to site development where the clearing of vegetation and disturbance of soil is carefully limited to a prescribed distance from proposed structures and site improvements. The application of MD/MM site design as a best management practice is most commonly found on sites possessing existing vegetation in the form of tree cover. However, the term existing vegetation may also encompass any natural vegetative cover, including scrub vegetation which is capable of providing significant water quality and quantity benefits. This approach to site development has the dual benefit of minimizing the effects of land disturbing activities, such as increased rate and volume of stormwater runoff, increased levels of pollutants, and also preserving existing areas of vegetation, thus retaining all of their naturally occurring stormwater management function.

A number of design elements and approaches exist to minimize the disturbed area and amount of impervious land cover arising from the development of a given site. The first is simply to reduce roadway widths. A typical primary road section consists of two 18' drive lanes, with curb and gutter present on each side. Imperviousness is often further increased by the installation of sidewalk sections on each side of a roadway. In locations where traffic volumes permit, a rural residential roadway section may be used in place of the primary road section. Reduction of drive aisle width from 18 to 12 feet results in a 33 percent reduction in impervious area. Furthermore, with the attempted preservation of natural runoff patterns and drainage ways, curb and gutter may, in some instances, be omitted. The disturbance of native soils and vegetation can also be reduced by locating proposed structures and roadways along existing contours and ridge lines. Site earthwork and clearing can be further minimized by orienting the major axis of proposed buildings parallel to a site's existing contours and staggering multiple floor levels to adjust to grade changes.

Development projects inherently increase the amount of impervious cover on a given site. Designing with an emphasis on MD/MM not only attempts to minimize impervious cover, but also seeks to keep the essential impervious portions of a site disconnected from one another to the extent possible. Disconnection of site impervious areas provides an opportunity for infiltration and evaporation thus reducing the volume of concentrated stormwater runoff from a given site. Methods of disconnecting impervious areas include the following (Prince George's County, Maryland, June 1999):

- Disconnecting roof drains and directing flows to vegetated areas
- Directing flows from driveways and other impervious areas to stabilized vegetated areas
- Breaking up flow directions from large paved surfaces
- Grading such that sheet flow is directed through vegetated areas
- Carefully locating impervious areas such that their runoff is directed to natural systems, vegetated buffers, natural resource areas, or infiltration zones / soils

In addition to minimizing the total disturbed area of a proposed development, MD/MM design strategies also consider the site's existing hydrology. The traditional approach to development is to quickly and efficiently drain the developed site using collection techniques such as curb and gutter and storm sewer networks. By contrast, a minimum disturbance approach seeks to mimic a site's pre-developed hydrology as closely as possible. This hydrologically functional landscape is predicated on the preservation of streams and stream buffers, wetlands, high permeability soils, and woodlands. Additionally, natural drainage paths are retained to preserve, as closely as possible, a site's pre-development time of concentration. Methods of preserving pre-development times of concentration are as follows:

- Maximization of overland sheet flow.
- Designing such that site grading preserves or, if possible, lengthens pre-development runoff paths.
- Lengthening and flattening site and/or subdivision lot slopes to the extent that there is no conflict with the paramount goal of MD/MM – that is to minimize grading and clearing of vegetation**.**
- Maximizing open swale systems.
- Increasing and augmenting site and lot vegetation.

The impact on stormwater runoff quantity arising from a MD/MM design approach is highly variable by site, and can be difficult to quantify. Furthermore, the use of MD/MM principles during site design does not inherently eliminate the need for structural stormwater control practices. However, the employment of MD/MM design strategies almost certainly reduces the number and size of structural stormwater control practices needed to achieve allowable runoff rates from a developed site. Because the primary objective of MD/MM design is to maximize retention of the native vegetative cover on a site, post-development imperviousness will be less than if conventional site development methods were employed. Even sites whose native vegetation is nothing more than "scrub" growth or meadow will exhibit lower rates and volumes of stormwater runoff than if the site were cleared, graded, and then revegetated in the form of a manicured lawn. In addition to retaining a site's native vegetation, MD/MM design also retains the often highly permeable native soils present on an undeveloped site. With soils becoming less and less permeable through compaction and other manipulation, even sites with relatively low permeability can offer remarkably effective infiltration when compared to sites developed by a conventional approach. Finally, naturally vegetated zones retained on a site as a result of an MD/MM approach can be used to receive runoff from impervious portions of the development. In low-density developments, this approach alone may be adequate to address site stormwater management needs (DEDNREC, September 1997).

The impacts of an MD/MM design approach on water quality are quite unique. Unlike conventional landscaping, the native vegetation left in place on a site receives no chemical applications. Therefore, a significant water quality issue is completely avoided.

Research shows that nitrogen fertilizer application rates range from 100 – 200 lbs/ac/year for typical landscapes. Research also shows that the concentration of phosphorus in runoff from urban lawns was higher than from any other non-point source. In addition to fertilizers, the application of pesticides to developed landscape areas presents a significant problem for aquatic life. Storm events occurring shortly after the application of chemicals can be expected to produce runoff with significantly elevated pollutant levels. This water quality issue is avoided completely with an MD/MM design approach (DEDNREC, September 1997).

In development scenarios where an MD/MM site design approach completely negates the need for structural BMPs to control runoff quality and quantity, the benefit to cost ratio of such a design strongly supports its implementation. In situations where conventional BMPs must be implemented alongside MD/MM features, such an analysis is difficult to make. However, when site aesthetics and the reduced site work (site clearing, grubbing, rough and fine grading, and final landscaping) for an MD/MM design are considered, research suggests that the benefit to cost ratio is significantly greater than that of a conventional site design.

1.5 Structural Best Management Practices

Structural BMPs are the stormwater runoff management measures that typically come to mind when the engineering community thinks of surface runoff treatment. These practices can range from something as conceptually simple as porous pavement to large engineered wetlands where pollutant removal occurs at the physical, biological, and chemical level. The unifying feature found in all structural BMPs lies in the means by which they remove pollutants. "The basic mechanisms of pollutant removal operating in structural BMPs are the gravitational settling of pollutants, infiltration of soluble nutrients through the soil profile, and to a lesser extent, biological and chemical stabilization of nutrients" (FHWA, 1996, p.181). While the number and type of structural BMPs at an engineer's disposal inherently vary by geographic region, there are approximately 15 different measures widely used throughout the United States. These measures are identified in Table 1.1 and comprise the list of available BMPs in the Virginia Tech BMP Decision Support Tool. Each practice is discussed individually, in detail, in Chapter 3.

Table 1.1 Structural BMPs Available in the Virginia Tech BMP Decision Support Tool

Dry Extended Detention Basins	Sand Filters
Enhanced Extended Detention Basins	Bioretention Cells
Retention Basins	Constructed Stormwater Wetlands
Infiltration Trenches	Hydrodynamic Separators
Infiltration Basins	Catch Basin Inserts
Porous Pavement	Vegetated Roofs
Vegetated Buffer Strips	Rainwater Harvesting Techniques
Vegetated Swales	

Structural BMPs are often further grouped into classes comprised of BMPs that are designed to function in a similar manner. These classes of structural BMP include the pond or basin class, the infiltration class, the filter class, the wetlands class, the proprietary class, and the LID class. It is important to note that many BMPs function in a manner that spans multiple classes.

The mechanism by which the pond or basin class of BMP operates is through the detention of a "first flush" water quality volume until a desired percentage of the initially present pollutants has settled out of the water column. Upon being stored for some minimum hydraulic residence time, the runoff is then released to a downstream receiving channel. This class of structural BMP typically includes dry detention basins, enhanced detention basins, and retention basins. The class can be further expanded to include oversized pipes, underground vaults, and any other stormwater control measure whose primary objective is the detention and controlled release of runoff.

The infiltration class of BMP encompasses porous pavement, infiltration trenches, and infiltration basins. These practices function by infiltrating a designated volume of runoff into the underlying soil media. This infiltration process provides an opportunity for pollutants to be removed mechanically as runoff passes through the practice and into its underlying soil. Additionally, these practices provide a runoff control strategy capable of significantly contributing to groundwater recharge. Infiltration BMPs are generally regarded as providing very high pollutant removal efficiencies, but their implementation is limited by several physical site constraints. These constraints include the presence of shallow groundwater and/or bedrock, and the presence of very high or very low permeability soils (HSG A and D).

Filtration practices include vegetated filter strips, vegetated swales, sand filters, and bioretention. The primary means by which the filtration class of BMP improves the quality of surface runoff is through the mechanical filtering that occurs as runoff migrates through the practice. In the case of bioretention, there is also a significant water quality benefit provided through the uptake of pollutants by vegetation as well the infiltration of a portion of the inflow volume. Much like infiltration practices, the filtration class of BMP is generally considered to exhibit high pollutant removal capability. But, unlike the infiltration class of BMP, filtration practices are not subject to as many physical site constraints.

The unique, simultaneous removal of pollutants by physical, chemical, and biological means define the wetland class of structural BMP. Wetland BMPs can be naturally occurring or engineered. In many ways, stormwater wetlands function similarly to the pond class of BMP. However, the inclusion of a permanent marsh comprised of various depth zones permits hydraulic residence times far exceeding those observed in dry detention facilities. Additionally, the engineered mix of vegetative species inherent to a wetland BMP provides pollutant uptake at the biological level that is generally not observed in basins whose primary function is peak runoff rate attenuation.

The proprietary class of BMP encompasses manufactured devices predicated on a combination of settling and/or filtration to remove particulate pollutants from surface runoff. Proprietary practices vary widely in both size and function, with the most common variations being hydrodynamic separators and catch basin inserts. Hydrodynamic separation devices are designed to remove settleable solids, oil and grease, debris, and flotables from stormwater runoff through gravitational settling. As their name implies, catch basin inserts are filters which are placed in stormwater inlets. These replaceable filters allow runoff to pass through while a portion of the suspended pollutant load is intercepted. Proprietary BMPs are generally designed as flow-through structures, and do not provide significant detention volume or peak runoff rate reduction.

The LID class of structural BMP includes those practices which contribute to the preservation of a developing site's pre-development land cover and hydrologic runoff patterns. These practices include vegetated roofs and rainwater harvesting systems. A vegetated roof cover is a veneer of vegetation that is grown on and completely covers an otherwise conventional roof, thus more closely matching native surface vegetation than that of an impervious roof. With proper installation and selection of materials, even thin vegetated covers are capable of providing significant rainfall retention, runoff reduction, and water quality improvement. Rainwater harvesting measures include a number of devices intended to intercept precipitation, store it for a period of time, and provide a means for groundwater recharge or reuse of water. The use of rainwater harvesting systems as a runoff control strategy yields a positive impact on the volume, peak rate, and quality of stormwater runoff from a site. In instances when captured rainwater is used for onsite landscape irrigation, a site's pre-development hydrologic cycle can often be closely replicated in the developed state.

1.6 Current Approaches to Stormwater BMP Selection

Historically, to supplement personal experience and professional judgment, many in the engineering community have relied on various BMP selection matrices and flow charts to select an appropriate BMP for a particular application. One of the earliest collections of these BMP selection matrices is found in the Federal Highway Administration's 1996 publication titled Evaluation and Management of Highway Runoff Water Quality (FHWA, 1996). In many states, BMP selection matrices (or other, similar forms of guidance) are developed and published by the state's stormwater control program.

In the Mid-Atlantic region of the United States, the Maryland Department of the Environment (MDE) is a progressive leader in BMP design and selection research. Chapter four of the Maryland Stormwater Design Manual (MDE, 2000) is dedicated solely to the selection and location of BMPs. The MDE has developed a BMP selection process employing six primary criteria, with each criterion represented by a selection matrix. These matrices assist in the selection of appropriate site-specific BMPs by examining contributing watershed factors, terrain factors, stormwater treatment goals, physical feasibility factors, community and environmental factors, and permitting issues. Rather than providing a comparison or ranking of individual BMPs in these selection matrices, the MDE approach directs the designer to a particular category of BMP (basins, wetlands, infiltration, filters, etc.) from which the designer can then chose the specific BMP that he/she considers most appropriate. In effect, each selection matrix is superimposed onto other available matrices in an effort to determine which category of BMP meets performance goals and is physically feasible for the given site conditions and contributing watershed characteristics.

The matrix-based approach to BMP selection is not unique to the Mid Atlantic region of the United States. The Minneapolis – St. Paul Metropolitan Council's stormwater design manual presents a similar approach to BMP selection (MN, 2001). More abbreviated than the Maryland selection procedure, the Metropolitan Council employs a three step (matrix) process to BMP selection. The first matrix facilitates a comparison of the stormwater treatment capability of the competing BMP alternatives. Analogous to the stormwater treatment suitability matrix developed by the MDE, this matrix compares the respective ability of the various BMPs to meet runoff rate and volume reduction requirements as well as the ability of the BMPs to serve as a site's primary practice for pollutant removal. This matrix is supplemented by physical feasibility and environmental factors matrices, again similar to those developed by the MDE.

With such great focus currently placed on improving the quality of surface runoff, perhaps the most important BMP selection criterion is that of pollutant removal efficiency. Additionally, of great interest to any developer or municipal agency is the financial impact of implementing a BMP. Not only does the implementation cost exist, but there are long-term, often substantial maintenance costs associated with almost any BMP installation. Much like pollutant removal efficiency, implementation and maintenance costs should be integral considerations in the BMP selection process. However, the aforementioned flow charts and BMP selection matrices largely neglect these considerations. The Federal Highway Administration (FHWA) publication does contain a selection matrix which presents pollutant removal efficiencies and the costs associated with ten different BMPs. Pollutant removal efficiencies are expressed as nominal removal percentages. The costs associated with the various measures are categorized as capital costs, operation and maintenance costs, and long-term maintenance costs. These costs are expressed only as "high," "moderate," or "low." Brief examination of this matrix (FHWA, 1996, p.184) reveals that many of the removal efficiencies are not reported, listed only as "insufficient data." Similarly, the cost data presented in the matrix is vague and does not consider geographic location or the decline in performance as the BMP ages.

To address the issue of BMP pollutant removal performance, the Virginia Stormwater Management Handbook (Virginia DCR, 1999) endorses two different methods of BMP selection – the Performance-based and Technology-based approach. The Performance-based approach requires the designer to calculate the pre and post-development pollutant load (typically phosphorus) from the site of interest. Then, employing reported pollutant removal efficiencies, BMPs are chosen based on their ability to reduce the post-development pollutant loads to equal or less than pre-development levels.

An alternative BMP selection approach currently used by the Virginia Department of Transportation (VDOT) and others is the Technology-based approach. This approach requires the designer to compute the amount of new impervious area arising from a proposed development and make the BMP selection on the basis of the overall impervious fraction of the BMP's contributing drainage shed. This approach does not presume a specific pollutant removal target or efficiency and therefore contrasts the performance-based BMP selection procedure.

1.7 The Need for an Objective, Algorithmic BMP Selection Tool

Extending beyond traditional selection approaches, engineers are increasingly expected to examine more and more criteria when choosing a BMP for a particular application. Included among these criteria are physical site characteristics; local, state, and federal pollution control ordinances; and implementation and long-term maintenance costs. Progress in developing innovative approaches to stormwater management has made a broad array of structural and non-structural BMPs available to designers. Presently, there are approximately 15 different structural BMPs in wide-spread usage throughout the United States, each with its own intrinsic performance capabilities and limitations.

Introducing what is essentially an unlimited number of influential selection criteria to such a wide array of available BMP options make the selection of a single BMP for a particular application a daunting task. The BMP selection matrices (and other methods of BMP selection) available today are subject to personal bias and subjectivity despite their great value to engineers and planners. Consequently, stormwater management solutions too often default to the traditional "drain and detain" stormwater management approach with little or no consideration given to alternative design strategies and BMP options. An unfortunate reality is that, while effective for providing runoff rate attenuation, dry detention facilities are often not the best BMP option in terms of water quality improvement and cost. Clearly there exists the need for an objective, algorithmic means of introducing multiple criteria to the BMP decision process while giving equal consideration to each BMP alternative.

This report documents the application of the Analytic Hierarchy Process (AHP) decision support algorithm to the stormwater BMP selection process. "The analytic hierarchy process (AHP) provides the objective mathematics to process the inescapably subjective and personal preferences of an individual or a group in making a decision" (Schmoldt, 2001, p. 15). Fundamentally, the AHP works by developing comparisons among competing alternatives (in this application, individual BMP types) as well as the criteria used to judge the alternatives. The AHP permits mathematical comparison when the influential criteria exhibit vastly different scales (units) as is the case with the broad spectrum of factors influencing the BMP selection process.

Chapter 2. Project Objectives

The major objective of this project is to develop a software-aided decision support process to assist planners and engineers in the selection of urban stormwater BMPs for a particular application. To successfully achieve this objective, a number of individual project tasks were completed. This chapter introduces each of those tasks, with several of the tasks expanded upon in detail in Chapter 3.

2.1 Assembly of a Project Stakeholder Group

A major goal of this project was to identify project stakeholders who would serve as advisors to the project and who would also be the project participants in subsequent training workshops intended to disseminate the end-product of this project. The National Research Council report defines *stakeholder* as any *interested* or *affected p*arty (Stern and Fineberg 1996). Basically, stakeholders are individuals or entities who should be involved in the decision making process from the project onset and who are potential users of the end product. For this project, stakeholder selection was based on the following criteria: 1) individuals who are experts (planners, engineers, developers, and regulators) and decision makers in stormwater management issues; and 2) individuals who represent geographically various interests of the project demonstration sites within the study watershed and nearby localities. Table 2.1 shows the list of selected stakeholders who served as project advisors and are project training participants.

Table 2.1 Project Stakeholders, Affiliation and Expertise

Name	Affiliation	Title/Expertise
Bonnema, Ronald	Montgomery County, VA	County Engineer
Byrd, Kevin	New River Valley Planning District Commission	Regional Planner II
Dent, David	Virginia Tech	Manager, Site and Infrastructure Development
Dietz, Charles	Virginia Department of Conservation and Recreation	Stormwater Compliance Specialist
Nelson, Wayne	Town of Christiansburg	Director of Engineering and Public Works
Orndorff, Wil	Virginia Department of Conservation and Recreation	Karst Protection Specialist
Jones, Meredith	Tom's Creek Investors L.C., Colonial Green L.C.	Project Manager, Developer
Stolte, Mathew	Town of Blacksburg	Town Engineer
Harvey, Michael	New River Watershed Roundtable	Chair, Steering Committee
Rundgren, David	New River Valley Planning District Commission	Executive Director

During the course of the project, stakeholders frequently communicated individually with project investigators and met five times as a group to discuss project progress and to provide input to project investigators. Stakeholder group meeting took place the following dates: April 24, 2007; June 21, 2007; October 4, 2007; February 8, 2008; and June 18, 2008.

2.2 Development of BMP Decision Support Software

The introduction of what is essentially an unlimited number of influential selection criteria to a wide array of available BMP options makes the selection of a single BMP for a particular application a daunting task vulnerable to an individual's subjective interpretations and bias. Clearly a need exists for an objective, algorithmic means of introducing multiple criteria to the BMP selection process while giving equal consideration to each BMP alternative. One mathematical approach for decision support in the face of multiple influential criteria is the Analytic Hierarchy Process (AHP). First developed by mathematician Thomas Saaty in 1980, the AHP is an algorithm capable of assisting complex decision-making problems (Saaty, 1980). Perhaps the greatest strength of the AHP is that, although its foundation lies in complex matrix manipulation, it can be applied effectively without requiring the user to posses an in depth knowledge of multi-criteria decision-making theory.

Within the scope of this project, the AHP algorithm has been automated to function in the Microsoft® Windows® computing environment. Users of the self-contained AHP decision support software can simply select which BMPs to consider in a selection scenario, then, choose which criteria to apply in selecting from those competing BMP options a single practice. Users of the software are also provided the opportunity to weight the degree to which each individual criterion influences the BMP selection process. Table 2.2 shows the criteria presently available in the AHP decision support software. A detailed description of each criterion shown in Table 2.2 can be found in Appendix B of this report.

Table 2.2 Available Selection Criteria in the Virginia Tech BMP Decision Support Software

Contributing Drainage Area (CDA) < 1 ac	CDA Impervious Fraction < 21%
CDA 1-5 ac	CDA Impervious Fraction 21-37%
CDA 5-10 ac	CDA Impervious Fraction 38-66%
CDA 10-25 ac	CDA Impervious Fraction > 66%
CDA > 25 ac	Presence of Hotspot Runoff
Presence of Shallow Groundwater	Peak Runoff Rate Attenuation Ability
Presence of Shallow Bedrock	Aesthetic Benefit/Liability
Presence of Hydrologic Soil Group A	Public Safety
Presence of Hydrologic Soil Group D	Site Slopes/Topography
Ability to Recharge Groundwater	Total Suspended Sediment Removal
Implementation Cost	Total Phosphorus Removal
Annual Maintenance Costs	Total Nitrogen Removal

The AHP application described in this report does not comprise a classical optimization algorithm. The AHP, by design, does not possess an objective function, penalty function or randomization procedure. Rather it is a procedure for the systematic evaluation and ranking of BMP preferences, based on a wide range of criteria for selection and implementation. As developed within the scope of this project, the algorithm is capable of considering the 15 most popular structural BMPs presently used BMPs for urban nonpoint source pollution control.

2.3 Development of a Web-Based Geographic Information System (GIS) to Supplement the BMP Decision Support Software

Many of the criteria influencing the selection of a BMP for a particular runoff management application are functions of a site's physical characteristics. In order to optimally use the BMP decision support software described in Section 2.2 of this report, it is essential to have readily available input data depicting the physical characteristics of the site upon which the BMP is to be located as well as any offsite areas contributing runoff to the BMP. While some of these physical site characteristics can only be adequately evaluated through the completion of a detailed site investigation, some can be sufficiently assessed through the use of GIS software. This GIS-based desktop assessment is of particular value when stormwater management options are being evaluated at the planning stage of development. Completion of this project task yielded a web-based GIS for the Town of Blacksburg which related various physical characteristics to both individual parcels and sub-watersheds. Table 2.3 presents the various GIS layers compiled under the scope of this project, and their original data sources.

Table 2.3 GIS Data Compiled Within the Scope of this Project

Spatial BMP Selection Criteria	Description	Data Source(s)
Parcel Boundaries	Tax parcel boundaries within the Town of Blacksburg	.shp file from Town of Blacksburg GIS
Sub-Watershed Boundaries	Sub-watershed delineations	.shp file of sub-watersheds developed during the Town of Blacksburg MS-4 permitting process*
Land Cover	Identification of percentage imperviousness within parcel and sub-watershed boundaries.	Compilation of vector-format GIS data from various sources
Soil Type	Identification of area-weighted Hydrologic Soil Group within parcel and sub-watershed boundaries.	NRCS Soil Survey Geographic (SSURGO) Database
Site Slopes	Identification of average land slope within parcel and sub-watershed boundaries.	Town of Blacksburg LiDAR data

***** The delineation of subwatersheds within the Town was completed during the first phase of the Town of Blacksburg Storm Water Management Research project (Center for Geospatial Information and Technology (CGIT) June – November 2006). Completion of this phase yielded a shapefile of the urban subwatersheds contributing runoff to the Town's storm sewer system, based on the Town's existing storm sewer system data.

As seen in Table 2.3, the physical site characteristics that can be evaluated through the use of this GIS include percent imperviousness, hydrologic soil group, and average land slope. Each of these parameters can be evaluated on either the individual parcel or the sub-watershed scale. Relating these parameters to individual parcels is useful when the BMP installation will serve relatively small development projects confined to a single tax parcel. The ability to evaluate these parameters on the sub-watershed scale is useful when the BMP(s) will serve larger developments spanning multiple parcels.

2.4 Adaptation of EPA SWMM v 5.0 to the Modeling of Individual BMPs

Accurately predicting the performance of a stormwater management measure prior to its implementation is often a major challenge for stormwater engineers and regulators. Runoff management strategies, such as the preservation of existing soil and vegetation, can be modeled relatively easily in a number of different computing environments. However, modeling the performance of complex structural BMPs, such as bioretention cells, generally requires the creative manipulation of software elements. This project task sought to establish a standardized, repeatable means by which the BMPs presented in Table 1.1 could be effectively modeled for both hydraulic and pollutant removal performance.

The Environmental Protection Agency's Stormwater Management Model version 5.0 (EPA SWMM v.5) is a highly versatile, public-domain software tool used primarily for the hydraulic and hydrologic modeling of urban watersheds. EPA SWMM has the inherent ability to depict a variety of common hydraulic elements in urban stormwater modeling scenarios. These model elements include open-channels, pipe networks, pumps, detention facilities, and "treatment nodes" that permit the user to depict the removal of pollutants from stormwater runoff. However, except for detention basins, there is no automated means in EPA SWMM to simultaneously model various BMP types for their hydraulic and pollutant removal performance. A task of this project was to develop a methodology for representing individual BMP types within EPA SWMM. The developed methodology consists of assembling the hydraulic elements available in EPA SWMM in a way that reasonably depicts the hydraulic and pollutant removal performance of the various BMPs shown in Table 1.1. Techniques for modeling various BMPs in the EPA SWMM environment are documented in Appendix D..

Upon developing an effective, standardized means of modeling individual BMPs in EPA SWMM, a hydraulic model was built for a large commercial development presently under construction in the Town of Blacksburg, Virginia. The BMP representation techniques used in the hydraulic model are described in Appendix F. The developed techniques enabled a comparison of various runoff management strategies, each of which is discussed at length in Chapter 3.

2.5 Development of Users' Manuals

A total of six major project tasks are discussed in this report, which include the development of a new software application and two specific techniques for use in existing software applications. Users' guidance and tutorials for each of these applications are documented in Appendices E, F, and G.

2.6 Training Seminars

Unlike the active processes and enforcement associated with erosion and sediment control measures during construction, stormwater management has often tended to be a more passive process. As stormwater management becomes an increasingly focused upon element in land development and redevelopment there is a need to consider and evaluate alternative management options (BMPs) early in the planning stages of a project.

In an effort to facilitate interdisciplinary discussions earlier in the development process, the Virginia Tech BMP Decision Support Software was developed to provide a tool making stormwater management a more prominent aspect of the land development, redevelopment, and growth processes. The software was designed to increase all parties' knowledge of the stormwater management options available and to facilitate a common, unbiased basis for selection and evaluation of stormwater management facilities.

To encourage full utilization of the Virginia Tech BMP Decision Support Software a number of training sessions are planned. These education and outreach sessions were designed to be generally non-technical in nature in order to foster the interdisciplinary approach utilized throughout this project. Urban localities have been very active in their stormwater management in the past, but that is not the case with rural localities. In an effort to engage rural localities, some of the education and outreach sessions have deliberately targeted that audience. The New River Valley Planning District Commission (NRVPDC) is serving as the lead in this activity.

The following describes these training sessions, already conducted or currently planned by the NRVPDC.

Education and Outreach Sessions -- Virginia Association of Planning District Commissions

At the summer 2007 meeting of the Virginia Association of Planning District Commissions, participants were briefed on the project. The purpose of this briefing was to increase awareness regarding the development of this new tool in improving stormwater management.

In April 2008, the Planning District Commission Directors were again briefed on the status of the project. At this time, input was solicited to improve the potential efficiency and utilization rates across the Commonwealth. The presentation to the Directors included a short project summary, software description, and example project application. Again, the goal of this presentation was to increase awareness of the BMP software and its potential widespread use in the evaluation of stormwater management alternatives.

General Training Session

A comprehensive training session is scheduled for Tuesday, July 29, 2008. The session will be held from 10:00 AM to 4:30 AM at the New River Valley Competitiveness Center in Radford, VA. Approximately 65 local government officials, state-level regulators, private sector engineers and developers from the New River Valley region are invited to attend this training session.

The session will be broken into a morning and afternoon program. The morning program will provide participants with background information on the overall project, as well as a brief introduction to the BMP selection software. During the afternoon program, participants will be broken into smaller, interdisciplinary groups to work through BMP selection scenarios using the software on their own laptops. Through this small group work, we hope to obtain feedback from those individuals involved throughout the development project design, approval, and construction processes. Once the small groups have worked through several example sites, the larger group will come back together for discussion and a question and answer session. The software developers view this as an opportunity to identify any potential deficiencies or issues that arose when these new individuals utilize the BMP selection tool.

Depending on response and outcome of this first training session, the NRVPDC hopes to provide a second training session to individuals from a slightly larger regional area.

Rural Planning Caucus

In an effort to increase the stormwater management activities in rural areas, the NRVPDC will provide an abbreviated training session for rural planners at a date and location yet to be determined. In an attempt to have rural planners recognize that stormwater management is an essential component of every development project, they will be given an opportunity to see a demonstration of the BMP software. Understanding and utilizing the BMP decision support software will provide rural planners a valuable tool as they are required to more actively integrate stormwater management in the early stages of the development process.

Each of these education and outreach sessions was designed to inform individuals throughout the Commonwealth of Virginia about the applicability and availability of this new decision-making tool. The true success of this project can only be achieved through the widespread implementation and utilization of the BMP Decision Support Software. Only then will it have a measurable impact on the utilization of BMP alternatives more appropriate to specific sites, while still meeting the stormwater quality and quantity requirements imposed by the Virginia Department of Conservation and Recreation.

Chapter 3. Project Approach and Methodology

3.1 BMPs Chosen for Inclusion in the Decision Support Tool

A structural BMP is a device intended to remove targeted pollutants and contaminants from stormwater runoff, thus preventing the introduction of these pollutants to receiving waters. The number and type of structural BMPs available for the treatment of stormwater runoff varies geographically. The major objective of this research project was to develop a software-aided decision support process to assist planners and engineers in the selection of urban stormwater BMPs for a particular application scenario. In order to accomplish this objective, it was necessary to identify BMPs that should be included in the decision support software. The pilot site/watershed that was studied under the scope of this research project is located in the Town of Blacksburg, Virginia (see section 3.4 of this report). Consequently, BMPs that are recognized by the State of Virginia's Stormwater Management Program were prioritized for inclusion in the BMP decision support software.

In 1998, the Virginia Stormwater Management (SWM) regulations (4 VAC 3-20-10 et. seq.) were amended as a result of the evolutionary nature of effective stormwater management. One outcome of the amendments was the Virginia Stormwater Management Handbook published by the Virginia Department of Conservation and Recreation (DCR, 1999). The Handbook provides technical guidance for compliance with the State SWM regulations. Chapter 3 of the Handbook is comprised of technical design requirements, specifications, and maintenance requirements for each of the structural BMPs (Table 3.1) defined in section 4 VAC 3-20-10 of the Virginia Code.

Table 3.1 Structural BMPs Recognized in the Virginia Stormwater Management Regulations

Dry Extended Detention Basins	Porous Pavement
Extended Detention Basins - Enhanced	Bio-Retention
Retention Basins	Sand Filters
Constructed Wetlands	Grassed Swales
Infiltration Basins	Vegetated Filter Strips
Infiltration Trenches	Manufactured BMP Systems

The following is a brief definition of each of the BMPs shown in Table 3.1.

Dry Extended Detention Basins

A dry extended detention basin is defined as an impoundment which temporarily detains runoff and releases that runoff at a controlled rate over a specified period of time. By definition, extended dry detention basins are dry structures during non-precipitation periods. Extended dry detention basins are capable of providing water quality improvement, downstream flood control, channel erosion control, and mitigation of post-development runoff to pre-development levels. The primary mechanism by which a dry extended detention facility improves runoff quality is through the gravitational settling of sediment and associated pollutants.

Enhanced Extended Dry Detention Basins

Similar to dry extended detention basins, an enhanced basin is capable of temporarily detaining runoff and releasing that runoff at a controlled rate over a specified period of time. However, unlike dry basins, enhanced basins are equipped with an engineered permanent marsh area. This marsh area functions to improve the pollutant removal performance of the basin beyond that which is possible in a traditional dry detention basin. Enhanced extended dry detention basins are capable of providing water quality improvement, downstream flood control, channel erosion control, and mitigation of post-development runoff to pre-development levels. Enhanced extended detention facilities improve runoff quality through the gravitational settling of sediment as well as through pollutant uptake, absorption, and decomposition by the marsh. Also aiding in pollutant removal performance, the marsh area of the basin prevents the resuspension of captured pollutants.

Retention Basins

A retention basin (also called a “wet pond”) is, by definition, a basin which retains a portion of its inflow in a permanent pool such that the basin is typically wet even during non-precipitation or dry periods. Generally, stormwater runoff is stored above the permanent pool, as necessary, to provide flood control and/or downstream channel protection. Retention basins are capable of providing downstream flood control, water quality improvement, channel erosion control, and the reduction of post-development runoff rates to pre-development levels. Retention basins are regarded as exhibiting some of the highest pollutant removal efficiencies of any BMP option.

Constructed Wetlands

Constructed stormwater wetlands have the ability to improve the quality of stormwater runoff in much the same manner as retention and enhanced extended detention basins. Stormwater wetlands are seeded with a diverse mix of aquatic and emergent vegetation, which plays an integral role in the pollutant removal efficiency of the practice. Wetland BMPs improve the quality of runoff by physical, chemical, and biological means. The physical treatment of runoff occurs as a result of decreased flow velocities in the wetland, thus leading to evaporation, sedimentation, adsorption, and/or filtration. Chemical treatment occurs in the form of chelation (bonding of heavy metal ions), metal precipitation, and chemical adsorption. The biological treatment processes occurring in wetlands include decomposition, plant uptake and removal of nutrients, and biological transformation and degradation. (FHWA, 1996)

Infiltration Basin

Infiltration basins are impounding facilities which temporarily store surface runoff and infiltrate a designated portion of the stored water into the soil strata. Infiltration basins may also serve as peak mitigation facilities for flood control by providing “dry” storage above the designated infiltration volume. This dry, flood control volume is then released through a multi-stage riser and barrel system. Conceptually, an infiltration basin can be viewed as an extended dry detention basin where water infiltrates into the soil strata rather than being released through a small, low-flow orifice.

Infiltration Trenches
Infiltration trenches are shallow trenches underlain by an underground reservoir comprised of coarse stone aggregate. The void space created by the aggregate provides storage for surface runoff that has been diverted into the trench. This runoff then infiltrates into the surrounding soil, through the bottom and sides of the trench. Infiltration trenches act primarily as water quality BMPs. However, when equipped with underground piping, the temporary storage volume of the trench may be increased to a volume that provides peak runoff rate reduction for one and two year return frequency storms. Peak rate control of larger return frequency storm events is typically beyond the capacity of an infiltration trench practice.

Porous Pavement
Porous pavement is a pervious traffic-bearing surface placed over a gravel reservoir which is, in turn, underlain by highly porous (permeable) soil. The void space created by the gravel reservoir provides storage for surface runoff generated on or diverted onto the porous surface. The runoff then infiltrates into the surrounding soil, through the bottom and sides of the gravel reservoir. Porous pavement may substitute for conventional pavement on parking areas and areas with light traffic, though it is generally not suited for high traffic areas. Porous pavement acts primarily as a water quality BMP. However, much like an infiltration trench, when equipped with underground piping, the temporary storage volume of the reservoir may be increased to provide peak runoff reduction for the one and two year return frequency storms.

Bioretention Practices
Bioretention practices form a class of BMP whose primary function is to remove pollutants and improve the quality of stormwater runoff by means of adsorption, filtration, volitization, ion exchange, and microbial decomposition. However, some runoff rate and volume reduction is realized through the infiltration of runoff. In the most general sense, a bioretention BMP can be thought of as a modified infiltration area comprised of a specific mix of trees, plants, and shrubs intended to mimic the ecosystem of an upland (non-wetland) forest floor. There are two categories of bioretention BMP: basins and filters. Bioretention basins are planting areas constructed as shallow basins in which stormwater inflow is treated by filtration through the surface plant material, biological and chemical reactions within the soil and basin vegetation, and the eventual infiltration into the underlying soil media. Bioretention filters function much the same as bioretention basins, but are used in locations where full infiltration is not feasible due to inadequate soil permeability or the proximity to wells, drainfields, or structural foundations.

Sand Filters
Sand filters are practices employed when the runoff from a site is expected to contain very high pollutant levels. These sand filters function by first pre-treating and temporarily storing runoff to remove the bulk of the large particle sediment, then percolating the runoff through the filter's sand media. As runoff percolates through the sand media, water quality is improved through physical, chemical, and biological mechanisms. Various types of stormwater sand filters exist, and their application can be

tailored to meet individual site needs. Stormwater sand filters act primarily as water quality BMPs. However, the water volume entering the filter is detained and released at a rate potentially capable of providing downstream channel erosion control. Peak rate control of the 10-year and greater return frequency storm events is typically beyond the capacity of a stormwater filtering system.

Vegetated Swales

Vegetated swales are broadly described as surface depressions which collect and convey stormwater runoff from roadways, driveways, rooftops, and other impervious surfaces. However, when applied as a BMP, an engineered grassed swale functions beyond simple collection and conveyance, also contributing to improved quality of stormwater runoff through sedimentation and filtration. The inherent linear orientation of a vegetated swale makes it an attractive option for treatment and conveyance of highway runoff. Vegetated swales minimize flow velocity and induce water ponding behind strategically placed check dams. While the inevitable infiltration derived from ponding can attenuate peak runoff rates, this attenuation can be considered minimal at best. Vegetated swales are water quality improvement practices, and cannot be considered effective flood control strategies.

Vegetated Filter Strips

A vegetated filter strip is a densely vegetated strip of land, similar to a grassed swale, but engineered to accept runoff from upstream development only as overland sheet flow (Yu, 2004). The type of vegetation selected may range from native species, to grass meadow, to forest. In addition to serving as a primary water quality improvement practice, vegetated filters strips function extremely well as pre-treatment measures for other BMPs whose function may be compromised if sediment loading is excessive. Vegetated filter strips are water quality improvement practices, and cannot be considered effective flood control strategies.

Manufactured BMPs

Manufactured BMP systems encompass both hydrodynamic separation devices and catch basin media inserts. Hydrodynamic separation devices are designed to remove settleable solids, oil and grease, debris, and floatables from stormwater runoff through gravitational settling. Hydrodynamic separation devices are not intended to mitigate the peak rate of runoff from their contributing watershed. Their implementation is solely for water quality enhancement in urban and ultra-urban areas where surface BMPs are not feasible. Catch basins are chambers or sumps which provide the entrance point for surface runoff into a stormwater conveyance system. Catch basin inserts are employed to intercept coarse sediments, oils, grease, litter, and debris from the runoff prior to its entrance into the storm sewer. Catch basin inserts are well suited to parking lots, maintenance yards, and other locations where runoff travels directly from an impervious surface into the stormwater conveyance system. (VTRC, 2004)

Other BMPs
The Handbook states that additional BMPs may be implemented "*at the discretion of the local program administrator or the Department.*" Effective stormwater management programs are, necessarily, evolutionary in nature. As such, it is reasonable to anticipate the continued development of an increasing number of BMP alternatives. Two such BMP alternatives not specifically cited in the Handbook are vegetated roofs and rainwater harvesting (capture and reuse) systems. These runoff management practices have experienced increasing popularity and implementation since the publication of the Handbook in 1999.

A vegetated roof cover is a veneer of vegetation that is grown on and completely covers an otherwise conventional roof. With proper installation and selection of materials, even thin vegetated covers are capable of providing significant rainfall retention, runoff reduction, and water quality improvement. Rainwater harvesting measures include a number of devices intended to intercept precipitation, store it for a period of time, and provide a means for indoor and outdoor water use. The use of rainwater harvesting systems as a runoff control strategy yields a positive impact on the volume, peak rate, and quality of stormwater runoff from a site.

The structural BMPs shown in Table 3.1 along with vegetated roofs and rainwater harvesting systems comprise the list of available BMP options in the Virginia Tech BMP Decision Support Tool. Appendix B of this report provides a detailed discussion of each of these BMP options.

3.2 Selection Criteria for Inclusion in the BMP Decision Support Tool

When attempting to choose a single practice from a pool of competing BMP options, numerous factors influence the decision making process. Most of these factors can be categorized as either a functional goal or a physical site constraint. Functional goals include reducing the peak rate and/or volume of runoff from a site and the removal of targeted pollutants from the runoff. Physical site constraints comprise those factors that may preclude the use of certain BMPs or classes of BMPs. These constraints include the practice's contributing drainage area, site soil type(s), topography, and geologic factors. Yet other criteria exist that are neither a functional goal nor a physical site constraint. These criteria include the practice's aesthetic benefit or liability, the implementation and maintenance costs of the practice, and public safety issues associated with the practice.

The criteria deemed "essential" to the BMP selection process almost certainly vary among a project's stakeholders. While a site's owner or developer may view annual BMP maintenance cost as the paramount selection consideration, the stormwater engineer likely views any number of technical performance goals as being more important to the BMP selection process. The major objective of this research project was to develop a software-aided decision support process to assist both planners and engineers in the selection of urban stormwater BMPs for a particular application scenario. Reflecting this objective, Table 3.2 presents the available selection criteria in the Virginia Tech BMP

Decision Support Software. Following Table 3.2 is a discussion of each of these criteria as they relate to BMP selection. Appendix D of this report provides a detailed discussion of how BMP rankings were developed for each of these criteria.

Table 3.2 Available Selection Criteria in the Virginia Tech BMP Decision Support Software

Contributing Drainage Area (CDA) < 1 ac	CDA Impervious Fraction < 21%
CDA 1-5 ac	CDA Impervious Fraction 21-37%
CDA 5-10 ac	CDA Impervious Fraction 38-66%
CDA 10-25 ac	CDA Impervious Fraction > 66%
CDA > 25 ac	Presence of Hotspot Runoff
Presence of Shallow Groundwater	Peak Runoff Rate Attenuation Ability
Presence of Shallow Bedrock	Aesthetic Benefit/Liability
Presence of Hydrologic Soil Group A	Public Safety
Presence of Hydrologic Soil Group D	Site Slopes/Topography
Ability to Recharge Groundwater	Total Suspended Sediment Removal
Implementation Cost	Total Phosphorus Removal
Annual Maintenance Costs	Total Nitrogen Removal

The first physical site constraint available as a BMP selection criterion is contributing drainage area (CDA). The installation of most BMPs is influenced greatly by the total area contributing runoff to the practice. For example, small, source control practices such as bioretention cells are generally not recommended for the treatment of runoff from areas greater than 5 acres. By contrast, practices such as retention ponds and constructed wetlands require much larger drainage areas capable of providing baseflow to maintain their permanent pools. Regardless, it is essential that the BMP chosen for a particular application is adequately suited to receive the runoff from its CDA. The Virginia Tech BMP Decision Support Software allows its user to choose from four CDA ranges: less than 1 acre, 5-10 acres, 10-25 acres, and greater than 25 acres.

The presence of shallow or seasonally shallow groundwater depths (typically defined as less than two feet below a site's finished grade) usually precludes the use of infiltration practices. In addition to infiltration basins and trenches, this restriction extends to bioretention basins and porous pavement as well. Practices which infiltrate little or no runoff into the subsurface are favored as treatment options in the presence of a shallow groundwater table. These practices include grassed swales, vegetated filter strips, manufactured BMP systems, and rainwater harvesting systems. Retention ponds and constructed wetlands may be designed to utilize the presence of shallow groundwater as a source of baseflow, and thus such a site characteristic is often considered beneficial to their implementation.

Much like the presence of a shallow groundwater table, the presence of shallow bedrock depths on a site greatly restricts the BMP options at the designer's disposal. Infiltration practices and other BMPs which operate by employing subsurface filter beds are generally prohibited. As in the case of shallow groundwater depths, practices which allow little infiltration or no runoff into the subsurface are favored as treatment options. However, unlike the presence of a shallow groundwater table, the presence of shallow bedrock depths provides no benefit for the implementation of retention ponds and constructed wetlands, and in fact may preclude their installation without a liner to minimize infiltration.

Hydrologic soil group (HSG) A consists of sand, loamy sand, or sandy loam types of soils. These soils exhibit low runoff potential and high infiltration rates even when thoroughly wetted. The presence of HSG A on a site restricts the BMP options from which a designer can choose. Generally, this soil group exhibits infiltration rates beyond what is recommended for infiltration practices. Similarly, these excessively high infiltration rates may present difficulties in achieving acceptable hydraulic residence times in detention facilities, vegetated swales and filters, and wetlands. In the absence of synthetic liners, the presence of HSG A generally precludes the use of these practices.

HSG D consists primarily of clay loam, silty clay loam, sandy clay, silty clay, or clay. This HSG has the highest runoff potential among all soil groups. Characteristics of HSG D are high swelling potential and very low infiltration rates when thoroughly wetted. In terms of surface runoff potential, HSG D behaves analogously to an impervious surface. Typically, soils classified as HSG D do not exhibit the minimum infiltration rates required of infiltration practices. Consequently, the implementation of infiltration practices, and those practices exhibiting similar physical processes, is restricted in the presence of these soil groups. While this criterion impacts the selection of infiltration practices in much the same manner as the shallow groundwater or shallow bedrock criteria, it impacts the selection of basin practices in a considerably different manner. The presence of HSG D is considered beneficial to the implementation of basin practices because it significantly reduces the undesired exfiltration loss of detained runoff.

Groundwater recharge is the hydrologic process by which precipitation migrates downward from the land surface, eventually entering the groundwater table. This natural process is critical to the long-term sustainability of groundwater supplies where aquifer extraction rates must not exceed recharge rates. Groundwater recharge is often impeded by land use intensification and the resulting increase in imperviousness. Numerous locations in the United States now require land development projects to provide some minimum level of post-development groundwater recharge through the use of BMPs. The Maryland Department of the Environment (MDE) evaluates BMPs in terms of their ability to provide groundwater recharge (Table 3.3).

Table 3.3 Groundwater Recharge Ability of BMPs
Source: Maryland Department of the Environment, 2000

BMP	Groundwater Recharge Capability
Extended Dry Detention Basin	No
Retention Basin	No
Infiltration Trench	Yes
Infiltration Basin	Yes
Constructed Wetlands	Varies*
Bioretention	Yes
Vegetated Swale	Yes
Stormwater Filtering Systems	Varies*

*Indicates that, though direct infiltration does not occur, groundwater recharge may occur through exfiltration

Porous pavement is not specifically addressed by the MDE, but for purposes of this evaluation, it is reasonable to assume that porous pavement systems exhibit a comparable level of groundwater recharge to other infiltration practices. Filter strips, manufactured BMP technologies, and vegetated roofs are generally regarded as providing no groundwater recharge.

BMP construction and maintenance costs vary considerably on a site-by-site basis. With any number of physical, site-specific parameters influencing the size and design of an individual BMP it becomes impractical, if not impossible to confidently predict all of the material and labor costs associated with a given BMP type. In addition to the aforementioned physical site factors, there are issues such as land acquisition costs, contractor availability, seasonal impacts on construction activities, and non-essential BMP amenities that must be considered when preparing a detailed cost estimate for a proposed BMP installation. All of these factors, as well as many more, vary immensely both geographically and climatically. The Virginia Tech BMP Decision Support Software allows its user to consider both installation and annual maintenance costs during the BMP selection process. However, these cost comparisons are only relative comparisons among the competing BMP options and are not intended to replace the need for detailed construction cost estimates, nor do they address unforeseen, non-routine maintenance activities.

Described in Chapter 2 of the Virginia Stormwater Management Handbook (DCR, 1999), one approach to BMP selection is defined as “technology-based.” This approach requires the designer to compute the amount of new impervious area arising from a land development project, and then make the BMP selection on the basis of the overall impervious fraction of the BMP’s contributing drainage shed. This approach does not presume a specific pollutant removal target or efficiency and therefore contrasts a “performance-based” BMP selection procedure. The Virginia Tech BMP Decision

Support Software allows its user to choose from four impervious fraction ranges: less than 21%, 21-37%, 38-66%, and greater than 66%.

Stormwater hotspots are defined as runoff generating sites from which the runoff exhibits pollutant concentrations greatly in excess of those typically found in stormwater. More often, this definition is further extended to reflect the presence of hydrocarbons in the runoff. The Maryland Department of the Environment (MDE, 2000) cites all BMPs capable of accepting hotspot runoff, with the exception of infiltration practices and wet vegetative water quality swales. The Virginia Tech BMP Decision Support Software permits its user to consider the presence of hotspot runoff in the BMP selection process. Within the software, all BMPs capable of receiving hotspot runoff are ranked equally, while those practices to which hotspot runoff cannot be directed are ranked very low for this criterion.

Historically, the focus of stormwater management has been to reduce the peak rate of runoff from a developed site to pre-development (or other acceptable) levels. Providing flood control in the form of peak rate attenuation is still a highly prioritized goal in most stormwater management endeavors. In the state of Virginia, this functional stormwater management goal is required by "Minimum Standard 19"of the Virginia Erosion and Sediment Control Regulations (Section 4VAC50-30-40). Minimum Standard 19 states:

"Properties and waterways downstream from development sites shall be protected from sediment deposition, erosion, and damage due to increases in volume, velocity, and peak flow rate of stormwater runoff for the stated frequency storm of 24-hour duration in accordance with the following standards and criteria: Concentrated stormwater runoff leaving a development site shall be discharged directly into an adequate natural or man-made receiving channel, pipe, or storm sewer system. For those sites where runoff is discharged into a pipe or pipe system, downstream stability analyses at the outfall of the pipe or pipe system shall be performed."

The Virginia Tech BMP Decision Support Software enables it user to consider runoff rate attenuation capability when choosing among competing BMP options.

When the proposed installation is in a high profile location, the public perception of a BMP may become an essential selection consideration. Some BMPs, notably dry detention basins, offer very little potential to provide aesthetic benefit to a site and, in fact, may be an aesthetic liability. Other BMPs, while having little potential to provide aesthetic benefit to a site, can be designed to minimize their obtrusiveness. Still other BMPs, such as retention basins and constructed wetlands, can be designed such that they become a desirable site amenity capable of providing recreational opportunities and wildlife habitat. The aesthetic benefit or liability of the various BMP options is available as a selection criterion in Virginia Tech's BMP Decision Support Software.

Some BMPs have inherent public safety issues associated with their installation. The most notable safety concern arising from BMP implementation occurs when the practice exhibits a permanent pool, such as the case with enhanced detention basins, retention basins, and constructed stormwater wetlands. Practices exhibiting a permanent pool also have the potential to become marshy and stagnant, resulting in ideal habitat for mosquitoes and other disease carrying vectors. The Virginia Tech BMP Decision Support Software permits its user to consider public safety during the BMP selection process.

The topography of a site for which a BMP installation is proposed is an important factor in choosing the appropriate practice. BMPs employing underground reservoirs and/or infiltration beds generally require site slopes to be less than five percent. Similarly, the use of filtering practices such as grassed swales and vegetated filter strips is restricted to site slopes of less than 20 percent. When the site of interest exhibits steep slopes, users of the Virginia Tech BMP Decision Support Software can introduce this as a BMP selection criterion.

The runoff from urbanized areas carries a variety of soluble and particulate pollutants, typically at levels much greater than those observed in the runoff from undisturbed, natural spaces. Many of these pollutants pose significant threats to the aquatic ecosystems of receiving waters. The state of Virginia defines phosphorus as its "keystone pollutant." Phosphorus was selected because of the unique manner in which it exhibits characteristics of both soluble and particulate pollutants. Nutrients (phosphorus and nitrogen) are of concern because of their potential to cause eutrophication of surface waters. Notable levels of suspended sediment are also found in the runoff generated from impervious surfaces, managed lawns, and sites whose surfaces have been denuded through construction processes. Within the Virginia Tech BMP Decision Support Software, users are provided the opportunity to introduce the functional goals of removing suspended sediment, phosphorus, and nitrogen to the BMP selection process.

3.3 Development of a Decision Support Geographic Information System (GIS)

Many of the criteria influencing the selection of a BMP for a particular runoff management application are functions of a site's physical characteristics. In order to effectively use the BMP decision support software described in Section 2.2 of this report, it is essential to have readily available input data depicting the physical characteristics of the site upon which the BMP is to be located as well as any offsite areas contributing runoff to the BMP. While some of these physical site characteristics can only be adequately evaluated through the completion of a detailed site investigation, some can be sufficiently assessed through the use of a GIS. This GIS-based desktop assessment is of particular value when stormwater management options are being evaluated at the planning stage of development. Table 3.4 presents the GIS data compiled within the scope of this project. Following Table 3.4 is a discussion of each of these data layers, including their origin. Appendix G of this report presents a tutorial on the development of this type of GIS using ESRI® ArcMap® version 9.2.

Table 3.4 GIS Data Compiled Within the Scope of this Project

Data Category	Description	Data Source(s)
Parcel Boundaries	Tax parcel boundaries within the Town of Blacksburg	.shp file from Town of Blacksburg GIS
Sub-Watershed Boundaries	Sub-watershed delineations	.shp file of sub-watersheds developed during the Town of Blacksburg MS-4 permitting process
Land Cover	Identification of percentage imperviousness within parcel and sub-watershed boundaries.	Compilation of vector-format GIS data from various sources
Soil Type	Identification of area-weighted HSG within parcel and sub-watershed boundaries.	NRCS Soil Survey Geographic (SSURGO) Database
Site Slopes	Identification of average land slope within parcel and sub-watershed boundaries.	Town of Blacksburg LiDAR data

The Parcel Boundaries layer is a shapefile obtained from the Town of Blacksburg GIS (http://www.gis.lib.vt.edu/gis_data/Blacksburg/GISPage.html). This data layer depicts individual parcel boundaries as defined by the Montgomery County, Virginia tax maps. Within the context of the application described in this report, the various physical site parameters shown in Table 3.4 were joined to the Parcel Boundaries data layer. Attributing these parameters to individual parcels is useful when the proposed BMP installation will serve relatively small development projects confined to a single parcel. This enables users of the Virginia Tech BMP Decision Support Software to easily obtain land cover, soil type, and average slope data for the specific parcel upon which a BMP installation is proposed. The method by which the Parcel Boundaries shapefile was joined to these data layers is described, in detail, in Appendix G of this report.

The Sub-Watershed Boundaries layer is a shapefile developed during the first phase of the Town of Blacksburg Stormwater Management Research project by the Center for Geospatial Information and Technology (CGIT) in the fall of 2006. Completion of this research effort yielded a shapefile of the urban subwatersheds contributing runoff to the Town's storm sewer system. Within the context of the application described in this report, the various physical site parameters shown in Table 3.4 were joined to the Sub-Watershed Boundaries layer. The ability to evaluate these parameters on the sub-watershed scale is useful when the chosen BMP(s) will serve large developments spanning multiple parcels. The method by which the Sub-Watershed Boundaries shapefile was joined to these data layers is described, in detail, in Appendix G of this report.

The Land Cover data set represents a compilation of vector-format GIS data that spans the Town of Blacksburg political boundary and discretely categorizes land cover as either pervious or impervious. This land cover/imperviousness dataset was developed by CGIT during its stormwater management research work conducted for the Town of Blacksburg. Virginia's "technology-based" BMP selection approach requires the planner/engineer to compute the impervious percentage of the drainage shed contributing runoff to a BMP, and then make the BMP selection on the basis of the overall impervious fraction of the BMP's contributing drainage shed. Within the scope of this project, land cover vector data was converted to a raster format and then zonal statistics were computed to determine imperviousness at both the parcel and sub-watershed scale. This enables users of the Virginia Tech BMP Decision Support Software to readily obtain the impervious fraction of either a parcel or sub-watershed, thus facilitating BMP selection by the technology-based approach.

The land cover dataset employed within the scope of this project is rather detailed, based on local transportation and building inventory GIS data. The feasibility of developing land cover datasets at such a detailed level depends on the quality of existing GIS data available for the area, as well as the resources available for development and maintenance of the dataset. In instances when it is not possible to acquire detailed local-level land cover data, less detailed land cover data may be obtained from a variety of sources. At a nationwide level, the Multi-Resolution Land Characteristics Consortium (MRLC) produces the National Land Cover Database (NLCD) line of products, derived from satellite imagery. The primary NLCD product is a land cover classification raster with a 30 meter cell size, but additional datasets of imperviousness and forest canopy have also been developed.

The Soil Type data set represents a compilation of soils data originating from the Soil Survey Geographic (SSURGO) database. SSURGO soils databases are typically published on a countywide basis and are available for free download (http://soils.usda.gov/survey/geography/ssurgo/). This data is often the most detailed soils information available for any given study area. Upon download, the SSURGO data is delivered in two formats. One format is a shapefile and the other is a corresponding Microsoft® Access® database. The SSURGO shapefiles are comprised of "map unit polygons," and these polygons can be related to data held in the corresponding Access® database (although often the relationship between map unit polygons and records in a SSURGO table is not 1:1). Hydrologic Soil Group (HSG) data is reported in the "soil component table" of the SSURGO data, but many soil components may be present in any given map unit polygon. Therefore, to create a GIS dataset of HSG polygons, data aggregation within the SSURGO database is necessary.

Within the scope of this project, a two step process was applied to obtain HSG data and attribute that data to both parcels and sub-watersheds. First, the SSURGO soil component data was aggregated such that each map unit polygon exhibited a single HSG. A common aggregation method, and the one applied in completing this task, is "Dominant Condition," in which the attribute with the highest percent composition from among the various soil components present in a map unit is selected. For example, if

75% of the soil components present in a map unit have an HSG of C, then the entire map unit will be assigned an HSG of C. Upon completion of this step, the map unit polygons were converted to a raster format and then zonal statistics were computed to determine area-weighted HSG at both the parcel and sub-watershed scale. This procedure enables users of the Virginia Tech BMP Decision Support Software to obtain an estimate of the most prevalent HSG found within either a parcel or sub-watershed.

The Site Slopes data set represents an interpretation of Light Detection and Ranging (LiDAR) terrain data that enables the user to obtain the average land slope of either a parcel or sub-watershed. Using 2005 LiDAR data provided by the Town of Blacksburg, an elevation raster was first developed. Then, using the spatial analyst tool in ArcMap® this elevation raster was converted to a slope raster. From this slope raster, zonal statistics were computed to determine the average land slope at both the parcel and sub-watershed scale.

3.4 Demonstration Site

In order to evaluate the utility of the Virginia Tech BMP Decision Support Software a demonstration site was chosen in the Town of Blacksburg, Virginia. Upon selection of the site, two case studies were performed. The first case study, described in detail in Chapter 6 of this report, applied the AHP decision support algorithm to evaluate and rank BMP options for installation on the demonstration site. The second case study, described in detail in Chapter 7 of this report, consisted of building a hydrologic model of the demonstration site and evaluating various techniques for modeling individual BMPs in the EPA SWMM v 5.0 environment. The following is a discussion of the demonstration site used in this research project.

The First and Main Development Project is a large scale, mixed use development presently under construction (as of July 2008). The project is located in Blacksburg, VA, west of South Main Street, between Country Club Drive and King Streets. Prior to initiation of the First and Main project, the site was predominately undeveloped, but did have six small buildings and a small motel located in its southeast corner. The relative drainage pattern of the site is from the northwest to the southeast. See Figure 3.1 for aerial imagery and the predevelopment drainage pattern and basins.

The overall development project is comprised of two phases. Phase I occupies approximately 26 acres on the southern portion of the site and will consist of a small outdoor shopping mall, a theater complex, restaurants, and a stormwater detention facility. Phase II comprises approximately 13 acres on the northern portion of the site and is proposed as a “big box” retail development. It will consist of one large building and an associated parking area. For post-development watersheds and a schematic depiction of the post development site conditions see Figures 3.2 and 3.3.

Data for First and Main was obtained from the Town of Blacksburg and includes site plans for the First and Main development project as well as contours, imagery, and soil data. The soil data suggest that the site is predominately hydrologic soil group (HSG) C soil; however, visual inspection of the site suggests the existence of some HSG D soil. Upstream of the First and Main Phase I site there is a small retail shopping center, a few restaurants, and a residential area. This portion of the watershed was not considered in this project; therefore, the runoff contribution was ignored with respect to quality and quantity. This was done so that the runoff volume from existing development would not influence the results of the demonstration site.

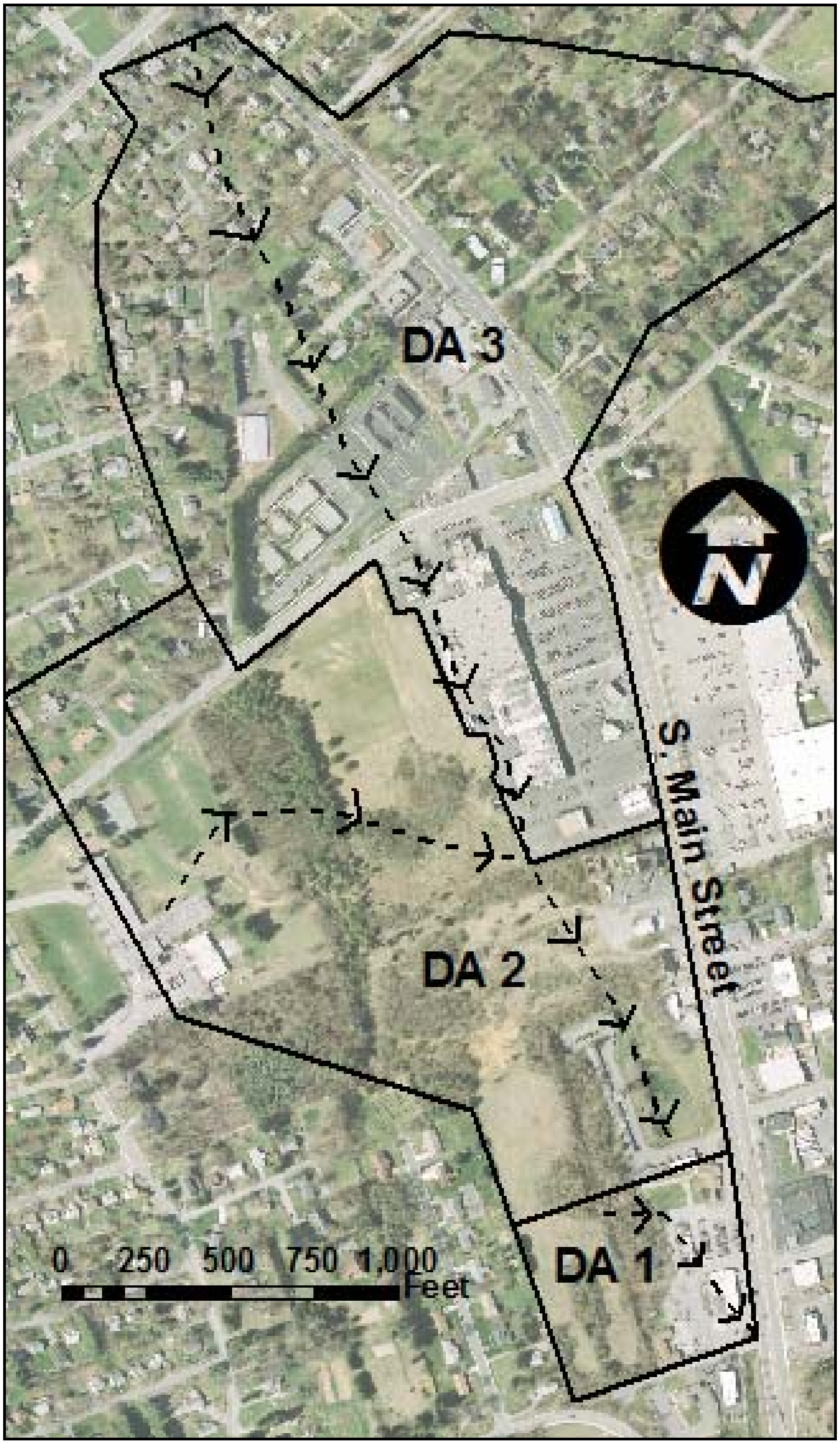


Figure 3.1 First and Main Pre-development
Aerial Imagery and Sub Drainage Areas (DA)

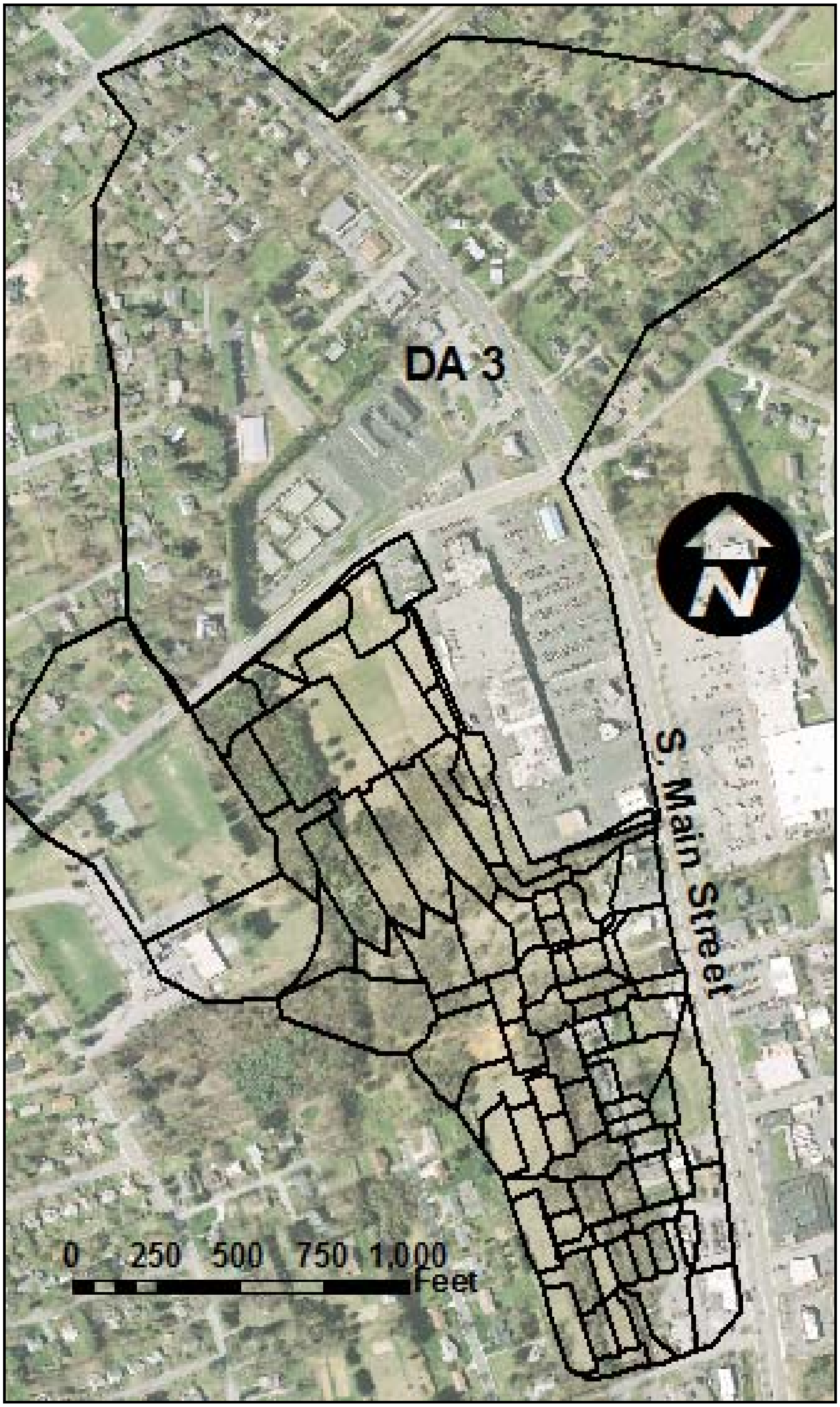


Figure 3.2 First and Main Post-development Drainage Basins

Figure 3.3 First and Main Schematic Post-development Site Plan

3.5 Modeling the Relative Performance of Competing Stormwater Management Strategies in EPA SWMM v. 5.0

Predicting the performance of a stormwater BMP prior to its installation with high confidence is a major challenge for stormwater engineers/planners and regulators. EPA SWMM is a highly versatile, public-domain hydrologic model used primarily for the modeling of urban watersheds. The model has the "off the shelf" ability to represent various hydraulic structures including open-channels, pipes, pumps, weirs, and detention facilities. However, there presently exists no automated means of inserting a specific BMP type into a SWMM model and then depicting its impact on surface runoff quality. Furthermore, while water quality treatment functions can be applied within storage elements and nodes, the bypass of inflow from large return frequency storms exceeding the capacity of a BMP cannot presently be modeled. These shortcomings limit the user to modeling only a small fraction of available BMP options, namely detention and retention basins.

The major objective of this research project was to develop a software-aided decision support process to assist planners, engineers, and regulators in the selection of urban stormwater BMPs for a particular application scenario. In support of this objective, standardized templates were developed to model each of the BMPs presented in Table 1.1 of this report. These BMP templates enable the modeling of both hydraulic and pollutant removal performance in the EPA SWMM v. 5.0 environment. The template input parameters are, generally, functions of the BMP's contributing drainage shed and include characteristics such as area, geometry, impervious fraction, and slope. This enables an evaluation of stormwater management alternatives during the planning stage of development, prior to the completion of detailed BMP design drawings and specifications. If design drawings of the proposed BMPs are available, these model templates can be adapted to incorporate actual design parameters such as outlet geometry and placement, water quality volume (WQV), and/or total storage volume.

Upon the development of effective BMP templates for use in the SWMM environment, a hydrologic model was constructed for the demonstration site described in Section 3.4 of this report. Using the BMP modeling templates, different runoff management strategies were evaluated and compared for this study site. Chapter 7 of this report provides a full discussion of this case study. The BMP modeling techniques developed within the scope of this research project are presented, as a tutorial, in Appendix F of this report. The following is a generalized discussion of these techniques.

The first BMP template configuration depicts those practices which discharge their treated water quality volume to the same outlet point as runoff that passes through the BMP untreated. These practices include the entire pond/basin class, constructed stormwater wetlands, stormwater filtering systems, vegetated buffers and swales, and bioretention basins. This template employs standard SWMM elements such as storage units, nodes/treatment nodes, links, pumps, and weirs. Within this template configuration, a pump conveys a portion of the inflow to a treatment node. The pump rate can be adjusted to reflect the actual rate at which the water quality volume migrates through the practice. Similarly, the treatment node can be adjusted to reflect the pollutant removal efficiency of the BMP type that is being modeled. After treatment, the water quality volume is then discharged from the practice, again using a pump rate that is reflective of the BMP's actual physical processes. Runoff that is not treated by the BMP is simply routed through the practice using storage, elevation, and discharge parameters representative of the actual BMP type. This template configuration is shown in Figure 3.4.

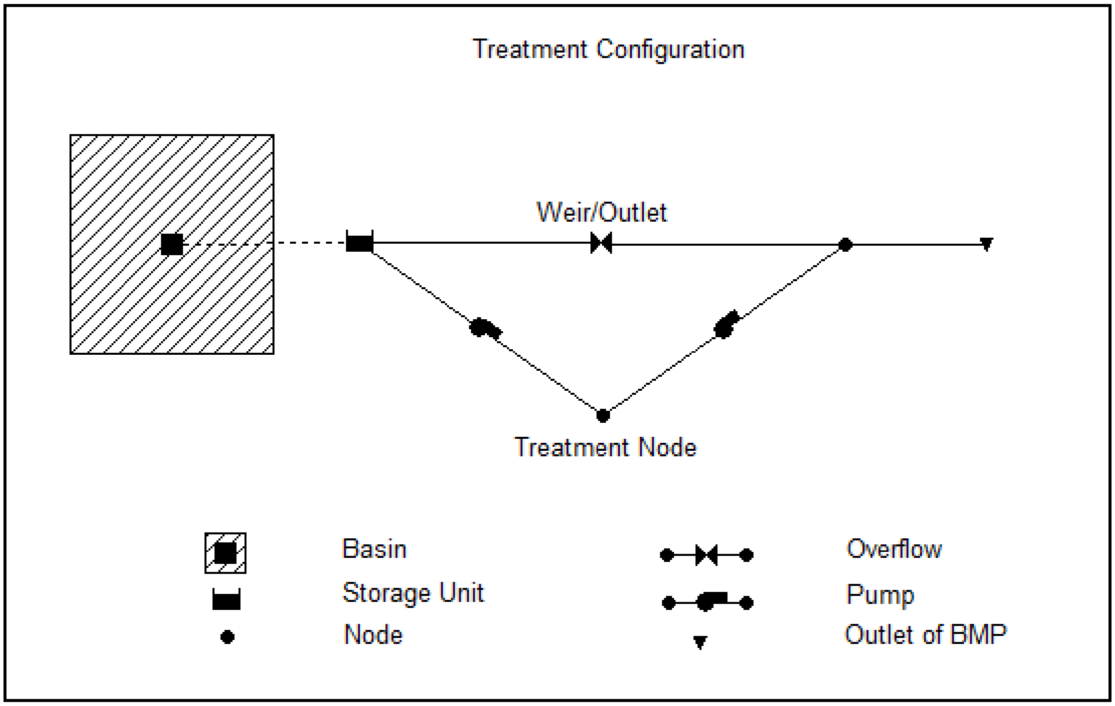


Figure 3.4 EPA SWMM v. 5.0 BMP Template – "Treatment Configuration"

The second BMP template configuration depicts those practices which infiltrate or otherwise completely remove a portion the overall surface runoff volume. Within this configuration, infiltrated runoff is not reintroduced to the system after its removal. These practices include the entire infiltration class of BMP as well as vegetated roof. This template employs standard SWMM elements such as storage units, nodes, links, pumps, and weirs. Within this template configuration, a pump conveys a portion of the inflow to an outlet/discharge node. The pump rate can be adjusted to reflect the actual rate at which the water quality volume exfiltrates from the practice. Runoff that is not treated by the BMP is simply routed through the practice and introduced to a downstream receiving channel. This template configuration is shown in Figure 3.5.

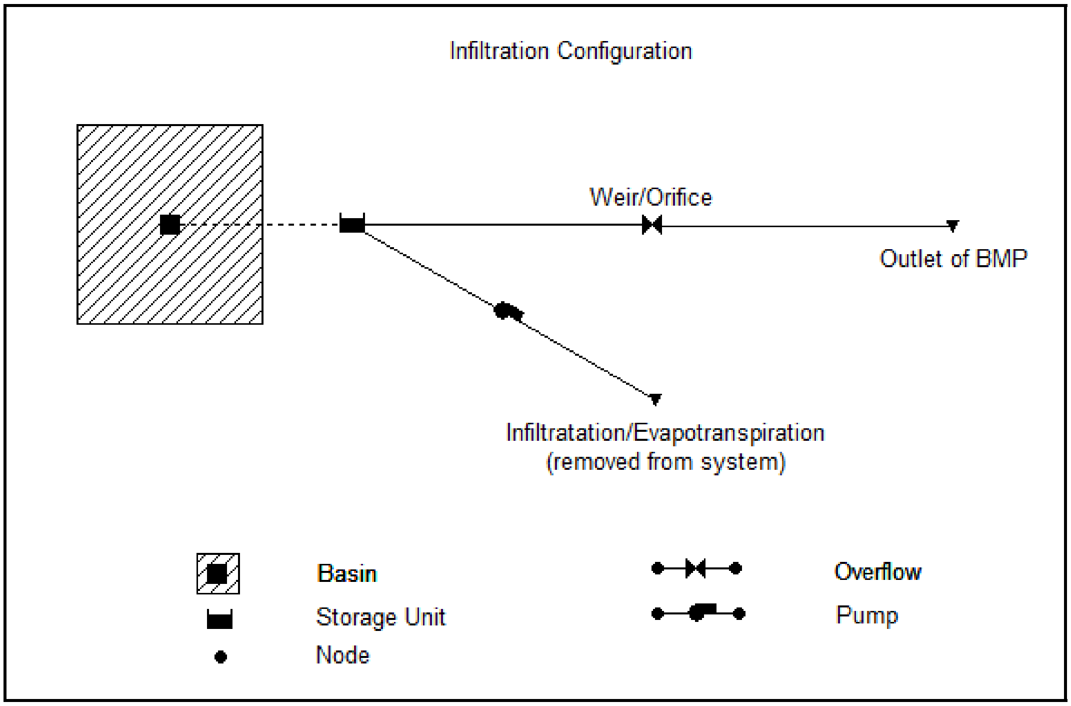


Figure 3.5 EPA SWMM v. 5.0 BMP Template – "Infiltration Configuration"

The third BMP template configuration depicts manufactured BMP systems. These practices are typically designed to provide water quality improvement, but do not attenuate the peak rate of runoff. This template employs standard SWMM elements such as flow dividers, nodes/treatment nodes, and links. Generally, manufactured BMP devices are designed for a specified flow rate. This contrasts with the water quality design of other BMPs, which is usually based on a runoff volume. Within this template configuration, a flow divider is applied at the upstream end of the practice to divert the device's design flow rate to a treatment node. The treatment node can then be adjusted to reflect the pollutant removal efficiency of the BMP device that is being modeled. Flow rates beyond the device's design capacity are not treated by the BMP and are simply routed through the practice and introduced to a downstream receiving channel. This template configuration is shown in Figure 3.6.

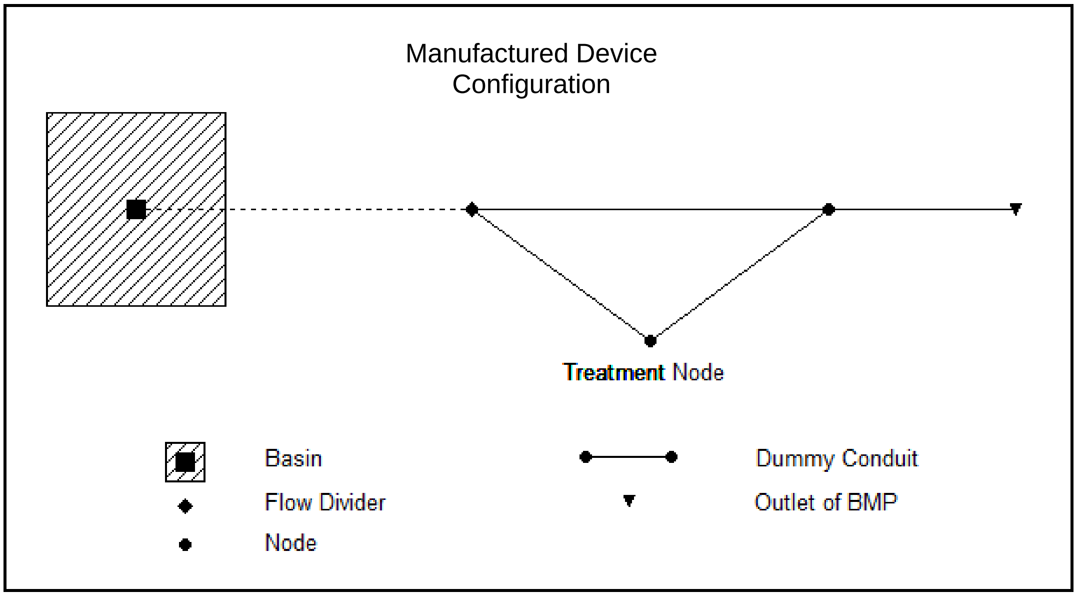


**Figure 3.6 EPA SWMM v. 5.0 BMP Template –
"Manufactured Device Configuration"**

The final BMP template configuration uniquely depicts rainwater harvesting systems. This template employs standard SWMM elements such as storage units, links, and overflow/weirs. Within this configuration, the storage unit can be sized such that it holds exactly the volume available in the cistern or tank being modeled. Then, a weir is placed at the elevation corresponding to available volume and excess runoff is instantly bypassed to a downstream receiving point. The volume of runoff contained in the storage unit can be held indefinitely, or drawn down at a rate reflective of the consumption rate for the actual BMP installation. This template configuration is shown in Figure 3.7.

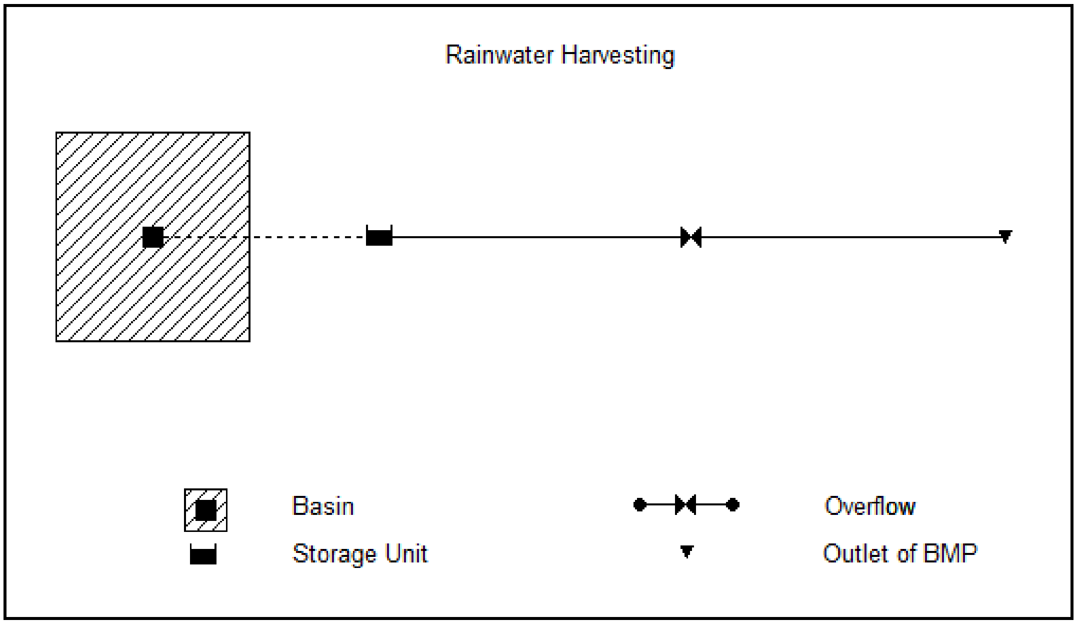


Figure 3.7 EPA SWMM v. 5.0 BMP Template –
"Rainwater Harvesting Configuration"

Chapter 4. The Analytic Hierarchy Process (AHP) Applied to BMP Selection

4.1 Background and Methodology

First developed by mathematician Thomas Saaty in 1980, the AHP is an algorithm capable of assisting complex decision-making problems. From its inception, and arising from its concise mathematics and easily obtained input data, the AHP has been of great interest to researchers in many different fields (Triantaphyllou and Mann, 1995). Perhaps the greatest strength of the AHP is that, although its foundation lies in complex matrix manipulation, when automated it can be effectively applied by users without an extensive background in multi-criteria decision-making theory.

When choosing between competing BMP options, in addition to readily quantified engineering and economic factors, an engineer must also address other, dimensionless considerations such as the public's willingness to accept the chosen practice. Traditional decision support tools, such as linear and non-linear programming, fall short when applied to the selection of BMPs because these tools lack the intrinsic ability to address multiple influential criteria with differing or non-quantifiable units. The AHP is capable of considering an unlimited number of influential criteria exhibiting different units or no units at all. "Fundamentally, the AHP works by developing priorities for alternatives and the criteria used to judge the alternatives" (Schmoldt, 2001). Through the construction of pairwise comparison matrices, the AHP ranks competing alternatives, such as different BMPs, in terms of each influential selection criteria. Additionally, the algorithm permits comparisons and prioritizations of the selection criteria themselves. These pairwise comparisons occur by establishing dimensionless rankings, or weights, among the competing alternatives and their influential selection criteria (Saaty, 1980). This weighting component of the AHP permits mathematical analysis when the influential criteria exhibit different scales, or even no scale (units) at all.

Conceptually, the AHP is a four-step process that enables the user to resolve the task of multiple criteria decision making into an objective algorithmic approach. Procedurally, application of the AHP for BMP selection can be viewed in terms of chronological steps, described as follows. Each of these steps is expanded upon, in detail, later in this chapter.

Step 1: Construction of BMP and Criteria Comparison Matrices – This step in the algorithm entails the development of BMP comparison matrices for *each* of the user-chosen selection criteria. These matrices serve to evaluate and rank the competing BMP alternatives in terms of their ability to satisfy each respective selection criterion. When the AHP algorithm is automated in a software interface, these BMP comparison matrices are hard coded such that the BMP rankings for each respective criterion do not change on an application-by-application basis.

In addition to constructing a BMP comparison matrix for each selection criteria, the criteria themselves are evaluated in the same manner through the creation of a single criteria comparison matrix. This step in the algorithm provides an opportunity for the user to establish the degree to which each individual criterion influences the overall BMP selection process. The criteria comparison matrix, unlike the BMP comparison matrices, is dynamic and can be adjusted on an application-by-application basis.

Step 2: Extraction of Priority Vectors – This step in the algorithm is a mathematical operation, and is comprised of computing (or approximating) the right principal Eigenvector of the BMP comparison matrices as well as the criteria comparison matrix. Execution of this step yields a collection of BMP ranking vectors (one for each selection criteria) and a single vector which ranks the selection criteria in terms of their user-defined influence on the BMP selection process.

Step 3: Consistency Evaluation – This step in the algorithm does not contribute directly to the goal of selecting a single BMP from the pool of competing alternatives, but rather exists to provide a logical check on the entries into the various comparison matrices. For example, consider competing BMP alternatives *"A," "B,"* and *"C"* and influential criterion *"N."* Now, further consider that alternative *"A"* outperforms alternative *"B"* in satisfying criterion *"N."* Additionally, alternative *"B"* outperforms alternative *"C."* Therefore, logically, alternative *"A"* must outperform *"C"* for this particular criterion. Execution of this step in the algorithm ensures that each comparison matrix is within an acceptable consistency tolerance, and therefore does not violate logical constraints such as the one described.

Step 4: Ranking of Competing Alternatives – As with step two, this step is a mathematical operation comprised of matrix algebra. The ranking vectors extracted from the various BMP comparison matrices are entered into a single BMP decision matrix. This matrix is then multiplied by the vector extracted from the criteria comparison matrix (the criteria priority vector). The result is a single vector which ranks the competing BMP alternatives in terms of their ability to simultaneously satisfy all of the influential criteria and their user-defined importances.

Figure 4.1 provides a schematic depiction of the AHP algorithm's use as a BMP selection tool.

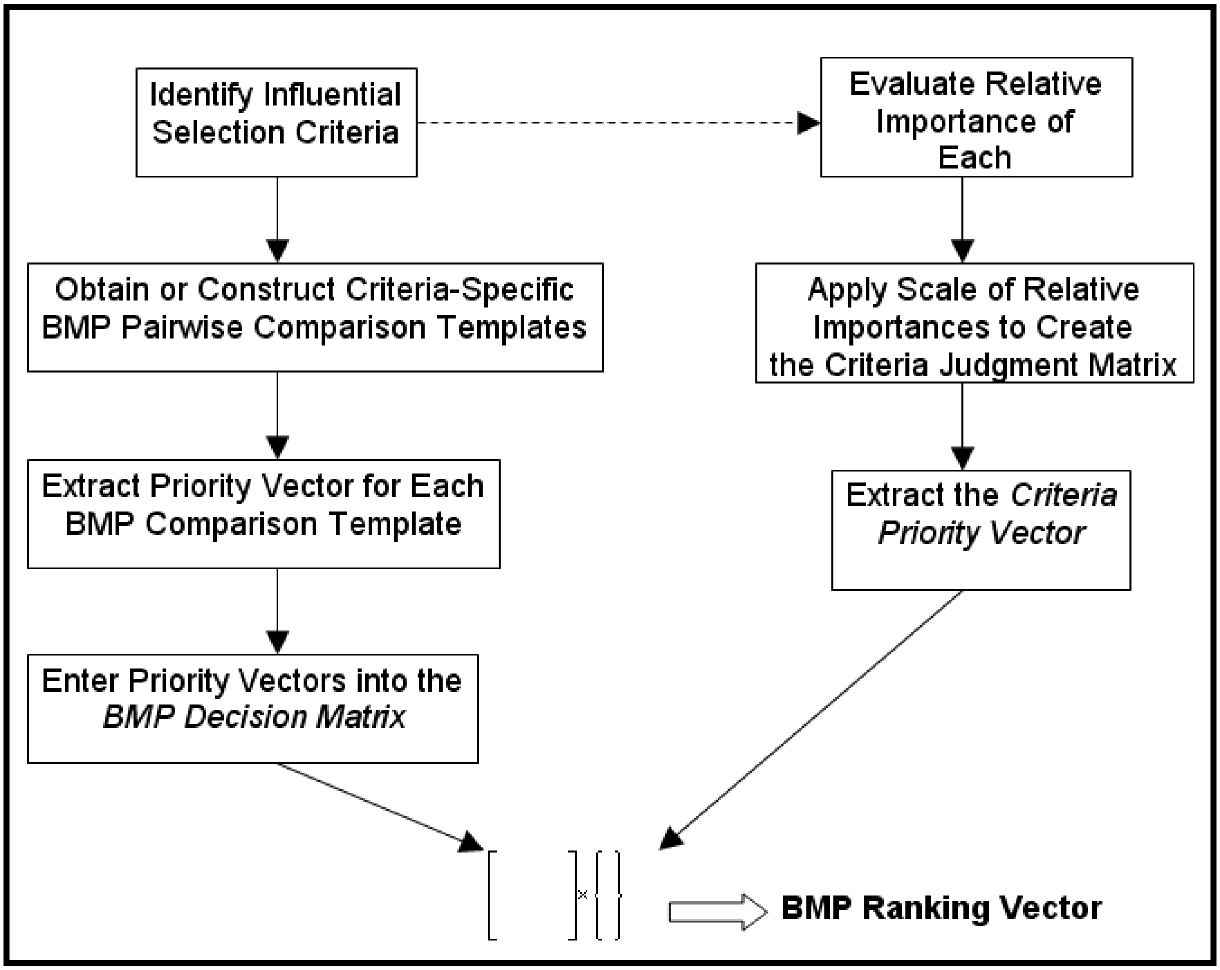


Figure 4.1 Schematic Flow Chart of AHP Algorithm in BMP Selection

4.2 Construction of Pairwise Comparison Matrices (Step One)

The first step in performing the AHP is to identify all possible BMP alternatives from which a single alternative is to be selected. Next, it is necessary to identify all relevant criteria influencing the selection of a single alternative from the pool of available alternatives. Because the numerous selection criteria exhibit varying units (or in some cases no units at all), mathematical evaluation of the criteria requires the user to determine the relative scale, or weight, of the alternatives in terms of each criterion. This task is accomplished by employing Table 4.1. Table 4.1 was first proposed by Saaty (1980) for determining the dimensionless scale of relative importances. This table and others developed since Saaty's initial work, permits pairwise comparisons within the AHP. "In this approach the decision-maker has to express his opinion about the value of one single pairwise comparison at a time." (Triantaphyllou & Mann, 1995) In other words, within every hierarchal comparison matrix, the user must compare each competing alternative against every other competing alternative employing a scale of relative importance. This type of comparison is executed for each influential criterion, and ultimately the influential criteria are compared and ranked against themselves.

Employing the scale of relative importances, one is able to construct BMP comparison matrices for each selection criterion. This step evaluates the performance of each BMP alternative against the other alternatives in terms of the various selection criteria. These comparison matrices are of dimensions $M \times M$, "M" being the total number of BMP alternatives considered. The final comparison matrix is termed the *criteria judgment matrix* and evaluates and ranks the importance of each individual criterion when compared against all other criteria. The criteria judgment matrix is of dimension $N \times N$, "N" being the total number of user-chosen criteria. It is during the construction of the criteria judgment matrix that the operator is able to prioritize the criteria influencing the selection of the competing alternatives.

Table 4.1 Scale of Relative Importances (Saaty, 1980)

Intensity of Importance	Definition
1	Equal Importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2,4,6,8	Intermediate values between the two adjacent judgments

Entries into the BMP comparison and criteria judgment matrices are expressed in terms of the importance intensities illustrated in Table 4.1. For instance, consider a matrix comparing BMP alternatives "*A*," "*B*," and "*C*" in terms of criterion "*N*." "By convention, the comparison of strength is always of an activity appearing in the column on the left against an activity appearing in the row on top." (Saaty, 1980, pg. 18) An element in the matrix is equally important when compared with itself, and thus the main diagonal of all judgment matrices must be 1. Employing Table 4.1, consider the following scenario:

- In terms of criterion "*N*," BMP *A* is demonstrably more important than BMP *B*. In practice, such a comparison would indicate that, in terms of satisfying criterion "N," alternative *A* strongly outperforms alternative *B*.

- In terms of criterion "*N*," BMP *C* is weakly more important than BMP *A*. In practice, this comparison expresses that, in terms of criterion "*N*," alternative *C* is slightly superior to alternative *A*.

- In terms of criterion "*N*," BMP *C* is absolutely more important than BMP *B*. Such a ranking indicates that, in practice, alternative *C* is absolutely superior to alternative *B* in satisfying criterion *"N."*

Following the aforementioned convention, notice that the relative importances from Table 4.1 are found in row one, while their reciprocal values are found in column one of Table 4.2. "It is not mandatory to enter a reciprocal value, but it is generally rational to do so" (Saaty, 1980). Furthermore, observe that, intuitively, BMP alternative *A* is equally important when compared to itself. At this point, the comparison matrix of criterion *N* appears as follows:

Table 4.2 BMP Comparison Matrix (Criterion "N")

	A	B	C
A	1	7	1/3
B	1/7	1	1/9
C	3	9	1

This step in the AHP is repeated until BMP comparison matrices are constructed for each influential criterion which the user has chosen to make available in the BMP selection process. As shown in Table 4.2, the competing BMP alternatives, in this example *A, B,* and *C*, must be compared in terms of each criterion. The final task in this step is the construction of a *criteria judgment matrix* that prioritizes each selection criterion by comparing one against all other selection criteria. The BMP comparison matrices remain static, and do not change on an application basis. The evaluations of individual BMPs in terms of the various available criteria are based on literature review, data compilation, and professional judgment. In practice, the user may select as many criteria to influence a single BMP selection scenario as he/she wishes. Additionally, the chosen criteria may be weighted differently on an application-by-application basis. Therefore, contrasting with the BMP comparison matrices, the criteria judgment matrix is dynamic and may be altered by the introduction or removal of criteria or by choosing to modify the weighting of individual criteria.

4.3 Extraction of Priority Vectors (Step Two)

Upon creating the various BMP comparison matrices as well as the criteria judgment matrix, the user then proceeds to the next step in the AHP, which is to extract the relative importances implied by each matrix. This task is accomplished by employing matrix algebra to compute or estimate the right principal Eigenvector of each judgment matrix. Mathematically speaking, the principal eigenvector for each matrix, when normalized, becomes the vector of priorities for that matrix. (Saaty, 1980, pg. 19) As matrix size grows, the task of computing this principal Eigenvector has the potential to become quite complex. In the absence of proprietary mathematical software, a number of computationally accessible methods exist to facilitate estimation of the priority vectors. One of these estimation techniques is demonstrated as follows for the matrix shown as Table 4.3.

The first step in estimating the principal Eigenvector is to divide the elements of each column by the sum of that column. This step effectively normalizes the elements of that column such that their sum is unity. Then, the elements in each row are summed and divided by the total number of elements in the row. This step averages the normalized columns to yield the estimated principal Eigenvector (Table 4.4). (Saaty, 1980, pg. 19) This method is illustrated as follows.

Table 4.3 Priority Vector Estimation Technique

	A	B	C
A	1	7	1/3
B	1/7	1	1/9
C	3	9	1
Column Sum	***4.143***	***17***	***1.444***

Table 4.4 Normalized Column Values and Resulting Row Averages

	A	B	C	***Row Sum***	***Row Average***
A	0.241	0.412	0.231	***0.884***	***0.295***
B	0.034	0.059	0.077	***0.170***	***0.057***
C	0.724	0.529	0.693	***1.946***	***0.649***

$$\begin{Bmatrix} 0.295 \\ 0.057 \\ 0.649 \end{Bmatrix} \textit{Estimated Principal Eigenvector}$$

The resulting, estimated priority vector indicates that in terms of criterion *"N,"* alternative *C* is prioritized, with alternatives *A* and *B* ranking second and third, respectively. The quantified results support the previously described qualitative comparisons of alternatives *A, B,* and *C.*

It is important to understand that this approach to priority vector calculation is merely an estimate. The exact solution to a matrix's principal Eigenvector is obtained by raising the matrix to arbitrarily large powers and dividing the sum of each row by the sum of the elements of the matrix. (Saaty, 1980, pg. 20)

4.4 Consistency Evaluation (Step Three)

This step in the algorithm does not contribute directly to the goal of selecting a single BMP from the pool of competing alternatives, but rather exists to provide a logic-based consistency check on the validity of the user's entries into the various comparison matrices. Execution of this step in the algorithm ensures that each matrix is within an acceptable consistency tolerance, and therefore does not inadvertently violate the comparison values intended by the user.

The first step in the consistency evaluation is to multiply the original comparison matrix by the estimated, normalized priority vector (termed A_{VE}) obtained by proprietary mathematical software or the previously described estimation technique. The resulting vector is termed A_W. Next, the first component of the A_W vector is divided by the first component of the estimated solution vector. This process is continued, dividing each entry of vector A_W by the corresponding entry of the estimated solution vector, A_{VE}. Then, the maximum or principal Eigenvalue (λ_{Max}) is estimated as the average of the entries in vector $\left\{\frac{A_W}{A_{VE}}\right\}$. This maximum Eigenvalue is then used to compute the matrix's consistency index (CI) using:

$$CI = \frac{(\lambda_{Max} - n)}{(n-1)}$$

Where n is the total number of activities (rows or columns) in the matrix. The final step in the consistency evaluation is to examine the ratio of the CI and the random index (RI) derived from the number of matrix activities. RI values for varying matrix sizes are shown in Table 4.5.

Table 4.5 Random Indices (Saaty, 1980)

Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

The ratio of CI to RI is called the consistency ratio (CR). Generally, a consistency ratio of 0.10 or less is acceptable (Saaty, 1980). In the event that the CR is greater than 0.10, the user must re-evaluate the weight assignments within the matrix violating the consistency limits.

This consistency check methodology is now applied to the previous example. First, the original matrix is multiplied by the computed priority vector.

$$\begin{bmatrix} 1 & 7 & 1/3 \\ 1/7 & 1 & 1/9 \\ 3 & 9 & 1 \end{bmatrix} \begin{Bmatrix} 0.295 \\ 0.057 \\ 0.649 \end{Bmatrix}$$

The resulting vector, A_W, is:

$$\begin{Bmatrix} 0.910 \\ 0.171 \\ 2.047 \end{Bmatrix}$$

The entries of vector A_W are then divided by the entries of the computed priority vector, yielding:

$$\begin{Bmatrix} 3.085 \\ 3.000 \\ 3.154 \end{Bmatrix}$$

The matrix's maximum Eigenvalue, λ_{Max}, is then estimated as the average of this vector, 3.080. The matrix exhibits three total activities, therefore the CI is:

$$CI = \frac{(3.080 - 3)}{2} = 0.04$$

For a matrix with three activities, the random index, RI, is 0.58 (see Table 4.5). The CR is then:

$$CR = \frac{0.04}{0.58} = 0.07$$

This value is less than the allowable value of 0.10. Therefore, the consistency of the matrix is found to be within an acceptable tolerance. The consistency evaluation must be performed for each BMP comparison matrix and the criteria judgment matrix. If the consistency index is found to be greater than 0.10 for any matrix, the cell-by-cell comparisons must be examined for that matrix and modified as necessary to avoid violating logic-based constraints.

4.5 Ranking of Competing Alternatives (Step Four)

The final step in the AHP begins with construction of the BMP decision matrix. Column entries in the BMP decision matrix are simply comprised of the Eigenvectors (priority vectors) obtained from each individual BMP comparison matrix. The decision matrix is of dimensions $M \times N$, "M" representing the number of BMP alternatives being considered, and "N" indicating the total number of influential criteria for which BMP comparison matrices were constructed. Considering three possible BMP alternatives (*A, B, and C*), three selection criteria (*i, j, and k*), and adopting the following priority vector subscript convention:

$$\begin{Bmatrix} A_n \\ B_n \\ C_n \end{Bmatrix} = \text{Priority vector for criterion } n \text{ comparison matrix}$$

The decision matrix would appear as follows:

$$\begin{bmatrix} A_i & A_j & A_k \\ B_i & B_j & B_k \\ C_i & C_j & C_k \end{bmatrix}$$

To obtain the overall ranking of the alternatives, the BMP decision matrix is multiplied by the transpose (column version) of the row priority vector from the criteria judgment matrix. Considering the following subscript convention for the row priority vector of the selection criteria:

$$\{A_{VE_i} \quad A_{VE_j} \quad A_{VE_k}\} = \text{ Row priority vector for criteria judgment matrix}$$

The matrix multiplication operation is then formulated as follows:

$$\begin{bmatrix} A_i & A_j & A_k \\ B_i & B_j & B_k \\ C_i & C_j & C_k \end{bmatrix} \begin{Bmatrix} A_{VE_i} \\ A_{VE_j} \\ A_{VE_k} \end{Bmatrix}$$

Executing this operation accomplishes weighting of each of the individual BMP priority vectors by the priority of the corresponding selection criteria. The overall rank of each alternative is shown as follows:

$$\begin{aligned} \textit{Rank of alternative A} &= A_i A_{VE_i} + A_j A_{VE_j} + A_k A_{VE_k} \\ \textit{Rank of alternative B} &= B_i A_{VE_i} + B_j A_{VE_j} + B_k A_{VE_k} \\ \textit{Rank of alternative C} &= C_i A_{VE_i} + C_j A_{VE_j} + C_k A_{VE_k} \end{aligned}$$

The alternative with the greatest rank is the most desirable, while successively lower ranks indicate less desirable alternatives.

Table 4.6 shows the various BMP selection criteria for which BMP judgment matrices are available in the Virginia Tech BMP Decision Support Software. As previously discussed, these judgment matrices are hard-coded and do not change on an application-by-application basis. However, the user may select as many or as few of these criteria as he/she wishes for an individual BMP selection scenario.

Table 4.6 Available Selection Criteria in the Virginia Tech BMP Decision Support Software

Contributing Drainage Area (CDA) < 1 ac	CDA Impervious Fraction < 21%
CDA 1-5 ac	CDA Impervious Fraction 21-37%
CDA 5-10 ac	CDA Impervious Fraction 38-66%
CDA 10-25 ac	CDA Impervious Fraction > 66%
CDA > 25 ac	Presence of Hotspot Runoff
Presence of Shallow Groundwater	Peak Runoff Rate Attenuation Ability
Presence of Shallow Bedrock	Aesthetic Benefit/Liability
Presence of Hydrologic Soil Group A	Public Safety
Presence of Hydrologic Soil Group D	Site Slopes/Topography
Ability to Recharge Groundwater	Total Suspended Sediment Removal
Implementation Cost	Total Phosphorus Removal
Annual Maintenance Costs	Total Nitrogen Removal

Figure 4.2 illustrates a typical, static BMP comparison matrix. In this example BMP options are individually compared against 13 other BMP options for their applicability on sites with shallow groundwater depths. A cell-by-cell comparison is made for each BMP against all other BMP alternatives.

Description	Dry ED Basin	Enhanced ED Basin	Retention Basin	Const. Wetlands	Veg WQ Swale	Veg Filter Strip	Infil. Trench	Infil. Basin	Porous Pvmt.	Bio-Retention	Sand Filters	Veg Roof	Capture & Reuse	Prop-prietary
Dry ED Basin	***1.00***	0.20	0.20	0.20	5.00	5.00	5.00	5.00	5.00	1.00	1.00	0.20	0.20	0.20
Enhanced ED Basin	5.00	***1.00***	1.00	1.00	9.00	9.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Retention Basin	5.00	1.00	***1.00***	1.00	9.00	9.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Constructed Wetlands	5.00	1.00	1.00	***1.00***	9.00	9.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Veg WQ Swale	0.20	0.11	0.11	0.11	***1.00***	1.00	1.00	1.00	1.00	0.20	0.20	0.11	0.11	0.11
Veg Filter Strip	0.20	0.11	0.11	0.11	1.00	***1.00***	1.00	1.00	1.00	0.20	0.20	0.11	0.11	0.11
Infil Trench	0.20	0.11	0.11	0.11	1.00	1.00	***1.00***	1.00	1.00	0.20	0.20	0.11	0.11	0.11
Infil Basin	0.20	0.11	0.11	0.11	1.00	1.00	1.00	***1.00***	1.00	0.20	0.20	0.11	0.11	0.11
Porous Pavement	0.20	0.11	0.11	0.11	1.00	1.00	1.00	1.00	***1.00***	0.20	0.20	0.11	0.11	0.11
Bioretention	1.00	0.20	0.20	0.20	5.00	5.00	5.00	5.00	5.00	***1.00***	1.00	0.20	0.20	0.20
Sand Filters	1.00	0.20	0.20	0.20	5.00	5.00	5.00	5.00	5.00	1.00	***1.00***	0.20	0.20	0.20
Veg Roof	5.00	1.00	1.00	1.00	9.00	9.00	9.00	9.00	9.00	5.00	5.00	***1.00***	1.00	1.00
Capture & Reuse	5.00	1.00	1.00	1.00	9.00	9.00	9.00	9.00	9.00	5.00	5.00	1.00	***1.00***	1.00
Proprietary	5.00	1.00	1.00	1.00	9.00	9.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	***1.00***

Figure 4.2 Typical BMP Judgment Matrix (Presence of Shallow Groundwater Depths)

The AHP provides a computationally accessible means of solving complex multi-criteria decision-making problems in which the influential criteria may be numerous and/or exhibiting varying units. However, one must be cautious when employing the AHP in engineering applications. Particular caution is issued when the final priority vector yields values very close to each other. When this is the case, the user should consider introducing additional influential criteria, which *may* yield greater discrimination among the competing alternatives. These shortcomings, however, are not unique to the AHP algorithm. In fact, close scrutiny is advised in the application of any multi-criteria decision-making approach. Multi-criteria decision-making algorithms should be viewed as one tool in the decision-making process and not as the lone means for obtaining a final answer.

Chapter 5. Application of the BMP Decision Support Software

5.1 Overview of Objective and Methodology

To meet project objectives described in Chapter 2 of this report, the Virginia Tech BMP Decision Support Software (VT BMP DSS) was applied in a demonstration site to select BMPs that would meet site's runoff management needs. An expanded description and maps of the demonstration site can be found in Section 3.4 of this report.

The VT BMP DSS automates the analytic hierarchy process (AHP) decision support algorithm, enabling the user to simultaneously consider multiple influential criteria during the BMP selection process. Users of the decision support software can identify a pool of BMPs to consider in the selection scenario, then, choose which criteria to apply for selecting a single BMP from the pool of identified alternatives. Users of the software can also weight the degree to which each criterion influences the BMP selection process. Table 5.1 shows the criteria available in the VT BMP DSS. A detailed description of each criterion shown in Table 5.1 can be found in section 5.3 of this report.

Table 5.1 Available Selection Criteria in the Virginia Tech BMP Decision Support Software

Contributing Drainage Area (CDA) < 1 ac	CDA Impervious Fraction < 21%
CDA 1-5 ac	CDA Impervious Fraction 21-37%
CDA 5-10 ac	CDA Impervious Fraction 38-66%
CDA 10-25 ac	CDA Impervious Fraction > 66%
CDA > 25 ac	Presence of Hotspot Runoff
Presence of Shallow Groundwater	Peak Runoff Rate Attenuation Ability
Presence of Shallow Bedrock	Aesthetic Benefit/Liability
Presence of Hydrologic Soil Group A	Public Safety
Presence of Hydrologic Soil Group D	Site Slopes/Topography
Ability to Recharge Groundwater	Total Suspended Sediment Removal
Implementation Cost	Total Phosphorus Removal
Annual Maintenance Costs	Total Nitrogen Removal

The goal of this VT BMP DSS application was to develop a distributed stormwater management approach for the demonstration site. The concept behind this runoff management strategy is to spatially distribute BMPs throughout the site in an attempt to preserve and mimic the site's predevelopment hydrologic patterns.

5.2 Demonstration Site

The First and Main development project is a large scale, mixed use development presently under construction (as of July 2008). The project is located in Blacksburg, VA, west of South Main Street, between Country Club Drive and King Streets. Prior to initiation of the First and Main project, the site was predominately undeveloped, but did have six small buildings and a small motel located in its southeast corner. The relative drainage pattern of the site is from the northwest to the southeast. See Section 3.4 of this report for aerial imagery and pre and post-development drainage patterns of the site.

The overall development project is comprised of two phases. Phase I of the development occupies approximately 26 acres on the southern portion of the site. It consists of a small outdoor shopping mall, theater complex, restaurants, and a stormwater detention facility. Phase II occupies approximately 13 acres on the northern portion of the site. It consists of a "big box" retail development, and an associated parking area.

Civil site design services for the project were provided by Anderson & Associates, Inc. Data for the First and Main project was obtained from the Town of Blacksburg and includes Anderson & Associates' site plans as well as contours, aerial imagery, and soil data. The soil data suggest that the site is predominately hydrologic soil group (HSG) C. Upstream of the First and Main Phase I site there is a small retail shopping center, a few restaurants, and a residential area. This portion of the watershed was not considered in this project and its runoff contribution was ignored with respect to quality and quantity. This was done so that the offsite runoff would not influence the results of the demonstration site.

5.3 Chosen BMP Selection Criteria

The first step in applying the VT BMP DSS to the demonstration site was selection of influential criteria to apply in the BMP selection process. Following is a description of the criteria available in the VT BMP DSS, including which criteria were included and which were omitted on the demonstration site.

Contributing Drainage Area (CDA) Criterion

The first physical site constraint available as a BMP selection criterion is contributing drainage area (CDA). The installation of most BMPs is influenced greatly by the total area contributing runoff to the practice. For example, small, source control practices such as bioretention cells are generally not recommended for the treatment of runoff from drainage areas greater than 5 acres. By contrast, practices such as retention ponds and constructed wetlands require much larger drainage areas capable of providing baseflow to maintain a permanent water pool. Regardless, it is essential that the BMP chosen for a particular application is adequately suited to receive the runoff from its CDA. The CDA criterion was deemed essential in this BMP selection scenario, and therefore included. Section 5.4 of this report describes the manner in which the CDA criterion was applied on the demonstration site.

Impervious Fraction Criterion
Described in Chapter 2 of the Virginia Stormwater Management Handbook (DCR, 1999), one approach to BMP selection is defined as "technology-based." It requires the designer to compute the amount of new impervious area arising from a land development project, and then make the BMP selection on the basis of the overall impervious fraction of the BMP's contributing drainage area. This approach does not presume a specific pollutant removal target or efficiency and therefore contrasts a "performance-based" BMP selection procedure.

While the impervious percentage of a BMP's contributing drainage area is an important consideration when evaluating the pollutant removal performance of a BMP, it is also an important consideration in terms of installation feasibility. For example, because of clogging concerns arising from runoff containing large sediment particles, stormwater sand filters are not recommended for installation on sites with an impervious fraction of less than 66%. The impervious fraction criterion was deemed important in this BMP selection scenario, and therefore included. Section 5.4 of this report describes the manner in which this criterion was applied on the demonstration site.

Soils Criterion
Hydrologic soil group (HSG) A consists of sand, loamy sand, or sandy loam types of soils. These soils exhibit low runoff potential and high infiltration capacity even when thoroughly wetted. The presence of HSG A on a site restricts the BMP options from which a designer can choose. Generally, this soil group exhibits infiltration rates beyond what is recommended for infiltration practices. Similarly, these excessively high infiltration rates may present difficulties in achieving acceptable hydraulic residence times in detention facilities, vegetated swales and filters, and wetlands. In the absence of synthetic liners, the presence of HSG A generally precludes the use of these practices.

HSG D consists primarily of clay loam, silty clay loam, sandy clay, silty clay, or clay. This HSG has the highest runoff potential among all soil groups. Characteristics of HSG D are high swelling potential and very low infiltration capacity when thoroughly wetted. In terms of surface runoff potential, HSG D behaves analogously to an impervious surface. Typically, soils classified as HSG D do not exhibit the minimum infiltration rates required of infiltration practices. Consequently, the implementation of infiltration practices, and those practices exhibiting similar physical processes, is restricted in the presence of these soil groups. The presence of HSG D is considered beneficial to the implementation of basin practices because it significantly reduces the undesired exfiltration loss of detained runoff.

HSG B and C are not available as selection criteria in the VT BMP DSS because their on site presence and medium infiltration capacity does not typically preclude the installation of any BMPs. Soils on the demonstration site were observed to be, predominately, HSG C. Therefore, the soils criterion was omitted from this application of the VT BMP DSS.

Geologic Site Constraints

The presence of a shallow or seasonally shallow groundwater table (typically defined as less than two feet below a site's finished grade) usually precludes the use of infiltration practices. In addition to infiltration basins and trenches, this restriction extends to bioretention basins and porous pavement. Practices which infiltrate little or no runoff into the subsurface are favored as treatment options in the presence of a shallow groundwater table. These practices include grassed swales, vegetated filter strips, manufactured BMP systems, and rainwater harvesting systems. Retention ponds and constructed wetlands may be designed to utilize the presence of shallow groundwater as a source of baseflow, and thus such a site characteristic is often considered beneficial to their implementation.

Much like the presence of a shallow groundwater table, the presence of shallow bedrock depths on a site greatly restricts the BMP options at the designer's disposal. Infiltration practices and other BMPs which operate by employing subsurface filter beds are generally prohibited. As in the case of a shallow groundwater table, practices which infiltrate little or no runoff into the subsurface are favored as treatment options. However, unlike the presence of a shallow groundwater table, the presence of shallow bedrock depths provides no benefit for the implementation of retention ponds and constructed wetlands, and in fact may preclude their installation without a liner that will minimize infiltration.

Neither shallow groundwater nor shallow bedrock was observed on the demonstration site. Therefore, these criteria were omitted during the BMP selection process.

Other BMP Implementation Considerations

The topography of a site upon which a BMP installation is proposed is an important factor in choosing the appropriate practice. BMPs employing underground reservoirs and/or infiltration beds, grassed swales, and vegetated filter strips are restricted to site slopes of less than 20 percent. When the site of interest has steep slopes, users of the *VT BMP DSS* can introduce this as a BMP selection criterion. Excessively steep slopes were not observed on the demonstration site. Therefore, this criterion was omitted.

Stormwater hotspots are defined as generating sites where pollutant concentrations in runoff greatly exceed concentrations typically found in stormwater. Often this definition is further extended to reflect the presence of hydrocarbons in the runoff. The Maryland Department of the Environment (MDE, 2000) cites that all BMPs are capable of accepting hotspot runoff with the exception of infiltration practices and wet vegetative water quality swales. Hotspot runoff is not expected from the project demonstration site. Therefore, this criterion was omitted.

When the proposed installation is in a high profile location, the public perception of a BMP may become an essential selection consideration. Some BMPs, notably dry detention basins, offer very little potential to provide aesthetic benefit to a site and, in fact, may be an aesthetic liability. Other BMPs, while having little potential to provide aesthetic benefit to a site, can be designed to minimize their obtrusiveness. Still other BMPs, such as retention basins and constructed wetlands, can be designed such that they become a desirable site amenity capable of providing recreational opportunities and wildlife habitat. Given the high profile nature of the demonstration site, the aesthetic benefit of the available BMP alternatives was considered during the selection process. Section 5.4 of this report describes the manner in which this criterion was applied.

Some BMPs have inherent public safety issues associated with their installation. The most notable safety concern arising from BMP implementation occurs when the practice has a permanent pool of water, such as the case with enhanced detention basins, retention basins, and constructed stormwater wetlands. Practices exhibiting a permanent pool also have the potential to become marshy and stagnant, resulting in ideal habitat for mosquitoes and other disease carrying vectors. Public safety was considered an important consideration on the demonstration site. Section 5.4 of this report describes the manner in which this criterion was applied.

BMP construction and maintenance costs vary considerably on a site-by-site basis. With any number of physical, site-specific parameters influencing the size and design of an individual BMP it becomes impractical, if not impossible to confidently estimate detailed material and labor costs associated with a given BMP type. In addition to the aforementioned physical site factors, there are issues such as land acquisition costs, contractor availability, seasonal impacts on construction activities, and non-essential BMP amenities that must be considered when preparing a detailed cost estimate for a proposed BMP installation. All of these factors vary immensely both geographically and climatically. The VT BMP DSS allows its user to attempt to minimize both installation and annual maintenance costs during the BMP selection process. However, these cost evaluations are only relative comparisons among the competing BMP options and are not intended to replace the need for detailed construction cost estimates, nor do they address unforeseen, non-routine maintenance activities. Both installation and annual maintenance costs were considered in selecting BMPs for the demonstration site. Section 5.4 of this report describes the manner in which these criteria were applied.

Performance Goals

Historically, the focus of stormwater management has been to reduce the peak rate of runoff from a developed site to pre-development (or other acceptable) levels. Providing flood control in the form of peak rate attenuation is still a highly prioritized goal in most stormwater management endeavors. In the state of Virginia, this functional stormwater management goal is required by “Minimum Standard 19”of the Virginia Erosion and Sediment Control Regulations (Section 4VAC50-30-40). The VT BMP DSS enables its user to consider runoff rate attenuation capability when choosing among competing BMP options. The peak mitigation criterion was deemed essential in this BMP selection scenario, and therefore included. Section 5.4 of this report describes the manner in which this criterion was applied on the demonstration site.

Groundwater recharge is the hydrologic process by which precipitation percolates downward from the land surface, eventually entering the groundwater table. This natural process is critical to the long-term sustainability of groundwater supplies where aquifer extraction rates must not exceed recharge rates. Groundwater recharge is often impeded by land use intensification and the resulting increase in imperviousness. Numerous locations in the United States now require land development projects to maintain at least some minimum level of post-development groundwater recharge through the use of BMPs. Groundwater recharge was not required on the demonstration site, and was therefore omitted as an influential selection criterion.

The runoff from urbanized areas carries a variety of soluble and particulate pollutants, typically at levels much greater than those observed in the runoff from undisturbed, natural spaces. Many of these pollutants pose significant threats to the aquatic ecosystems in receiving waters. The state of Virginia defines phosphorus as its “keystone pollutant.” Phosphorus and other nutrients such as nitrogen are of concern because of their potential to cause eutrophication of the water bodies to which they are introduced. Notable levels of suspended sediment are also found in the runoff generated from impervious surfaces, managed lawns, and sites whose surfaces have been denuded through construction processes.

Within the VT BMP DSS, users can choose to introduce the pollutant removal performance of competing BMP alternatives as a selection criterion. For a given pollutant, this criterion can be expressed as a “threshold” pollutant removal efficiency (80% for TSS, 35% for TP, and 30% for TN) or as simply the relative pollutant removal efficiency of a given BMP when compared to other BMP options. When the threshold pollutant removal criteria are employed in the algorithm, BMPs are rigidly evaluated on their ability to achieve the threshold values. All BMPs capable of achieving the explicitly stated removal efficiency are ranked equally, while those practices unable to attain the expressed removal efficiency are given very low preference. When the relative pollutant removal criteria are selected, BMPs are ranked *relatively* against other competing BMP alternatives in terms of their ability to remove the pollutant of interest from stormwater runoff. The relative pollutant removal performance of both total suspended sediment and total phosphorus were introduced as selection criteria in this application of the VT BMP DSS.

5.4 Ranking the BMP Selection Criteria

Upon identification of criteria that are critical to the BMP selection process, the user must qualitatively define the relative importance of each criterion. This process is inherently subjective, and the relative importance of each criterion may be viewed differently by different users. However, certain guidelines do exist that improve the reliability of results obtained from the VT BMP DSS.

First, it is suggested that any physical site constraints be given the highest degree of influence during the BMP selection process. The rationale behind this recommendation lies in the fact that the chosen BMP must be absolutely suited to the physical constraints of the site upon which it is to be installed. For example, consider a site whose in situ soils are primarily HSG D. These soils will not exhibit the minimum infiltration rate required for installation of the infiltration class of BMP. Consequently, if this physical site constraint was omitted or not prioritized during BMP selection, the algorithm could conceivably rank an infiltration BMP very favorably. Such a situation would require the user to manually override the BMP rankings obtained from the algorithm.

As with physical site constraints, it is generally advisable to provide any regulatory or functional stormwater management objectives with a great deal of influence during the BMP selection process. More often than not, particularly on land development projects, the driving factor behind a BMP installation is to meet the stormwater management requirements imposed by the local review authority and/or the State. These regulatory requirements may include flood control in the form of peak runoff rate attenuation, providing groundwater recharge, or a reduction in pollutant loads found in the runoff. If a regulatory requirement, such as peak runoff rate reduction, was omitted or not prioritized during the BMP selection process, the algorithm may rank a particular BMP very favorably when, in reality, that BMP is not be capable of providing any runoff rate reduction.

Influential BMP selection criteria that are not categorized as a physical site constraint or a regulatory/functional objective can be given the degree of influence deemed appropriate by the individual user or stakeholder group.

Adhering to these guidelines, Table 5.2 qualitatively summarizes the relative importances assigned to each of the influential criteria considered on the demonstration site.

Table 5.2 Qualitative Assessment of Influential Selection Criteria

Criterion	Category	Relative Importance
Contributing Drainage Area	Physical Constraint	Highest
Impervious Percentage	Physical Constraint	Highest
Aesthetic Benefit/Liability	Other	Moderate
Safety and Nuisance Liability	Other	Moderately High
Implementation Cost	Other	Moderate
Annual O&M Cost	Other	Moderate
Peak Mitigation Ability	Functional Objective	Highest
Relative TSS Removal	Functional Objective	Highest
Relative TP Removal	Functional Objective	Highest

5.5 Contributing Drainage Area Criterion

One possible exception to the inclusion and prioritization of physical site constraints is the Contributing Drainage Area (CDA) criterion. When stormwater management options are being evaluated at the planning stage of development, the user may wish to omit this criterion completely. Doing so will provide a ranking of candidate BMPs that is not influenced or limited by CDA, but that presumably meets other physical site constraints and functional goals. This allows the design engineer to approach runoff management in a distributed manner, employing multiple BMPs distributed throughout the site. Upon identification of feasible BMPs, the site's grading being manipulated to ensure that the drainage area to the chosen BMP(s) does not exceed that which the BMP can accommodate. This situation contrasts application of the VT BMP DSS during the design stage of development, when site grading is complete and the location of the proposed BMP(s) is identified. In this situation, the CDA to the BMP will be known, and the CDA criterion should be included and emphasized during the BMP selection process. This is the case with the First and Main demonstration site.

Based on site design drawings prepared by Anderson & Associates, Inc., the most logical application of the VT BMP DSS to the First and Main demonstration site was to evaluate sub-drainage basins whose areas ranged between one and five acres. Subdivision of the demonstration site at this scale yielded a total of six sub-watersheds not including rooftops. Roofs were considered to be individual sub-watersheds within the distributed model. Four of the six sub-watersheds fell into the 38 to 66 percent impervious cover range. The remaining two sub-watersheds were highly impervious, falling into the greater than 66 percent impervious cover range.

5.6 Application of the VT BMP DSS

This section describes the application of the VT BMP DSS to the aforementioned demonstration site. For detailed instructions on using the VT BMP DSS, see Appendix E of this report.

First, the VT BMP DSS was applied on the demonstration site's four sub-watersheds whose impervious fraction ranged from 38-66 percent. Reflecting the qualitative criteria assessments shown in Table 5.2, Figure 5.1 illustrates these rankings being expressed quantitatively in the VT BMP DSS.

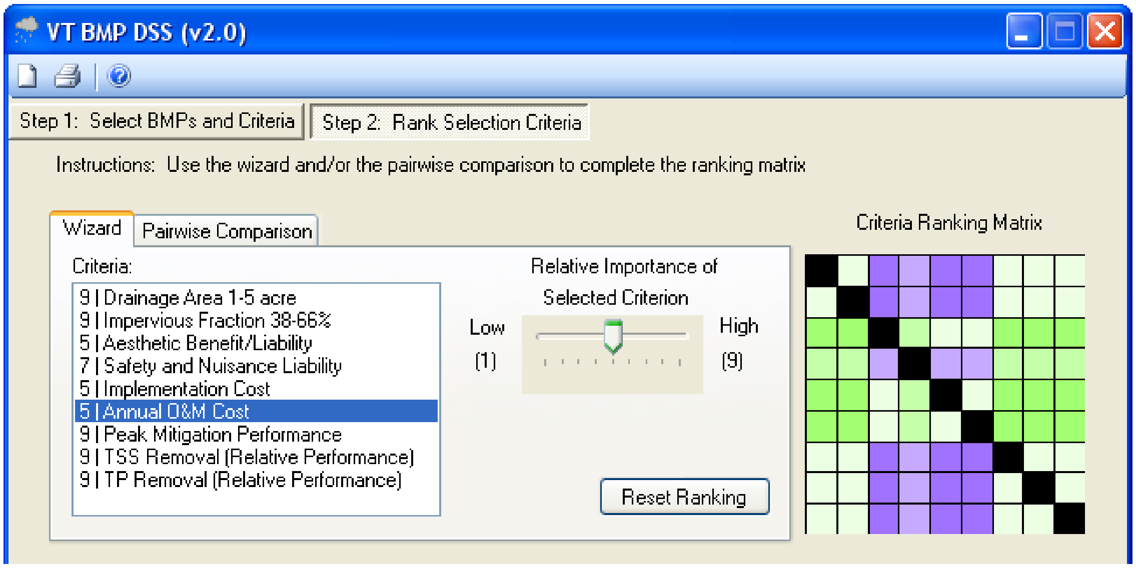


Figure 5.1 Criteria Ranking (Watershed Imperviousness 38-66%)

Next, a solution vector was computed, effectively ranking the candidate BMPs in terms of their ability to simultaneously satisfy the user-chosen and user-weighted criteria. Figure 5.2 illustrates the results obtained from the VT BMP DSS.

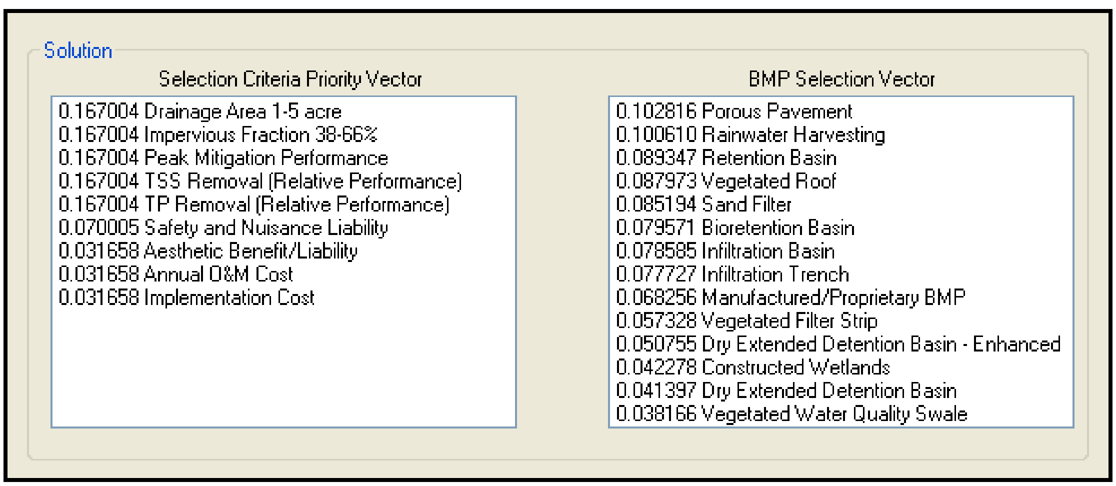


Figure 5.2 VT BMP DSS Output (Watershed Imperviousness 38-66%)

Examination of the results reveals that porous pavement is the highest ranking BMP for this particular selection scenario. Given that the four sub-watersheds represented by this scenario are comprised of paved parking spaces, drive aisles, and parking lot islands, the results appear to be feasible in terms of installation of the practice. Chapters 6 and 7 of this report detail the hydrologic modeling of porous pavement on the demonstration site and the performance of the practice in terms of water quantity and quality improvement.

Further examination of Figure 5.2 shows that the desired, qualitative criteria rankings were successfully expressed quantitatively by the VT BMP DSS. All physical site constraints and functional objectives were ranked equally with one another, and given the greatest overall influence. Following these criteria, safety and nuisance liability was considered to be of moderate importance. Finally, the selection criteria depicting aesthetics and costs were given the lowest degree of influence in the BMP selection.

Next, the VT BMP DSS was applied on the demonstration site's two sub-watersheds whose impervious fraction exceeded 66 percent. Reflecting the qualitative criteria assessments shown in Table 5.2, Figure 5.3 illustrates these rankings being expressed quantitatively in the VT BMP DSS.

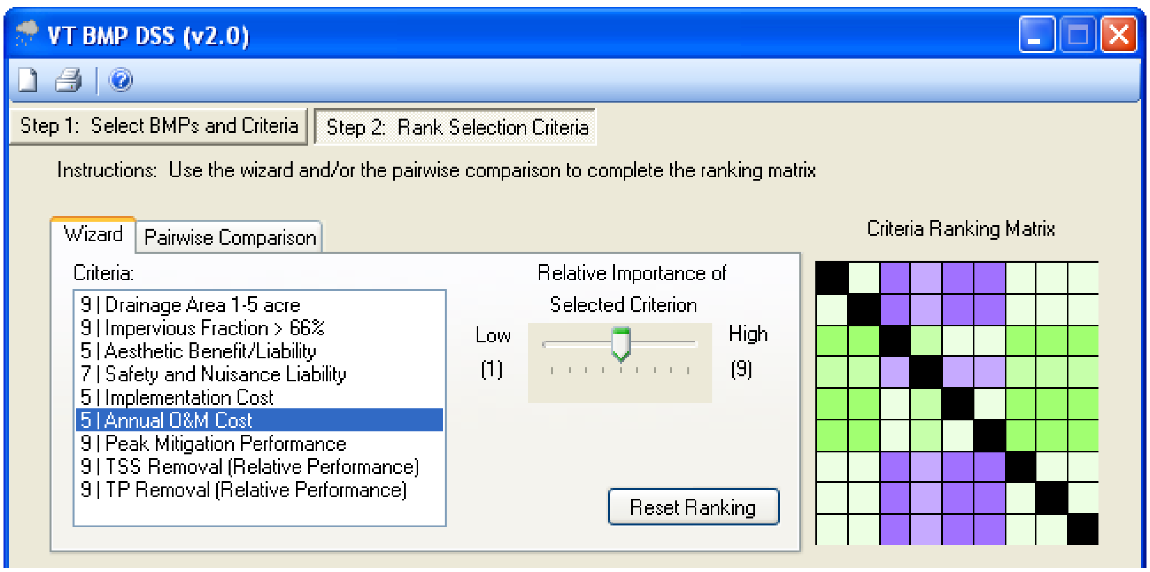


Figure 5.3 Criteria Ranking (Watershed Imperviousness >66%)

Following, a solution vector was computed, effectively ranking the candidate BMPs in terms of their ability to simultaneously satisfy the user-chosen and user-weighted criteria. Figure 5.4 illustrates the results obtained from the VT BMP DSS.

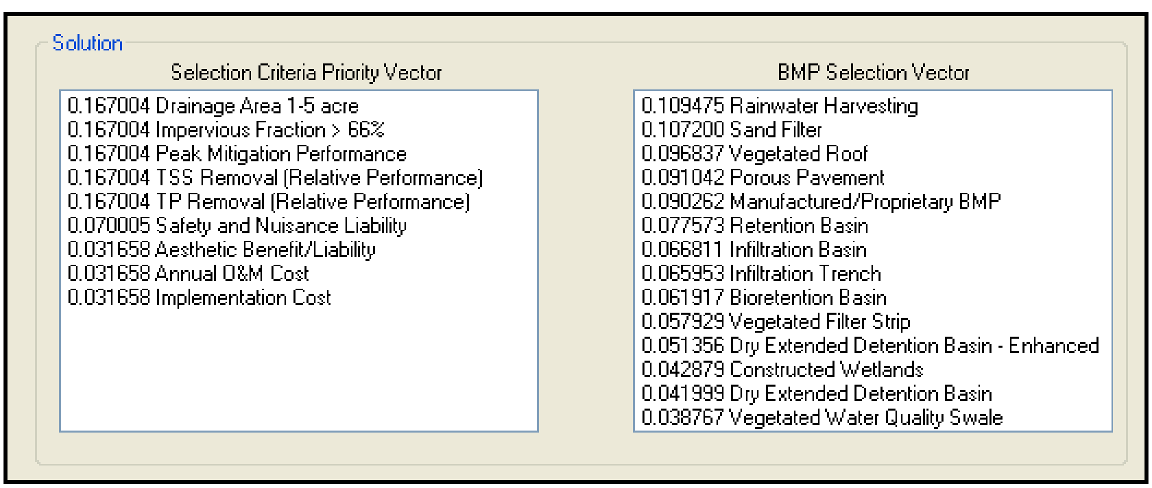


Figure 5.4 VT BMP DSS Output (Watershed Imperviousness >66%)

Examination of the results reveals that rainwater harvesting is the highest ranking BMP for this particular scenario. Given that the two sub-watersheds represented by this scenario are comprised of paved parking spaces, drive aisles, and parking lot islands, rainwater harvesting does not appear to be a feasible BMP. Further examination of the results reveals sand filters as the next highest ranking alternative. Given the high imperviousness and small drainage areas comprising the two sub-watersheds of interest, the installation of stormwater sand filters appears to be fully feasible. Chapters 6 and 7 of this report detail the hydrologic modeling of sand filters on the demonstration site and the performance of the practice in terms of water quantity and quality improvement.

Further examination of Figure 5.4 shows that the desired, qualitative criteria rankings were successfully expressed quantitatively by the VT BMP DSS. All physical site constraints and functional objectives were ranked equally with one another, and given the greatest overall influence. Following these criteria, safety and nuisance liability was considered of moderate importance. Finally, the selection criteria depicting aesthetics and costs were given the lowest degree of influence in the BMP selection.

Finally, the site's proposed building roof runoff was considered as an individual sub-watershed. For this sub-watershed, neither CDA nor impervious fraction were included as selection criteria, but all other criteria remained as in the previous selection scenarios. Reflecting the qualitative criteria assessments shown in Table 5.2, Figure 5.5 illustrates these rankings being expressed quantitatively in the VT BMP DSS.

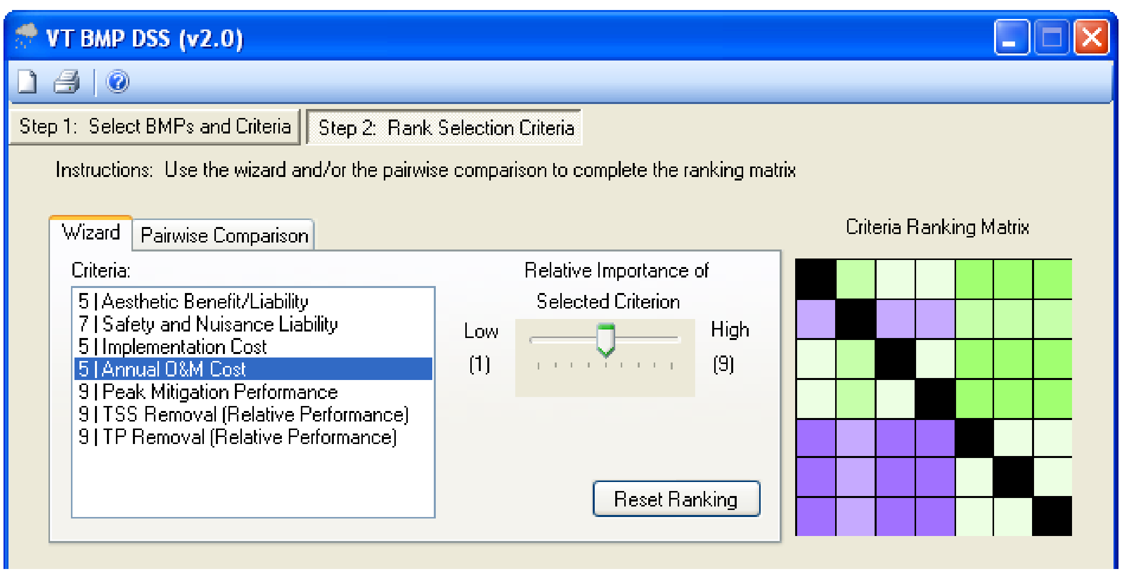


Figure 5.5 Criteria Ranking (Building Roof)

Following, a solution vector was computed, effectively ranking the candidate BMPs in terms of their ability to simultaneously satisfy the user-chosen and user-weighted criteria. Figure 5.6 illustrates the results obtained from the VT BMP DSS.

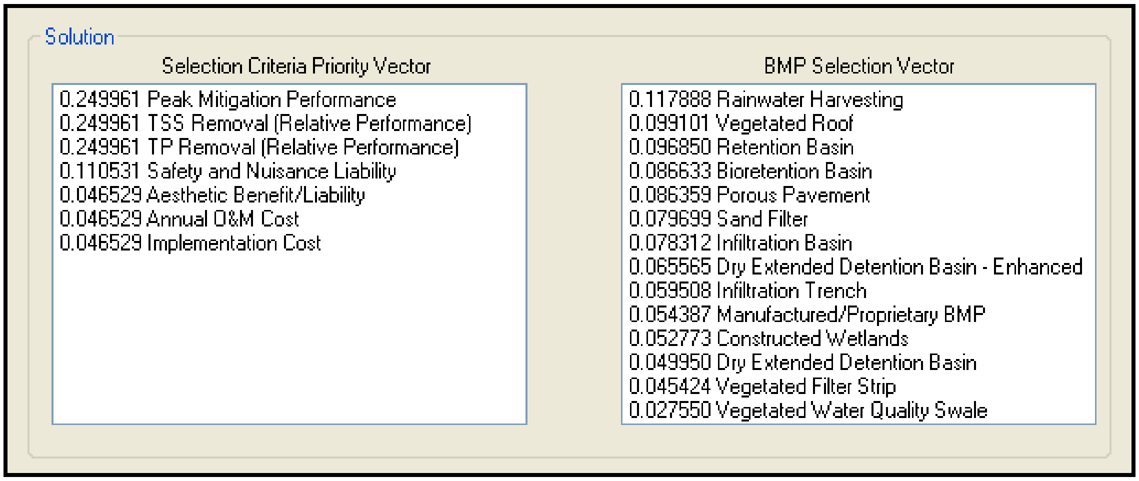


Figure 5.6 VT BMP DSS Output (Building Roof)

Examination of the results reveals that rainwater harvesting is the highest ranking BMP for this particular selection scenario. Chapters 6 and 7 of this report detail the hydrologic modeling of a rainwater harvesting system on the demonstration site and the performance of the practice in terms of water quantity and quality improvement.

Further examination of Figure 5.6 shows that the desired, qualitative criteria rankings were successfully expressed quantitatively by the VT BMP DSS. All functional objectives were ranked equally with one another, and given the greatest overall influence. Following these criteria, safety and nuisance liability was considered to be of moderate importance. Finally, the selection criteria depicting aesthetics and costs were given the lowest degree of influence in the BMP selection.

Applying the BMPs recommended by the VT BMP DSS, a hydrologic model was built for the demonstration site. This distributed stormwater management model was then compared against a baseline model using no BMPs and a centralized stormwater management model using mass storage detention. The construction and results of these models are discussed in Chapters 6 and 7 of this report respectively.

Chapter 6. Application of BMP Modeling Strategies in EPA SWMM

6.1 Overview of Objective and Methodology

In completing the project objectives described in Chapter 2 of this report, a demonstration site was selected to test BMP modeling strategies using EPA SWMM version 5.0. Site description and maps of the site can be found in Section 3.4 of this report. Three separate models were developed to depict three different surface runoff scenarios: a “baseline” model with no BMPs; a centralized stormwater management model utilizing a conventional mass storage/detention BMP; and a distributed model utilizing multiple, source-control BMPs distributed throughout the demonstration site.

The following is an overview of the steps taken to complete this project objective. Detailed explanations of these steps are provided in the subsequent sections.

1. Base data was compiled and processed in Environmental Systems Research Institute (ESRI®) ArcMap® Software (version 9.2)

2. GIS data was converted into EPA SWMM elements (nodes, pipes, outfalls, etc)

3. The baseline SWMM model was error-checked and iteratively refined to yield stable results with continuity errors minimized

4. The Virginia Tech BMP Decision Support Software was employed to select the BMPs used in the distributed stormwater management scenario

5. An EPA SWMM modeling approach was developed for each of the BMPs available in the Virginia Tech BMP Decision Support Software

6. Pollutant buildup and wash off functions were developed for total suspended sediment (TSS) and total phosphorus (TP), and related to proposed land use on the demonstration site

7. A single design storm event was developed and was applied to all three runoff scenario models

8. The centralized and distributed stormwater management models were compared against the baseline model in terms of peak runoff rate and pollutant load

While the results obtained from the model runs cannot be validated with actual monitoring data, completion of this project objective enabled a relative comparison of centralized and distributed stormwater management strategies.

6.2 Demonstration Site

The First and Main development project is a large scale, mixed use development presently under construction (as of July 2008). The project is located in Blacksburg, VA, west of South Main Street, between Country Club Drive and King Streets. Prior to initiation of the First and Main project, the site was predominately undeveloped, but did have six small buildings and a small motel located in its southeast corner. The relative drainage pattern of the site is from the northwest to the southeast. See Section 3.4 of this report for aerial imagery and pre and post-development drainage patterns of the site.

The overall development project is comprised of two phases. Phase I occupies approximately 26 acres on the southern portion of the site and will consist of a small outdoor shopping mall, a theater complex, restaurants, and a stormwater detention facility. Phase II encompasses approximately 13 acres on the northern portion of the site and is proposed as a “big box” retail development, consisting of one large building and its associated parking area.

Civil site design services and site plans for the project were provided by Anderson & Associates, Inc. The Town of Blacksburg provided contour maps, aerial imagery, and soil data for the First and Main project site. The soil data suggest that the site is predominately hydrologic soil group (HSG) C. Upstream of the First and Main Phase I site there is a small retail shopping center, a few restaurants, and a residential area. The runoff contribution from this portion of the watershed was not considered in the model so that offsite runoff quantity and quality would not influence the results of the project demonstration site.

6.3 Construction of a Baseline Model and Data Processing

The first step to meet this project objective was construction of a baseline model for the demonstration site. The baseline model does not include any stormwater BMPs, and serves to depict the behavior and characteristics of stormwater runoff from the demonstration site if it were left unmanaged upon project completion. Storm events were applied to this model to generate baseline hydrographs and pollutographs at various points of interest within the project development site. These baseline values were then used to evaluate and compare the centralized and distributed stormwater management approaches for both runoff quantity and quality.

In the case of the First and Main site, the baseline model includes major nodes (catch basins and manholes), stormwater conveyance piping, and sub-basin acreages and land cover as they were proposed by the engineering consultant. Figure 6.1 illustrates the baseline model superimposed onto aerial imagery.

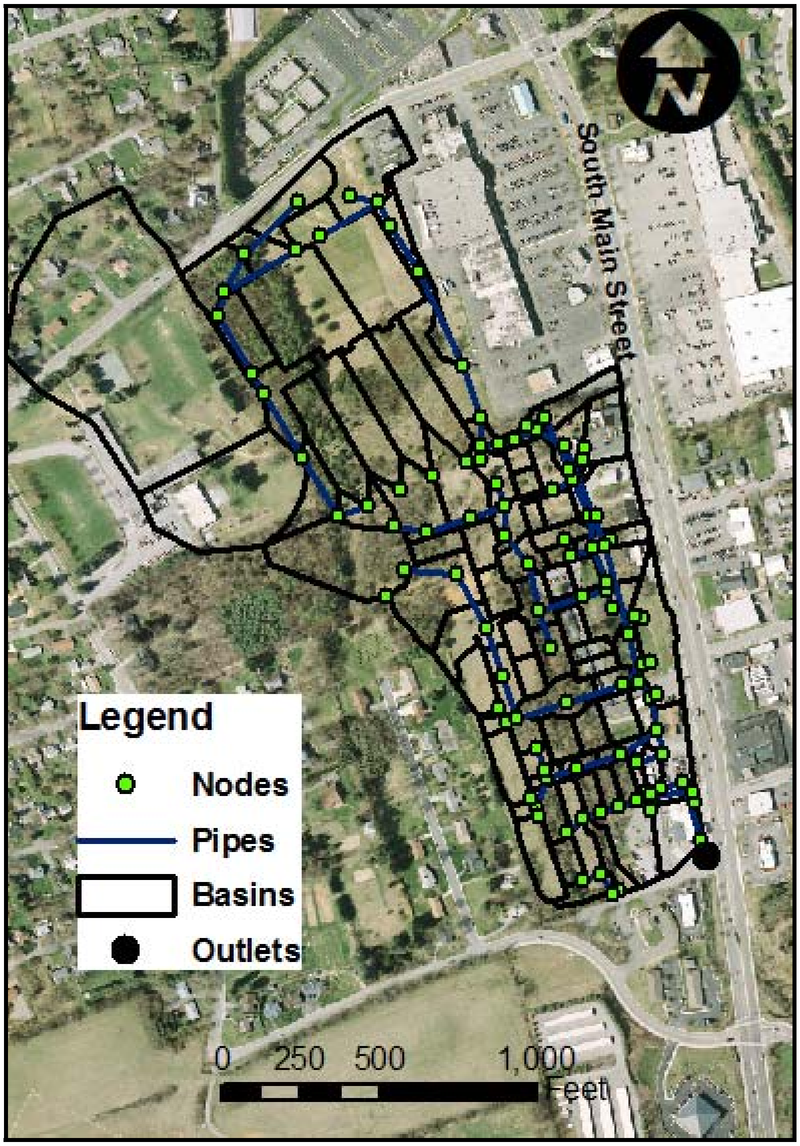


Figure 6.1 The First and Main Base Model

Base data was compiled and processed in Environmental Systems Research Institute (ESRI®) ArcMap® Software (version 9.2). Following is the approach used to build the baseline SWMM model.

1. Approximately twenty scanned engineering design drawings were imported as images into ArcMap®.

2. The engineering design drawings were then georeferenced onto the aerial imagery provided by the Town of Blacksburg.

3. ArcMap® feature classes were created and defined based on required inputs for the ArcGIS® to SWMM Converter (ASC)*. In order to use the ASC, each desired SWMM element requires the creation of key attribute fields in ArcMap®.

Basin elements require attributes for acreage, impervious percentage, slope, curve number, and the basin width parameter computed as the basin area divided by its longest flow path. Node elements require invert and depth attributes. Pipe elements require the definition of upstream and downstream nodes, and attributes for inverts, Manning's roughness coefficient, shape, dimension, length, and number of barrels. The outfall element requires an attribute for the invert elevation.

4. ASC was used to convert the GIS data into SWMM elements and, subsequently, a functioning SWMM model.

5. The SWMM model was iteratively refined to function within acceptable continuity tolerances. This process is explained further in Section 6.4. The refined model was then used as the baseline model at the First and Main site.

*The ArcGIS® to SWMM Converter (ASC) is a software tool developed at Virginia Tech by graduate student Brian Houston. ASC facilitates the conversion of ArcMap® layers into SWMM objects. ASC has the ability to create six object classes including basins, nodes, pipes, channels, ponds, and outlets; however, the user needs only to create the layers that apply to the site being modeled. For the demonstration site, layers for the basins, nodes, pipes, and outfalls were created. The proposed site's basins (sub-watersheds), manholes, catch basins, and pipes were digitized into these layers based on the design drawings and orthoimagery.

6.4 Model Refinement

When developing a stormwater model in SWMM, in order to control and minimize continuity errors, the model must be evaluated and iteratively refined through multiple test runs. Continuity errors reflect mass balance discrepancies between initial system storage at the onset of a model run, system inflow, final system storage, and total outflow from the system. Continuity errors may arise for surface runoff, flow routing, and water quality routing. If not addressed, these errors can compound and eventually reach a magnitude on the same order as the overall storage or treatment efficiency of the system, effectively undermining the validity of the model results (Houston, 2006).

The magnitude of continuity errors is largely a function of the size and complexity of the system being modeled. Often, the complexity of a model can be simplified through the elimination of very short pipe segments, with the assumption that these pipes exhibit negligible influence on overall system performance. Another source of continuity errors are mistakes in data entry. Common data entry errors include assigning negative pipe slopes and entering pipe inverts at elevations above or below their respective nodes. Ultimately, the level of acceptable continuity error is determined by the user. However, continuity errors should be significantly less than the water quality and peak mitigation efficiencies of the overall system. EPA SWMM suggests an acceptable upper limit of about ten percent error for any given metric.

To evaluate and refine the First and Main base model, a one-hour duration, two-year storm event was applied to the model. Upon completion of model runs, SWMM reports were generated to determine the magnitude and potential source of continuity errors. Through careful examination of SWMM status reports, problem nodes and links were identified and corrected. Additionally, the system was scrutinized, and small pipe runs were eliminated in locations where their impact was believed to have negligible influence on overall system performance. Completion of this task yielded a baseline SWMM model with continuity errors falling below the maximum recommended in EPA SWMM v. 5.0 literature. Figure 6.2 presents a schematic depiction of the First and Main baseline model.

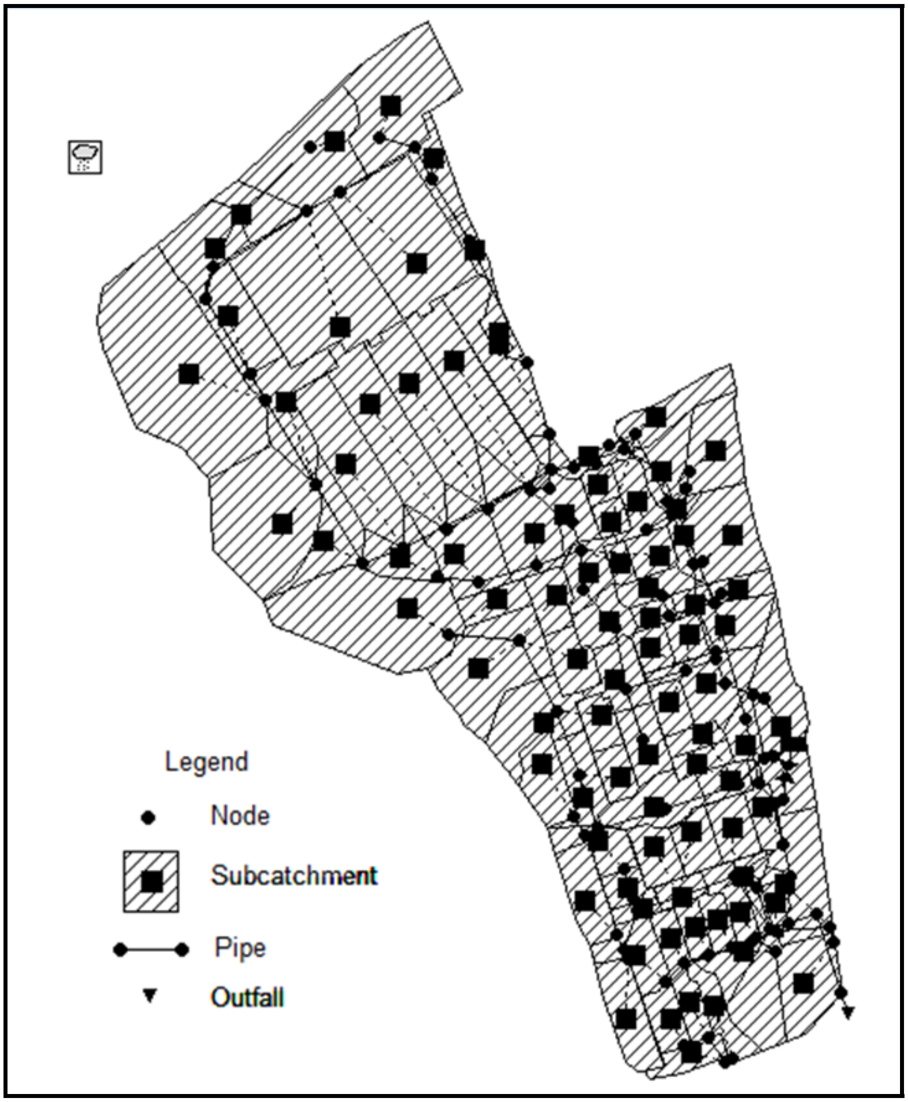


Figure 6.2 Baseline SWMM Model of the First and Main Demonstration Site

6.5 Application of the Virginia Tech BMP Decision Support Software

The Virginia Tech BMP Decision Support Software (VT BMP DSS) was applied in selecting which BMPs to be used in the distributed stormwater management scenario for the First and Main demonstration site. Recall that the VT BMP DSS ranks competing BMP options by attempting to simultaneously satisfy the user-chosen and user-weighted selection criteria. Chapter 5 of this report provides a full description of how the VT BMP DSS was applied on the demonstration site. Most drainage sub-watersheds on the First and Main site ranged from one to five acres; however, percent imperviousness of these sub-watersheds varied from 38% to greater than 66%. Table 6.1 provides a summary of the BMP rankings obtained from the VT BMP DSS.

Table 6.1 VT BMP DSS Rankings for the First and Main Development Project

Drainage Area: 1 - 5 acres		Drainage Area: 1 - 5 acres		Building Roofs	
Impervious Percentage: 38 % - 66 %		Impervious Percentage: > 66 %		Impervious Percentage: 100 %	
Rank	BMP	Rank	BMP	Rank	BMP
1	Porous Pavement	1	Rainwater Harvesting	1	Rainwater Harvesting
2	Rainwater Harvesting	2	Sand Filter	2	Vegetated Roof
3	Retention Basin	3	Vegetated Roof	3	Retention Basin
4	Vegetated Roof	4	Porous Pavement	4	Bioretention
5	Sand Filter	5	Manufactured/Proprietary	5	Porous Pavement

Based on these rankings, the distributed stormwater management model for the First and Main site recommends three different BMP strategies: porous pavement, sand filters, and rainwater harvesting systems.

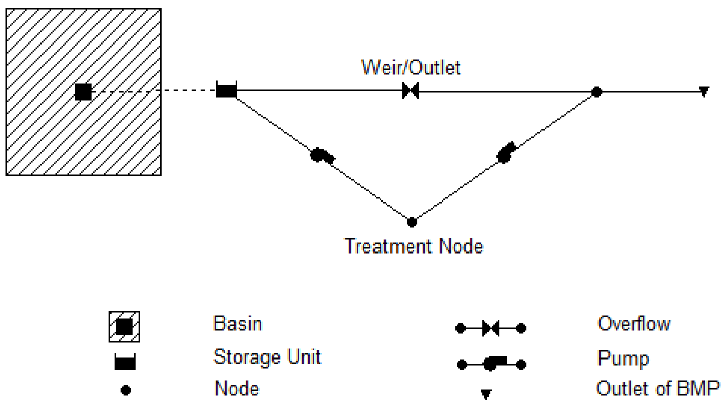
6.6 Development of BMP Modeling Strategies in EPA SWMM v. 5.0

Like most hydrologic modeling software, EPA SWMM is not capable of directly simulating all of the BMP options available in the VT BM DSS. Therefore, model modifications were developed to simulate the runoff treatment processes for these BMPs using the intrinsic elements of SWMM such as storage units, pipes, nodes, orifices, weirs, flow dividers, and pumps. Appendix F of this report comprises a manual on the modeling of water quality BMPs in the EPA SWMM v. 5.0 environment. The techniques presented in Appendix F are founded on the use of "templates" that allow the modeler to quickly represent the BMP of interest within a hydrologic model.

It is noted that the BMP modeling techniques described in this report may not be the only effective means by which to model water quality BMPs in SWMM.

6.6.1 BMP Modeling Templates

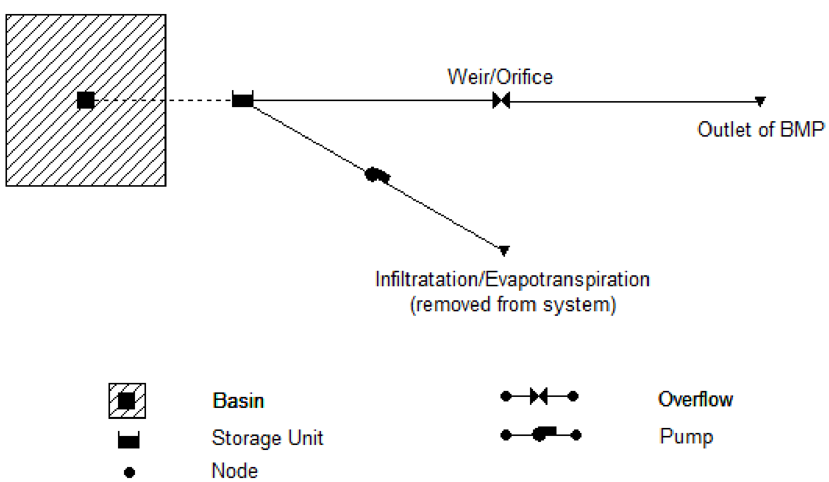
Before beginning assembly or sizing of a BMP, the appropriate template configuration must be determined. Figures 6.3 to 6.6 illustrate four different BMP templates and identify which BMPs can be effectively modeled by each configuration.



Applicable BMPs:

- Pond/Basin Class BMPs
  - Extended Dry Detention
  - Enhanced
  - Retention
- Sand Filters
- Constructed Wetlands
- Vegetated Buffers and Swales

Figure 6.3 EPA SWMM Treatment Template



Applicable BMPs:

- Infiltration Basins/Trenches
- Porous Pavement
- Bioretention
- Vegetated Roofs

Figure 6.4 EPA SWMM Infiltration Template

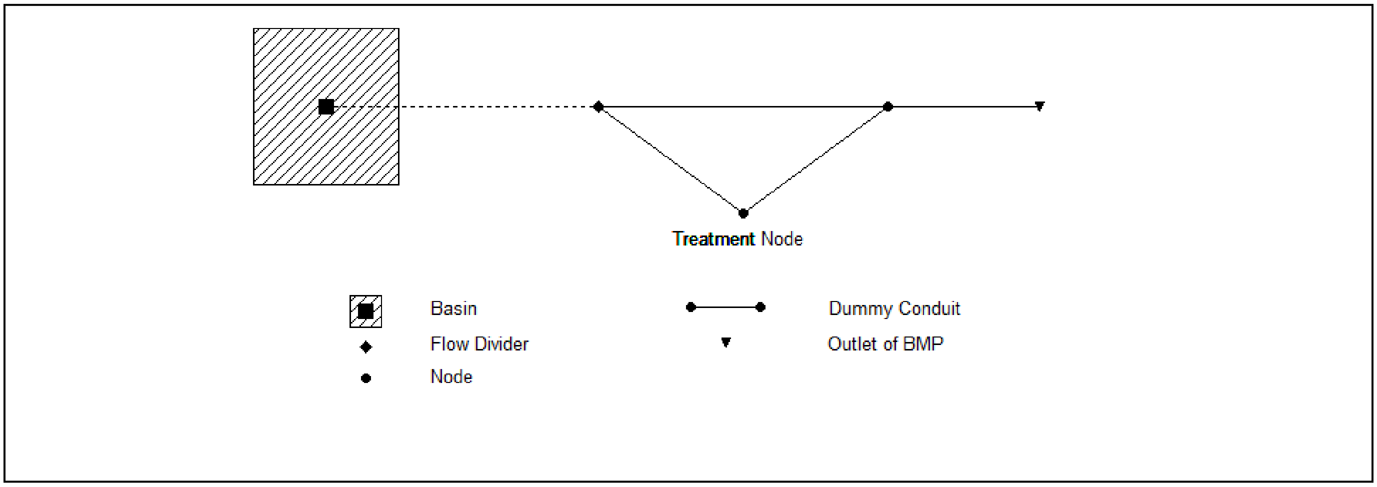


Figure 6.5 EPA SWMM Manufactured/Proprietary BMP Configuration

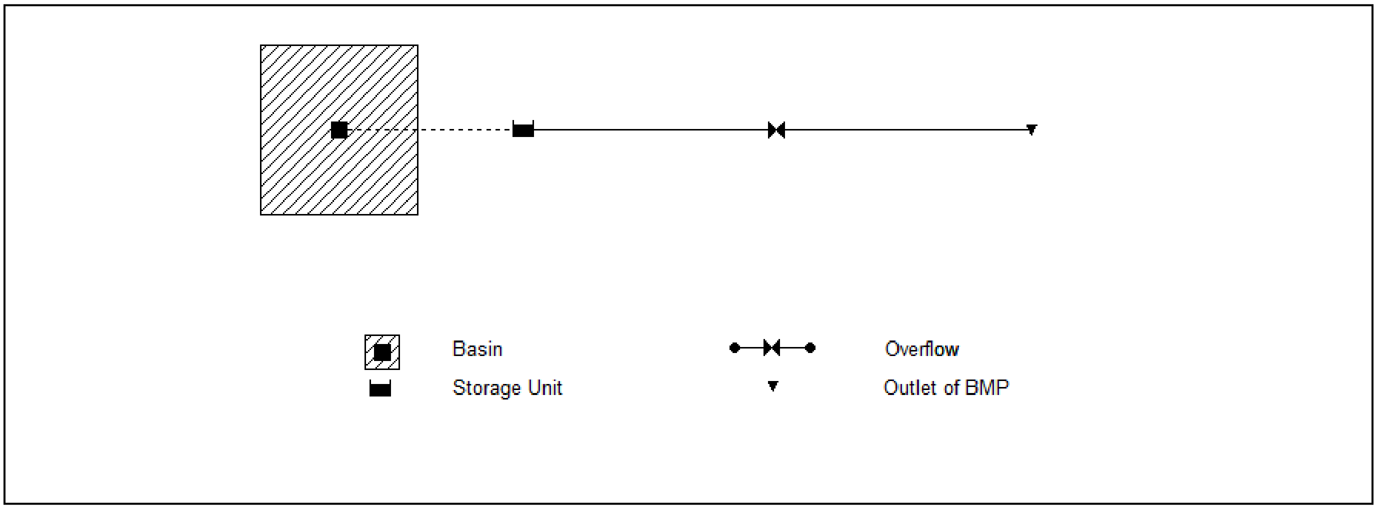


Figure 6.6 EPA SWMM Rainwater Harvesting Template

6.6.2 BMP Assembly and Sizing Procedures

Following development of the previously described templates, a means of assembling and sizing the SWMM elements comprising the templates was developed. Assembly and sizing procedures, described in detail in Appendix F of this report, assume that the BMP model representations are being used as planning tools, and that engineering drawings of the BMPs have not yet been developed. Consequently, the procedures described in this report enable the modeler to approximate a given BMP's performance very early in a project's planning stages. To model a BMP's performance prior to its detailed design, sizing of the BMP elements must be a function of basin characteristics such as area, geometry, impervious area, slope, etc. If BMP performance modeling is desired at the design stage, and detailed engineering drawings of the BMP *are* available, these modeling procedures can be adapted to incorporate actual design parameters such as outlet geometry and placement, water quality volume (WQV), and total storage volume.

None of the BMP assembly and sizing procedures described in this report are intended to model BMP performance for storms with a return frequency of greater than two years. This is because the primary objective of these model representations is to evaluate the water quality benefits of BMP installation. The majority of pollutant runoff from a given site is derived from small, frequently occurring storm events; therefore, the proposed model representations do not take large storms into account. Even though water quantity control is not the primary concern of this research effort, the effects of the BMPs on water quantity can still be estimated for storm events equal to or below the 10-year event (i.e. most rainfall events). The full procedures for evaluating each individual BMP within SWMM are included in Appendix F.

6.6.3 The Use of Pumps in SWMM

As seen in the template schematics (Figures 6.3-6.6), pumps are sometimes used in conjunction with storage elements and treatment nodes to simulate the physical processes of different BMPs. Within a SWMM model, pump rates are determined in one of two ways depending on the BMP of interest. For the infiltration template, the pump rate is a function of the anticipated infiltration rate of the BMP's underlying soil media. For the treatment template, the design hydraulic residence time of the water quality volume is the variable by which the pump rates are determined. The pump rates tend to be very small when compared to overall flowrates within the BMP, so their omission could possibly be considered.

While neglecting the pumps' relatively small flowrates would simplify the model in some respects, the pump configurations were ultimately used for two reasons. First, when runoff reaches a BMP modeled with the infiltration template, infiltration is nearly instantaneous. For small storms, this initial infiltration of runoff allows for more available storage volume within the BMP's storage element as runoff continues to enter the BMP. Consequently, better runoff rate reduction and water quality enhancement is observed than if the pumping (infiltration) function were omitted.

Secondly, to relatively compare water quality performance of the distributed and centralized management approaches, total TSS and TP mass loads were compared for both alternatives. Choosing to evaluate the two runoff management alternatives by total pollutant load made it essential, especially within the treatment template, to reintroduce the WQV to the system following a certain drawdown time so that its impact could be accounted for and observed. In the treatment template, the WQV is pumped to a treatment node where pollutant removal efficiencies are applied for each pollutant of interest through simple removal equations. From the treatment node, the treated WQV is pumped slowly back into the system at the desired rate. These small flowrates have a negligible effect on the water quantity, but are vital for quality evaluation of the modeled stormwater management strategies.

6.6.4 Constant Parameters in SWMM Models

In order to model and compare alternative stormwater management scenarios on a relative basis, certain SWMM parameters must remain constant across all scenarios. The first of these parameters are land use and associated pollutant buildup and wash off. The second parameter is the storm event which is applied to all models.

Land Uses & Pollutants

To analyze the water quality impacts of different BMP strategies, pollutant buildup and wash-off was simulated in SWMM. The state of Virginia defines phosphorus as its "keystone pollutant" because of the unique manner in which it exhibits characteristics of both soluble and particulate pollutants. Notable levels of suspended sediment are also often found in the runoff generated from impervious surfaces, managed lawns, and construction sites. Therefore, these two pollutants were chosen for study within the scope of this research project. Within the SWMM models, the buildup and wash-off of these pollutants were defined as a function of land use. For this project, three distinct land uses were chosen: impervious, rooftop, and green space. The impervious land use was applied to represent any driving or parking lot surface. Green space was used to represent any naturally occurring or manmade pervious land cover.

For each of the respective land uses, pollutant buildup and wash-off functions were entered. SWMM provides the user with a variety of mathematical functions to use in the definition of pollutant buildup and wash-off processes. Buildup can be defined with an exponential, power, or saturation function. Wash-off can be defined by a rating curve, an event mean concentration, or by an exponential function. Each function requires the input of additional coefficients and exponents. Within the scope of this project, physically-based buildup and wash-off functions were deemed unnecessary because the runoff management alternatives would only be compared using relative pollutant removal efficiencies. This means that as long as the functions are defined identically in each alternative model, the method of buildup and wash-off is not of critical importance.

According to Zhang and Hamlett (2006), pollutant buildup and wash off are best defined by a power function and a rating curve function, respectively. Applying the power function option, buildup rates and the coefficients for maximum buildup were chosen arbitrarily and iteratively adjusted until stable pollutographs were obtained for several design storm events.

During the course of the modeling exercise, quality routing continuity was found to be much more stable using an exponential wash-off function instead of a rating curve wash off function. For the exponential wash off exponents, arbitrary values were chosen from a range of values recommended by Huber and Dickinson (1992). Similar to maximum buildup in the power buildup function, the wash-off coefficients were initially assumed and then adjusted to create suitable pollutographs over several storm events.

The overall goal in selecting which functions and coefficients to depict pollutant buildup and wash-off was to create stable pollutograph behavior and continuity during water quality routing. If buildup and wash off functions and their respective input parameters are not chosen and calibrated carefully, the result can be a pollutograph with several peaks, often at concentrations that far exceed pollutant runoff concentrations suggested in literature. Tables 6.2 and 6.3 summarize the constants applied within the various buildup and wash off functions available in SWMM.

Table 6.2 Buildup Function Parameters Applied in SWMM

Buildup Function Parameters (power)				
	TSS		TP	
Land Use	**Max Buildup**	**Rate Constant**	**Max Buildup**	**Rate Constant**
Impervious	10	1	5	0.5
Rooftop	5	0.5	5	0.5
Green	5	0.5	2.5	0.25

Table 6.3 Wash Off Function Parameters Applied in SWMM

Wash Off Function Parameters (exponential)				
	TSS		TP	
Land Use	**Coefficient**	**Exponent**	**Coefficient**	**Exponent**
Impervious	1.5	2	0.5	3
Rooftop	1.5	2	0.5	3
Green	0.5	3	0.5	5

Storm Event

The selection and creation of design storm events was critical both for sizing BMPs and for the SWMM model runs used in the comparison of centralized and distributed stormwater management approaches. Quantity control is a concern for this project; however, more emphasis was placed on water quality because of increasingly stringent stormwater quality regulations and the resultant concern among planners and developers. For this reason, large, infrequent storm events were ignored and the storm events employed were small, short-lived rainfall events. Previous research has shown that the highest pollutant loadings in stormwater runoff occur in what is referred to as the "first flush" (LID Center, 2000). The first flush is often considered to be the first half-inch of runoff; therefore, a short-lived storm with an excess rainfall depth of one half-inch was assumed to be a reasonable starting point in the design of most of the BMP model configurations.

For comparison modeling of the alternative stormwater management strategies, a storm event was chosen that met the stated research objectives. The primary criterion by which this storm event was selected was its ability to produce runoff from all sub-watersheds on the demonstration site but not being so large that the runoff caused flooding within the system. The chosen rainfall depth was arbitrary except that it consistently met the stated criteria. Storm durations were established as one hour. Because pollutants tend to be washed off at the onset of a precipitation event, storms of longer duration do not typically affect water quality (Roseen, et. al., 2006).

The storm event applied to the alternative runoff management models was chosen through a trial and error procedure. The Virginia Tech Penn State Urban Hydrology Model (VTPSUHM) was used to create the rainfall hyetograph that was eventually applied in the SWMM models. The required inputs included storm duration and the associated rainfall depth for that storm duration in the geographic location of interest. For this project, the rainfall depth first considered was that of the one-year return frequency storm with duration of one hour taken from the "Precipitation-Frequency Atlas of the United States," NOAA Atlas 14. This storm was later determined to be too large and not representative of a typical storm for which most BMPs are intended to provide water quality improvement. Also, because of the complexity of the pipe network in the models, a large storm produces very high continuity errors. After several trials, a storm event with a 24-hour rainfall depth of 1.25 inches, applied over a one hour period, was chosen for comparison of the centralized and distributed models.

The resulting VTPSUHM SCS Type II rainfall hyetograph, seen in Table 6.4, was directly entered as a rainfall time series in the rain gage element of SWMM. When a SWMM model is run, hyetographs are applied to the modeled watershed resulting in runoff hydrographs which can be observed at any link or node. The continuity errors associated with this storm event were small enough that the validity of the results from each model was not questioned.

Table 6.4 VTPSUHM SCS Type II Hyetograph Used in Comparison of SWMM Models (24 hr depth = 1.25", Duration = 1 hr)

Time (hrs)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Intensity (in/hr)	0.353	0.432	1.045	1.411	5.003	1.879	1.173	0.49	0.39	0.325

It is reiterated that as long as certain variables, including rainfall events, are kept consistent for all models, the model results can be compared relatively. The hyetograph shown above was used on all models.

6.6.5 Performance Metrics Used in Model Comparison

To relatively compare performance of the centralized and distributed stormwater management models, various performance metrics were identified. The metrics decided upon were peak runoff rate reduction/mitigation and the removal of total suspended sediment and total phosphorus.

Peak runoff rate reduction describes how well a certain stormwater management strategy performs at quantity control. To evaluate peak mitigation performance, the peak flow rates from the two alternative stormwater management strategies were compared to the peak flow rate observed from the baseline model for the same rainfall event. Percent reduction of peak flow rate was the metric used to describe the peak mitigation performance of the centralized and distributed stormwater management scenarios.

Pollutant removal efficiency was the metric used to evaluate the water quality performance of the two alternative runoff management strategies. To calculate removal efficiency, the total pollutant load from each of the alternative stormwater management strategies was compared to the total pollutant load from the baseline model. The percent reduction of total pollutant load was the metric used to describe the water quality performance of the centralized and distributed stormwater management scenarios.

6.7 EPA SWMM Model of the Centralized Stormwater Management Approach

A centralized stormwater management model was created for the demonstrations site in an effort to depict the traditional approach to stormwater management. This management approach is termed "centralized" because runoff from the site is directed to one or a few relatively large storage facilities. Runoff is then released from the facility at a controlled flow rate. Often, the centralized storage facility is a basin of some variety equipped with a multi-stage outlet to control multiple return frequency events. Runoff is usually conveyed to the basin by a curb and gutter system and/or storm sewer piping. This is often the default approach employed by stormwater engineers because of the abundance of information surrounding proper design and implementation of this stormwater management strategy. In a centralized system, most or all of the water quality benefits are attributed to settlement of suspended solids in the storage facility, while nutrient concentrations may not be significantly affected.

At the First and Main demonstration site, the Anderson and Associates, Inc. design proposed three mass-storage facilities including two underground storage tanks and one surface basin. The underground storage facilities are designed to act like an aboveground basin with a multistage outlet to handle design storms of varying return frequency. The basin is located on the eastern edge of Phase I in the approximate location of an existing stormwater pond.

The engineering design plans were used as the basis for the centralized SWMM model for this site. The first underground storage tank is located at the southern edge of Phase

II. The second is located in the southern half of Phase I. Both tanks are preceded by proprietary water quality inlets primarily intended to remove suspended sediment. To reflect the estimated performance of the proprietary water quality inlets, a removal efficiency of 74 % was applied within the model for total suspended solids (NPRD, 2000). Such manufactured BMPs are generally regarded to provide little removal of nutrients; however, to remain conservative for comparison to the distributed runoff management model, a total phosphorus removal efficiency of 15 % was applied.

In order to remain consistent with the distributed stormwater management model, the Anderson and Associates, Inc. plans were only used to locate the underground storage facilities, not to size them. Instead, the facilities were modeled in SWMM according to the methods described in Appendix F of this report. The aboveground basin was, however, modeled as it was designed in the plans because it was included in both the centralized and the distributed models and is primarily intended for aesthetic benefit on the site.

6.8 EPA SWMM Model of the Distributed Stormwater Management Approach

As a comparison alternative to the centralized stormwater management strategy, a distributed management strategy was also modeled. The concept behind this runoff management strategy is to spatially distribute BMPs throughout a site in an attempt to preserve and mimic the site's predevelopment hydrologic patterns. This strategy is sometimes known as low-impact development (LID) and is rapidly gaining popularity as stormwater engineers look for innovative ways to mitigate the effects of land development activities. In this runoff management approach, no single BMP is expected to store the runoff volume associated with a large storm event, but the cumulative storage provided by multiple BMPs can be engineered to attenuate peak runoff rates to an acceptable level. The VT BMP DSS was applied to determine which BMP options were best suited for a distributed stormwater management approach on the First and Main demonstration site.

The VT BMP DSS allows its user to evaluate and compare competing BMP alternatives by the total area contributing runoff to the practice. Based on site design drawings prepared by Anderson & Associates, Inc., the most logical approach for application of the VT BMP DSS to the First and Main demonstration site was to evaluate sub-drainage basins whose areas ranged between one and five acres. Subdivision of the demonstration site at this scale yielded a total of six sub-watersheds not including roofs. Roofs were considered to be individual watersheds within the distributed model. Four of the six sub-watersheds fell into the 38 to 66 percent impervious cover range. The remaining two sub-watersheds were highly impervious, falling into the greater than 66 percent impervious cover range. The VT BMP DSS ranked porous pavement as the most suitable BMP for the four moderately impervious sub-watersheds, and ranked sand filters as the best BMP for the two highly impervious sub-watersheds. As for the roofs, rainwater harvesting was ranked the highest. Based on these results, the distributed First and Main

SWMM model is comprised of three different BMP strategies: porous pavement, sand filters, and rainwater harvesting.

Chapter 7. Results and Conclusions

This chapter compares the quantity and quality modeling results for two runoff management strategies studied on the First and Main demonstration site. All hydrologic models were created in EPA SWMM version 5.0, using the BMP modeling techniques described in Chapter 6 and Appendix F of this report.

7.1 Summary of Methodology

To evaluate the utility of the Virginia Tech BMP Decision Support Software (VT BMP DSS), a demonstration site was chosen in the Town of Blacksburg, Virginia. Upon selection of the site, two case studies were performed. The first case study, described in detail in Chapter 5 of this report, applied the VT BMP DSS to identify the best BMP alternatives for a distributed runoff management strategy on the demonstration site. The concept behind this runoff management strategy is to spatially distribute BMPs throughout a site in an attempt to preserve and mimic the site's predevelopment hydrologic patterns. Based on actual site design plans of the demonstration site, the VT BMP DSS was applied to six sub-watersheds and proposed building rooftops. Four sub-watersheds exhibited post-development impervious percentages ranging from 38-66% while two exhibited post-development impervious percentages in excess of 66%. All six of these sub-watersheds ranged in area from one to five acres. Rooftops were analyzed independently of the site's surface drainage sheds. Table 7.1 shows the BMP rankings obtained for the three categories of sub-watershed on the demonstration site.

**Table 7.1 VT BMP DSS Rankings for
Phase II of the First and Main Development Project**

Drainage Area: 1 - 5 acres Impervious Percentage: 38 % - 66 %		Drainage Area: 1 - 5 acres Impervious Percentage: > 66 %		Building Roof Impervious Percentage: 100 %	
Rank	**BMP**	**Rank**	**BMP**	**Rank**	**BMP**
1	Porous Pavement	1	Rainwater Harvesting	1	Rainwater Harvesting
2	Rainwater Harvesting	2	Sand Filter	2	Vegetated Roof
3	Retention Basin	3	Vegetated Roof	3	Retention Basin
4	Vegetated Roof	4	Porous Pavement	4	Bioretention
5	Sand Filter	5	Manufactured/Proprietary	5	Porous Pavement

The second case study, described in detail in Chapter 6 of this report, consisted of building three hydrologic models to evaluate two alternative runoff management strategies for the demonstration site. First, a baseline model was constructed for the demonstration site. The baseline model did not include any stormwater BMPs, and served only to depict the behavior and characteristics of stormwater runoff from the demonstration site if it were left unmanaged following project construction. Next, a centralized stormwater management model was created for the demonstrations site to depict the traditional approach to stormwater management. This management approach is termed “centralized” because runoff from both phases of the site was directed to one of three large storage facilities. These storage facilities were preceded by proprietary water quality control devices per the actual site design plans. Finally, a distributed stormwater management model was built for the demonstration site. The distributed model applied those BMPs suggested by the VT BMP DSS.

Within the three models, pollutant buildup and wash off was established as a function of proposed land cover. Described in detail in section 6.6.4 of this report, identical buildup and wash off functions were applied to each of the three models. Similarly, the same rainfall event was applied to each model. Details of this storm event can also be found in section 6.6.4 of this report.

In order to compare performance of the centralized and distributed stormwater management models, various performance metrics were identified. These performance metrics include peak runoff rate reduction and the removal of total suspended sediment and total phosphorus. The First and Main development project is comprised of two phases. Phase I occupies approximately 26 acres on the southern portion of the site and consists of a small outdoor shopping mall, a theater complex, and several restaurants. Phase II encompasses approximately 13 acres on the northern portion of the site and is proposed as a “big box” retail development, consisting of one large building and its associated parking area. Proposed site grading shows that surface flow patterns generally mimic that of the pre-developed condition, tending from north to south. The aforementioned performance metrics were evaluated at the outfall of Phase II and at the outfall of Phase I, which represents the outfall of the entire demonstration site.

7.2 Comparison of Runoff Rate Reduction

Historically, the focus of stormwater management has been to reduce the peak runoff rate from a developed site to pre-development (or other acceptable) levels. Providing flood control in the form of peak rate attenuation is still a highly prioritized goal in most stormwater management endeavors. As described in section 6.6.4 of this report, a storm event with a 24-hour rainfall depth of 1.25 inches, applied over a one hour period, was chosen for comparison of the centralized and distributed models. Table 7.2 summarizes the runoff rate reduction of the two stormwater management strategies, observed at the outlet of Phase II of the First and Main demonstration site.

Table 7.2 Runoff Rate Reduction
(Observed at Outlet of Phase II)

Model	Peak Flow Rate (cfs)	% Reduction
Base	33.05	--
Centralized	8.31	74.9%
Distributed	5.97	81.9%

Table 7.2 reveals that both the centralized and distributed stormwater management strategies provide significant runoff rate reduction, with the distributed model outperforming the centralized model by a margin of 7.0% (81.9% compared to 74.9%). Recall that, in the distributed management scenario, runoff from four of the six sub-watersheds comprising the demonstration site was managed by porous pavement. Consequently, the substantial peak rate reduction observed at the outlet of Phase II can be largely attributed to the water quality volume being infiltrated and thus entirely removed from the system. Additionally, the observation at the outfall of Phase II reflects the performance of only one of three mass storage facilities present in the centralized model.

Table 7.3 summarizes the runoff rate reduction of the two stormwater management strategies observed at the most downstream release point of the First and Main demonstration site. The runoff rates show in Table 7.3 reflect contributions from both Phase I and Phase II of the First and Main development.

Table 7.3 Runoff Rate Reduction (Observed at Outlet of Overall Site)

Model	Peak Flow Rate (cfs)	% Reduction
Base	46.22	--
Centralized	7.00	84.8%
Distributed	13.03	71.8%

At the site outfall, the centralized management approach yields 13.0% more peak rate reduction than the distributed model (84.8% compared to 71.8%). This result is not entirely unexpected, due to the large storage volume provided by the three centralized mass-storage facilities. This observation implies that, in order to achieve peak rate reduction comparable to a centralized stormwater management approach, a distributed approach may require a supplementary BMP that provides additional detention and controlled release. However the storage volume required of this supplemental facility will be substantially smaller than if it were implemented as the lone runoff management BMP as in the case of the centralized approach.

7.3 Comparison of Pollutant Removal

Table 7.4 summarizes the total suspended sediment (TSS) reduction of the two stormwater management strategies, observed at the outlet of Phase II of the First and Main demonstration site.

Table 7.4 TSS Reduction (Observed at Outlet of Phase II)

Model	TSS Load (kg)	% Reduction
Base	66.08	--
Centralized	36.82	44.3%
Distributed	13.92	78.9%

Table 7.4 reveals that the distributed stormwater management approach greatly outperforms the conventional, centralized approach in terms of removing suspended sediment from surface runoff. While both runoff management approaches remove a significant portion of TSS from the demonstration site's runoff, the distributed model achieves a nearly 35% greater removal efficiency.

Table 7.5 summarizes the TSS reduction of the two stormwater management strategies observed at the most downstream release point of the First and Main demonstration site. The sediment loads shown in Table 7.5 reflect contributions from both Phase I and Phase II of the First and Main development.

Table 7.5 TSS Reduction
(Observed at Outlet of Phase II)

Model	TSS Load (kg)	% Reduction
Base	115.46	--
Centralized	81.61	29.3%
Distributed	35.53	69.2%

Again, the distributed stormwater management approach greatly outperforms the centralized approach in terms of removing TSS from surface runoff. At the outfall of the demonstration site, the distributed strategy provides nearly 40 % more TSS removal than the centralized model.

Table 7.6 summarizes the total phosphorus (TP) reduction of the two stormwater management strategies, observed at the outlet of Phase II of the First and Main demonstration site.

Table 7.6 TP Reduction
(Observed at Outlet of Phase II)

Model	TP Load (kg)	% Reduction
Base	33.68	--
Centralized	17.31	48.6%
Distributed	6.53	80.6%

Table 7.6 reveals that the distributed stormwater management approach greatly outperforms the conventional, centralized approach in terms of removing phosphorus from surface runoff. While both runoff management approaches remove a significant portion of TP from the demonstration site's runoff, the distributed model achieves 32% greater removal efficiency.

Table 7.7 summarizes the TP reduction of the two stormwater management strategies observed at the most downstream release point of the First and Main demonstration site. The phosphorus loads shown in Table 7.7 reflect contributions from both Phase I and Phase II of the First and Main development.

Table 7.7 TP Reduction
(Observed at Outlet of Phase II)

Model	TP Load (kg)	% Reduction
Base	52.94	--
Centralized	36.45	31.2%
Distributed	16.31	69.2%

Again, the distributed stormwater management approach greatly outperforms the centralized approach in terms of removing TP from surface runoff. At the outfall of the demonstration site, the distributed strategy provides nearly 40 % more TP removal than the centralized model.

For each pollutant considered in this study, the distributed model, representative of hydrologic source control, out-performs the centralized model. This pollutant removal performance is directly attributed to the increased infiltration and removal of the water quality volume by the porous pavement, and rainwater capture and reuse systems respectively, as well as the high pollutant removal efficiencies of stormwater sand filters.

7.4 Summary of EPA SWMM Continuity Errors

Table 7.8 presents the EPA SWMM continuity errors reported at the outlet of the First and Main demonstration site.

Table 7.8 Summary of Continuity Errors

Continuity Error, %			
Model	**Surface Runoff**	**Flow Routing**	**Quality Routing**
Base	-1.37	1.61	-10.11
Centralized	-1.38	0.71	-8.55
Distributed	-1.37	0.28	-4.81

The continuity errors reported by SWMM for surface runoff and flow routing are minimal, and well within the tolerances recommended in literature. The continuity errors related to quality routing are noteworthy, and, in the case of the base model, slightly exceed the recommended 10% maximum. However, due to the relatively complex storm sewer network being modeled, it was not possible to reduce the quality routing continuity errors beyond those presented in Table 7.8. Even with quality routing errors exceeding 10 %, the results are meaningful because both the distributed model and centralized model achieve pollutant removal efficiencies significantly greater than 10 %.

7.5 Conclusions and Opportunities for Future Research

A limitless number of possible criteria may influence the choice of a BMP for a particular site or runoff management application. As more and more selection criteria are introduced to the selection process, the task of objectively selecting a BMP becomes increasingly complex. This report documents the application of the AHP decision support algorithm in a BMP selection scenario. While the application example successfully demonstrates the basic capability of the AHP algorithm in assisting the BMP selection process, opportunities exist to expand and improve upon application of the AHP to stormwater management.

First, save for a trial and error approach, there is no readily available means by which to apply the AHP algorithm to evaluate combinations of BMPs. In many localities, when infiltration is not feasible, two (or more) BMPs placed in series are required. The application of these treatment "trains" is also common in localities designated as Special Protection Areas (SPAs). As the AHP presently exists in the realm of BMP selection, the only means by which to select multiple BMPs for a given site is to examine the site as individual sub-watersheds. While this may be a justifiable approach for many scenarios, it yields a group of BMPs functioning independently throughout the site of interest. This approach would likely not satisfy the requirements of a locality requiring multiple BMPs installed in series. Initial research suggests that the AHP may be used in conjunction with various optimization techniques and algorithms to facilitate the selection of optimal combinations of BMPs, but little work has been carried out on this approach to date.

Next, close scrutiny is advised in the application of any multi-criteria decision-making technique. Multi-criteria decision-making algorithms should be viewed as one tool in the decision-making process and not as the lone means for obtaining a final answer. When the AHP process is applied to BMP selection, the algorithm attempts to satisfy all selection criteria while adhering to the respective weights assigned to each criterion by the user. This attempt to simultaneously satisfy potentially conflicting criteria may yield results that do not fully satisfy each criterion individually. Therefore, the BMP rankings attained by the VT BMP DSS must be critically scrutinized. Opportunities exist to modify the code of the VT BMP DSS such that these violations are found and accounted for before results are presented to the user.

Presently, there is considerable interest among stormwater engineers and land planners in developing new ways to effectively model the wide variety of BMP options. These modeling techniques enable the evaluation and comparison of alternative runoff management strategies prior to the field installation of BMPs. The methods and results from this research project begin to explore software modeling of BMPs, but research opportunity remains in the field of predictive BMP models.

Before predictive BMP modeling strategies can be utilized with a high level of confidence, a major calibration effort is necessary. This project only considers the relative effectiveness of BMPs because the SWMM models were not calibrated and, therefore, do not represent real results that might be obtained with field measurements.

Furthermore, because the output from models using BMP templates is only relative, the direct impact of using alternative BMPs is difficult to quantify. Calibration of the various BMP template configurations suggested in this research report would help quantify the benefits of each BMP and ultimately allow planners and regulators to estimate the impact of individual BMPs before costly design and construction begins.

In SWMM, the major elements in need of calibration efforts are the pollutant buildup and wash off functions, BMP pollutant removal rates, and the hydrologic response to applied storm hyetographs. This could be accomplished by applying the methods suggested in this report to a site that has monitoring data available at several points within the drainage network. The essential data includes flow and pollutant concentration data immediately upstream and downstream of any BMPs present in the monitored system. With this data, BMP design parameters such as water quality volumes, pollutant removal efficiencies, and pump rates could be adjusted to fit the recorded monitoring data. Duplicating this effort at several sites would expand and improve upon the techniques presently available for modeling different BMPs in the EPA SWMM environment.

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Appendix B. Structural BMPs Included in the VT BMP DSS

A structural BMP is a device intended to remove targeted pollutants and contaminants from stormwater runoff, thus preventing the introduction of these pollutants to receiving waters. The number and type of structural BMPs available for the treatment of stormwater runoff varies geographically. The major objective of this research project was to develop a software-aided decision support process to assist planners and engineers in the selection of urban stormwater BMPs for a particular application scenario. In order to accomplish this objective, it was necessary to identify which BMPs should be included in the decision support software. The pilot site/watershed that was studied under the scope of this research project is located in the Town of Blacksburg, Virginia (see section 3.4 of this report). Consequently, those BMPs recognized by the State of Virginia's Stormwater Management Program were prioritized for inclusion in the BMP decision support software.

Fundamental to the Analytic Hierarchy Process (AHP) decision support algorithm is the construction of pairwise comparison matrices. Within the context of this application of the AHP, these pairwise comparison matrices serve to compare and rank the various BMP alternatives in terms of each selection criteria. Appendix D of this report describes the construction of these BMP comparison matrices. The following is a description of each BMP available in the VT BMP DSS, including the performance characteristics and implementation guidelines used in constructing the pairwise comparison matrices presented in Appendix D.

Dry Extended Detention Basins and Enhanced Detention Basins

Since the early 1970's, the most common approach to stormwater management in the United States has been to drain a developed site as quickly and efficiently as possible, and then detain this runoff and release it to a downstream channel or facility at a controlled rate. Without question, the most popular means by which this management approach occurred has been through the use of dry detention basins. Dry detention basins are earthen structures constructed either by impoundment of a natural depression or by the excavation of existing soil. These basins are configured to provide temporary storage of runoff while attenuating the peak rate of runoff. Historically, the emphasis when constructing a dry detention basin has been on peak runoff rate mitigation.


Extended Detention Basin (DCR, 1999)

However, due to the gravitational settling of the larger particulate fraction of suspended solids in the runoff, some water quality benefit has always been observed in these facilities. The extended version of dry detention facilities seeks to enhance and further this water quality benefit by providing an extended storage volume in which runoff is held and released over a much longer period than is necessary for peak runoff rate mitigation. Yet another variation on the traditional detention basin design is the *enhanced extended detention basin.* The enhanced basin generally exhibits an even greater pollutant removal efficiency arising from the presence of a shallow marsh in its bottom. This marsh aids in pollutant reduction by incorporating wetland plant uptake, adsorption, physical filtration, and decomposition. Additionally, the shallow marsh vegetation also helps reduce the problem of pollutant resuspension.

The primary purpose of a detention basin is the attenuation of peak stormwater runoff rates from a site. Most often, these basins are equipped with multi-stage riser outlets which permit peak attenuation for multiple return frequency storms such as the 2, 5, 10, 25, and 50 year runoff producing events. To achieve increased water quality benefits, extended detention basins are equipped with a storage volume above and beyond that which is required for peak runoff rate mitigation. This volume is held in the pond over some pre-determined time period, often a minimum of 24 hours, so that gravitational settling of pollutants may occur. Release of the water quality volume from the basin is achieved, most often, by flow through a designated water quality orifice. While the outlet orifices designated for peak attenuation are sized to provide a controlled rate of flow from the basin, the water quality orifice is sized to ensure that the minimum allowable detention time is achieved for the computed water quality volume.

Often an extended dry detention facility is equipped with sediment forebays and/or a micropool in order to further improve water quality control through increased sedimentation. The sediment forebays of a detention basin are vegetated with specific plant species to improve the filtering of runoff, reduce potentially erosive velocities, and to stabilize the basin soils. Sediment forebays are typically constructed as shallow marsh areas and, while requiring routine maintenance, are commonly sized to provide sediment trapping over a period of two to 10 years.

When an extended dry detention basin is considered for implementation on a site, a number of key design elements must be considered. Detention basins are major structural practices with significant land area requirements, implementation and maintenance costs, and potential safety concerns. Consequently, their implementation is often restricted to sites whose contributing drainage area is a minimum of 10 acres, with 25 acres or more recommended. Detention basins must be sized to mitigate the peak rate of runoff from multiple return frequency events. In some localities peak attenuation is required up to the 100 year return frequency event. When the water quality volume and peak attenuation volume are considered together, the area required for an extended detention basin can be a significant fraction of an overall site land area. Therefore, when a site comprises less than 10 acres, adequate runoff management is often achieved more economically by the use of multiple, smaller BMPs.

Detention basins are further restricted in their application when sites exhibit shallow water table depths. In the absence of a synthetic liner, there exists an inevitable loss of detained runoff through infiltration. This infiltration has the potential to contaminate ground water supplies in areas where the seasonally high water table is less than two feet below the finished ground surface. Furthermore, the construction of detention basins on exceptionally well-draining soils is often restricted. In the presence of well-drained soils, such as hydrologic soil groups A and B, ponds may require a synthetic liner to reduce infiltration losses through the pond bottom and its embankments.
Extended detention basins are applied throughout the United States to meet residential, commercial, industrial, and highway stormwater management needs. However, their use is limited in ultra urban settings by two factors. First, as previously discussed, extended detention basins require a significant fraction of land area compared to the watershed area from which they are capturing runoff. In highly urbanized environments, this large land area requirement often precludes their use. Second, because the water quality benefits in an extended detention basin occur primarily through gravitational settling, the pollutant removal percentages for soluble contaminants such as phosphorus and nitrogen are relatively low when compared to other structural BMP measures such as infiltration practices. Runoff from urban hotspot areas often contains pollutant levels which cannot be adequately treated by gravitational settling (soluble phosphorus for example).

The following table presents the relative stormwater management function of extended dry detention basins.

Table B.1 Relative Stormwater Management Function –
Extended Dry Detention Basins

Source: Pennsylvania Stormwater Best Management Practices Manual, (PA DEP, 2006)

Volume Reduction	Low
Groundwater Recharge	None
Peak Rate Control	High
Water Quality Improvement	Low

Retention Basins

Retention basins are structural BMPs capable of removing sediment, BOD, organic nutrients, and trace metals from stormwater runoff. Retention basins, like their dry counterparts, are also capable of providing significant peak mitigation benefits. The recognized water quality benefits of retention basins are achieved by reducing flow velocity and detaining stormwater using an in-line permanent pool. Biological processes occurring in the permanent pond aid in reducing the amount of soluble nutrients present in the runoff, such as nitrate and ortho-phosphorus. Retention basins also provide aesthetic benefits that many other BMPs do not. Because of this, the inclusion of a retention basin on a developed site may serve the two fold purpose of adding to the site's value while greatly improving the quality of runoff from the site.

When a retention basin is under consideration for a site, of critical design concern is the presence of adequate baseflow. The designer is strongly encouraged to perform a low flow analysis of the drainage area being considered. The anticipated baseflow from a fixed drainage area can exhibit great variability, and insufficient baseflow may require consideration of alternate BMP measures. Should the basin become dry or stagnant, problems such as algae blooms and undesirable odors will arise. The minimum contributing drainage area that should be considered for a retention basin is 10 acres. Typically the maximum contributing drainage area will be limited to 10 square miles. (FHWA, 1996). In terms of land area requirements, the designer should consider that between one and three percent of a contributing drainage area is required for construction of a retention basin. (FHWA, 1996)

Retention Basin located on the Virginia Tech Campus

Site soils are a vitally important consideration during the proposed installation of a retention basin. To maintain a permanent pool, the pond must be constructed such that water does not exfiltrate from the permanent pool into the surrounding soil. The presence of extremely permeable soils on the site (Hydrologic Soil Groups A and B) often require installation of an impermeable geotextile or clay liner.

Retention basins provide optimal water quality benefits when they are constructed long and narrow such that “short- circuiting” of inflow does not occur. Short-circuiting occurs when runoff entering the basin quickly exits the basin before mixing with the permanent pool. Short-circuiting can be discouraged by increasing the basin length to width ratio or by installing baffles near basin inflow point(s). A minimum length to width ratio of 2:1 should be maintained, with ratios of 4:1 or greater providing even greater protection against runoff short-circuiting. (FHWA, 1996)

The depth of the permanent pool within a retention basin must be maintained within a desirable range. Shallow basins, in the absence of adequate stabilizing vegetation, possess the ability to easily resuspend sediment as a result of wind. Basins with excessively deep pools give rise to safety concerns as well as potentially stratifying the pool and creating anoxic conditions near the pond bottom. The average depth of a retention basin’s permanent pool should range between 3 and 6 feet with depths in excess of 8 feet avoided completely. (FHWA, 1996)

Generally, a specific mix of vegetation is planted or preserved around a retention basin’s perimeter. Vegetation reduces erosion on both the side slopes and the shallow shore areas. Vegetation located near the inlet to the basin can provide the benefit of helping to trap sediment. Additionally, algae growing on these plants can also filter soluble nutrients in the water column. Thicker, higher vegetation can also help hide any debris which may collect near the shoreline. Native turf-forming grasses or irrigated turf are planted on sloped areas, while aquatic species should be planted on the littoral areas. (FHWA, 1996)

Much like dry detention basins, when a retention basin is considered for implementation on a site, a number of key design elements must be considered. Retention basins are major structural BMP practices with significant land area requirements, implementation and maintenance costs, and potential safety concerns. Retention basins require a source of permanent baseflow to ensure that the basin holds a permanent pool even during periods of extended drought. Further, retention basins are typically sized to mitigate the peak rate of runoff from multiple return frequency events. In some localities peak attenuation is required up to the 100 year return frequency event. When the water quality volume and peak attenuation volume are considered together, the area required for a retention basin can be a significant fraction of an overall site land area. Therefore, when a site's contributing watershed area is less than 10 acres, adequate runoff management is achieved more economically by the use of multiple smaller BMPs.

Retention basins are applied throughout the United States in residential, commercial, industrial, ultra urban, and highway stormwater management scenarios. Retention basins may be successfully implemented on sites exhibiting shallow water table depths. In many cases, interaction with groundwater can provide a source of baseflow to assist in maintaining the basin's permanent pool during periods of little inflow.

The following table presents the relative stormwater management function of retention basins.

Table B.2 Relative Stormwater Management Function – Retention Basins

Source: Pennsylvania Stormwater Best Management Practices Manual, (PA DEP, 2006)

Volume Reduction	Low
Groundwater Recharge	Low
Peak Rate Control	High
Water Quality Improvement	Medium

Infiltration Trenches

An infiltration trench is a linear stormwater BMP which functions by detaining and infiltrating inflow over a designated period of time. Usually an infiltration trench is part of a stormwater conveyance system and is designed so that even large storm events are conveyed through the trench with some runoff volume reduction. During small storm events, the observed volume reduction may be quite significant. While different types of infiltration trenches exist, (surface versus subsurface), the core design element of an infiltration trench is sizing the aggregate infiltration volume and its available pore space. Thus, the methodology applied in the respective designs of both surface and subsurface trenches is similar.

Infiltration trench BMPs are applied throughout the United States in residential, commercial, industrial, ultra urban, and highway stormwater management scenarios. In ultra urban settings, local ordinances may dictate the pre-treatment of hotspot runoff prior to its introduction to the trench. The contributing drainage area to an infiltration trench must be limited to no more than 10 acres. Larger drainage areas may result in sediment loading levels which can significantly impair the performance of infiltration practices.

Infiltration Trench located between two roads (DCR, 1999)

With a design approach targeted toward infiltrating a significant portion of polluted runoff, infiltration practices are subject to a number of unique application restrictions. Sites exhibiting shallow bedrock and water table depths generally preclude the installation of infiltration trenches. Additionally, when infiltration practices are deemed feasible for a site, most localities will require that they be located no closer than 100 feet from any water supply well. Many localities further restrict the construction of infiltration practices in the vicinity of structural foundations and septic drainfields.

Soil permeability rates are typically the single most important consideration in an infiltration trench feasibility study. The minimum soil infiltration rate for an infiltration practice to function effectively is 0.5 inches per hour. Typically, the maximum allowable infiltration rate for the soil underlying an infiltration trench is 12 inches per hour. Generally, hydrologic soil group D is not considered suitable for the construction of infiltration practices. Soils with excessively high infiltration rates, such as hydrologic soil group A, may also preclude the installation of infiltration BMPs. However, exceptionally well drained soils may be amended with other soils to yield acceptable infiltration rates.

Infiltration trenches are limited in width to eight feet, and in depth to no more than six feet. Their relatively small land area requirements make them an appealing option on smaller sites. Biological process associated with infiltration and the contact of inflow with the trench’s vegetative lining result in exceptional removal of both suspended and soluble pollutants. Consequently, when water table and bedrock depths are sufficient and soil infiltration rates adequate, infiltration trenches are an excellent option for the treatment of polluted runoff. The following table presents the relative stormwater management function of infiltration trenches.

Table B.3 Relative Stormwater Management Function – Infiltration Trenches
Source: Pennsylvania Stormwater Best Management Practices Manual, (PA DEP, 2006)

Volume Reduction	Medium
Groundwater Recharge	High
Peak Rate Control	Medium
Water Quality Improvement	High

Infiltration Basins
Infiltration basins are shallow, impounded areas designed to temporarily store and infiltrate stormwater runoff. Infiltration basins use the existing soil mantle to reduce the volume of stormwater runoff by infiltration and evapotranspiration. The quality of the runoff is improved by the natural filtering process of the existing soil mantle and also by the vegetation planted in the basins.

Infiltration basin BMPs are applied throughout the United States in residential, commercial, and industrial settings. Typically, their implementation in ultra urban and highway settings is limited. The contributing drainage area to an infiltration basing must be limited to no more than 50 acres. However, infiltration basins function much more efficiently when the contributing drainage area is considerably less than this. Larger drainage areas are usually best treated by basin or wetland BMPs.


Infiltration Basin located in Clarksburg, MD

With a design approach targeted toward infiltrating a significant portion of polluted runoff, infiltration practices are subject to a number of unique application restrictions. Sites exhibiting shallow bedrock and water table depths generally preclude the installation of infiltration trenches. Additionally, when infiltration practices are deemed feasible for a site, most localities will require that they be located no closer than 100 feet from any water supply well. Many localities further restrict the construction of infiltration practices in the vicinity of structural foundations and septic drainfields.

Soil permeability rates are often the single most important consideration in determining infiltration basin feasibility. The minimum infiltration rate for an infiltration practice to function efficiently is 0.5 inches per hour. Typically, the maximum allowable infiltration rate for the soil underlying an infiltration basin is 12 inches per hour. Generally, hydrologic soil group D is not considered suitable for the construction of infiltration practices. Soils with excessively high infiltration rates, such as hydrologic soil group A, may also preclude the installation of infiltration BMPs. However, exceptionally well drained soils may be amended with other soils to yield acceptable infiltration rates.

To avoid stagnant conditions, mosquito habitat, and other nuisances, infiltration basins must be designed such that the underlying soil provides a complete drawdown of stored water in less than 72 hours. When the surrounding soil is not capable of draining the pond within a 72 hour time period, the basin may be equipped with an underdrain system to expedite draining of detained runoff.

Infiltration basins must be equipped with a sediment forebay or riprap apron at their inflow point(s) to provide velocity reduction and ensure even distribution of inflow within the basin. Along with a maximum allowable basin embankment slope of 3H:1V, the requirement of forebays and protective aprons at all inflow points results in infiltration basins exhibiting a high land area requirement when compared to many other practices. Additionally, sufficient depth must exist within an infiltration basin to provide freeboard between the top of embankment and the outfall invert of their overflow structure. The large land area requirement associated with infiltration basins often impedes their use on smaller sites.

Biological process associated with infiltration and the contact of inflow with the basin's vegetative lining result in exceptional removal of suspended and soluble pollutants. Consequently, when water table and bedrock depths are sufficient and soil infiltration rates adequate, infiltration basins are an excellent option for the treatment of polluted runoff from larger sites. The following table presents the relative stormwater management function of infiltration basins.

Table B.4 Relative Stormwater Management Function – Infiltration Basins

Source: Pennsylvania Stormwater Best Management Practices Manual, (PA DEP, 2006)

Volume Reduction	High
Groundwater Recharge	High
Peak Rate Control	Medium/High
Water Quality Improvement	High

Porous Pavement

Porous pavement systems consist of permeable surfaces underlain by a uniformly graded stone bed. The types of porous surfaces include asphalt, concrete, and various structural pavers all placed upon uncompacted soil. Porous pavement systems are found in use throughout the United States in residential, commercial, ultra urban, and industrial settings.

Porous pavement systems are usually restricted to locations where the contributing off-site drainage area is less than 10 acres. The sediment loading from areas larger than 10 acres is usually in great excess of what is recommended for porous pavement applications. Additionally, for runoff contributing areas larger than 10 acres, the cost effectiveness of porous paving systems is considered marginal compared to that of other BMPs. The application of porous paving systems is further restricted to terrains which will permit the construction of a level infiltration bed and traffic-bearing surfaces that do not exceed five percent grade in any direction. Porous surface systems may be implemented in cold weather climates, provided that the reservoir layer extends to a depth beyond the frost line. Sites exhibiting shallow bedrock and water table depths generally preclude the installation of porous pavement systems. Additionally, when infiltration practices are deemed feasible for a site, most localities will require that they be located no closer than 100 feet from any water supply well. Many localities further restrict the construction of infiltration practices in the vicinity of structural foundations and septic drainfields.

Soil permeability rates are often the single most important consideration in determining the feasibility of porous pavement installation. The minimum infiltration rate for an infiltration practice to function efficiently is 0.5 inches per hour. Typically, the maximum allowable infiltration rate for the soil underlying a porous pavement system is 12 inches per hour. Generally, hydrologic soil group D is not considered suitable for the construction of infiltration practices. Soils with excessively high infiltration rates, such as hydrologic soil group A, may also preclude the installation of infiltration BMPs. However, exceptionally well drained soils may be amended with other soils to yield acceptable infiltration rates.

The stone bed underlying a porous surface system typically ranges between 12 and 36 inches in depth. The void space of this stone bed, at a minimum, must be equipped to accommodate the computed water quality volume of the porous surface and any off-site contributing areas. When comprised of stone aggregate, approximately 40% void space is found in the bed. A number of proprietary interlocking units are now available as an alternate option to stone in the infiltration bed. While costing considerably more than their stone counterparts, these proprietary systems often provide a much greater storage volume. Usually, the infiltration bed underlying a porous surface system is equipped with a perforated underdrain pipe. This pipe assists the movement and subsequent infiltration of inflow during heavy runoff producing events capable of saturating the infiltration bed. All porous pavement designs require surface inflow points and a safe overflow conveyance system in the event that the infiltration surface becomes clogged or the infiltration bed becomes fully saturated.

Porous pavement is generally 10% to 20% more expensive than standard pavement on a unit area basis. Additionally, the stone bed underlying a porous system is usually wrapped in a synthetic filter fabric and is much greater in depth than that underlying a conventional asphalt installation. However, when compared to conventional asphalt, these added costs are often more than offset by a significant reduction in the number of required pipes and inlets. Porous surface systems are also often incorporated into a site’s natural topography, resulting in reduced earthwork and excavation costs. When all factors are considered, porous asphalt is very comparable in cost to its traditional, impervious counterpart. The following table presents the relative stormwater management function of porous pavement systems.

Table B.5 Relative Stormwater Management Function – Porous Pavement
Source: Pennsylvania Stormwater Best Management Practices Manual, (PA DEP, 2006)

Volume Reduction	Medium
Groundwater Recharge	Medium
Peak Rate Control	Medium
Water Quality Improvement	Medium

Vegetated Filter Strip
Vegetated filter strips are permanent strips of vegetation located between nonpoint sources of pollution and receiving water bodies for the purpose of removing or mitigating the effects of pollutants such as nutrients and sediment. Vegetated filter strips often serve as one component in an integrated stormwater runoff management system or BMP “treatment train.” Properly constructed and maintained, filter strips are capable of reducing runoff velocity, reducing runoff volume, improving runoff quality, reducing site impervious area, and providing aesthetic benefit to developed sites. Vegetated filter or buffer strips are most commonly found in residential, commercial, and highway settings.

A number of different criteria influence the design of a vegetated filter strip. As with many filtration BMPs, the first of these criteria is that of site soils. Typically, the underlying soils must be of low permeability, such as hydrologic soil groups C and D, to ensure that the majority of runoff entering the strip remains as surface runoff. The range of desirable soil permeability for a filter strip is between 0.06 and 0.6 inches per hour. Typical soil classifications will be clay, clay loam, and silty clay. The presence of organic matter in the soils is desirable in that it can potentially improve the strip’s pollutant removal capabilities, much like a bioretention facility. Filter strips are suitable in cold climates. However, their effectiveness is limited in treating runoff from snowmelt. Strips cannot be effectively implemented in arid regions and regions otherwise not capable of supporting year-round dense vegetation.

The water quality effectiveness of a filter strip is dependent on maintaining sheet flow conditions across the strip. The concentration of runoff must be avoided to achieve optimal pollutant removal benefits. To ensure that the volume of runoff is such that concentration of flow does not occur, the maximum contributing drainage area to a vegetated filter strip should not exceed five acres. Careful attention must be given to examine the anticipated hydraulic flow regime when drainage areas approach the five acre maximum to ensure that runoff entering the filter strip remains as sheet flow. An additional concern in preventing concentrated flow through the filter strip is that of the longitudinal slope. The designer must be aware that as filter strip slope increases its pollutant removal ability decreases. Optimal pollutant removal is observed when filter strip slope is kept at five percent or less. Usually, filter strips cannot be used effectively when their longitudinal slope exceeds eight percent. Consequently, the implementation of filter strips in mountainous terrain is limited.

Vegetated filter strips can often be integrated into a site's landscaping plan. When this is the case, concern for the BMP land area requirement becomes negligible, as a portion of the site is not "lost" to the BMP. Typically, the minimum allowable length in the strip's direction of flow is 20 feet. However, lengths in excess of 100 feet may be necessary to attain high removal percentages of smaller particulates. (FHWA, 1996) As filter length increase, hydraulic residence time increases proportionally. To achieve desirable pollutant removal efficiencies, the hydraulic residence time of the water quality volume entering a filter strip is typically maintained at nine minutes or greater, and should under no circumstances be less than five minutes. The hydraulic residence time of the water quality volume entering the filter strip is, obviously, a function of flow velocity. In addition to meeting the minimum hydraulic residence time, the average flow velocity across the filter strip is normally kept less than 1 foot per second. The strip's contributing drainage area, vegetative roughness, filter strip slope, and length of flow path should not produce a depth of flow exceeding one half inch. (FHWA, 1996)

Filter strips must be planted with dense, soil-binding deep rooted water-resistant plants. If a grass filter strip is to be employed, a dense turf is necessary to achieve desirable pollutant removal percentages while avoiding erosion. If turf grass is used, the height must be rigorously maintained between two and four inches. The specific species of vegetation should be appropriate for the climatic conditions and expected maintenance schedule. The presences of trees, shrubs, and other woody vegetation can further increase the water quality performance of vegetated filter strips. In addition to intercepting a portion of stormwater before it even reaches the ground, trees and shrubs increase the infiltration and retention present in the filter strip. However, when trees are incorporated into the filter strip design, one must be aware that the overall density of vegetation is decreased. Consequently, while filter strips with trees and other woody vegetation can demonstrate higher pollutant removal efficiencies than their strictly grass counterparts, they require that the filter strip be longer in length to account for the reduced vegetation density. Additionally, tree and shrub trunks have the potential to support the development of gullies and channels in the strip. To offset this, filter strips equipped with trees and shrubs must be designed with flatter slopes than those employing only grass.

When considering the costs associated with a vegetated filter strip, the critical factor is the land required for the practice. When unused land is readily available on a site, a vegetated filter practice provides improved site aesthetics as well as a potentially cost-effective runoff treatment option. When land is not readily available, as in an ultra urban setting, filter strip practices may prove cost-prohibitive. The following table presents the relative stormwater management function of vegetated filter strips.

Table B.6 Relative Stormwater Management Function – Vegetated Filter Strip

Source: <u>Pennsylvania Stormwater Best Management Practices Manual</u>, (PA DEP, 2006)

Volume Reduction	Low / Medium
Groundwater Recharge	Low / Medium
Peak Rate Control	Low
Water Quality Improvement	High

Vegetated Water Quality Swale

Vegetated water quality swales are another type of filtration BMP. Engineered water quality swales are used throughout the United States in residential, commercial, industrial, and highway settings. Typically, vegetated swales are not suited to receive hotspot or ultra urban runoff unless additional treatment of the inflow is planned beyond that occurring in the swale itself. Engineered water quality swales are usually heavily vegetated with a dense, diverse mix of native water-resistant plants exhibiting high pollutant removal potential. Vegetated swales are most often broad, shallow, earthen-lined channels which permit infiltration, and filtering of runoff. The environmental benefits of a vegetated stormwater conveyance channel far outweigh those of conventional curb and gutter systems. Swales often serve as a pretreatment BMP in instances where a BMP “treatment train” approach is required to sufficiently address runoff pollutant removal needs. Most often, vegetated swales are characterized by a layer of dense vegetation, underlain by at least 30 inches of high to moderate permeability soil

Vegetated Water Quality Swale with check dams (DCR, 1999)

A number of different criteria influence the design of a water quality swale. The first criterion is that of channel geometry. Because one of the fundamental goals of the grassed swale is to improve the quality of runoff, it is essential to avoid any concentration of flow. In addition to presenting problems of constructability, parabolic and triangular channels intrinsically concentrate low flows, and thus are undesirable. Similarly, rectangular channels are typically avoided because of the inherent instability of their side slopes. Therefore, to satisfy both the issues of constructability and that of desired flow regime, typically only trapezoidal cross section channels are considered. Bottom widths of less than two feet are essentially non-constructible, and are not considered. At the opposite end of the spectrum, bottom widths greater than eight feet will tend to concentrate small flow events thereby reducing the pollutant removal ability of the swale. To provide swale stability over a myriad of soil types and vegetative covers, the acceptable side slopes of a vegetated swale should not be greater than 2H:1V.

The required depth of a swale is governed, ultimately, by the volume of water for which treatment is required. The ponding of water in the channel is typically achieved by the use of stone or timber check dams. These dams are constructed such that the maximum ponded depth of water never exceeds 18 inches. Vegetated swales function as an online BMP practice, and as such may be subjected to flows in excess of what can be detained behind the swale’s check dams. As a minimum standard, the channel should be able to safely convey the 10-year flood with a minimum of six inches of freeboard. It is noted that applicable municipal regulations may require that the swale be capable of conveying less frequent storm events with the minimum six inch freeboard.

Another critical issue when considering implementation of an engineered grassed swale is that of anticipated flow velocity. The flow velocity should be as low as possible in order to achieve maximum pollutant removal. Additionally, the swale must be designed such that larger runoff events do not result in re-suspension of previously deposited sediments. To minimize flow velocity, water quality swales should be as flat as practically possible for the given site topography. The maximum allowable longitudinal slope will ultimately be governed by the flow depth and allowable flow velocities. In practice, however, this maximum slope will rarely exceed six percent. In hilly or mountainous terrain, the use of vegetated swales may prove difficult and costly.

Vegetated water quality swales are typically regarded as one of the lowest cost BMP options available. Furthermore, when used in place of traditional curb and gutter conveyance systems, vegetated swales become an even more cost-effective BMP choice. Vegetated swale BMPs require regular maintenance, which does result in higher average annual expenditures than more conventional stormwater conveyance structures. However, when the runoff treatment benefits are considered, along with the long lifespan of vegetated swales, they remain a very financially attractive runoff management option. The following table presents the relative stormwater management function of vegetated water quality swales.

Table B.7 Relative Stormwater Management Function – Vegetated Swales

Source: Pennsylvania Stormwater Best Management Practices Manual, (PA DEP, 2006)

Volume Reduction	Low / Medium
Groundwater Recharge	Low / Medium
Peak Rate Control	Medium / High
Water Quality Improvement	Medium / High

Sand Filters

Stormwater sand filters are practices employed when the runoff from a site is expected to contain very high pollutant levels. These sand filters function by first pre-treating and temporarily storing runoff to remove the bulk of the large particle sediment, then percolating the runoff through the filter's sand media. As runoff filters through the sand media, water quality is improved through physical, chemical, and biological mechanisms. Various types of stormwater sand filters exist, and their application can be tailored to meet individual site needs. The most common types of stormwater sand filters are the Washington D.C. underground vault sand filter, the Delaware sand filter, and the Austin surface sand filter.

Stormwater sand filters act primarily as water quality BMPs. However, the water quality volume entering the filter is detained and released at a rate potentially capable of providing flood control. Peak rate control of the 10-year and greater storm events is typically beyond the capacity of a stormwater filtering system, and may require the use of an additional BMP to meet rate release requirements.

Stormwater sand filters are commonly used in urbanized settings where entering runoff is generated from areas whose imperviousness ranges from 67 – 100 percent. The primary cause of failure in stormwater filtering systems is the clogging of the sand media through excessive sediment loading.

The minimum drainage area contributing to an intermittent stormwater sand filter is not restricted. These types of filters are best suited to small drainage areas. The maximum drainage area to a single stormwater sand filter varies by filter type. Table B.8 shows the impervious acreage which may be directed to a single filter, as a function of filter type.

Table B.8 Appropriate Drainage Area by Filter Type

Filter Type	Appropriate Drainage Shed (Impervious Acres)
D.C. Underground Vault	0.25 – 1.25
Delaware	1.25 Maximum
Austin Surface	Greater than 1.25

Austin surface sand filters have been applied on sites with drainage areas as large as 30 acres. However on sites greater than 10 acres, despite a reduction in cost per volume of runoff treated arising from the economy of scale, the cost-effectiveness of an Austin sand filter is often poor when compared to alternative BMP options.

The liner or concrete shell of a sand filter should generally be located 2 to 4 feet above the site's seasonally high water table. The presence of a high water table can flood the filter during construction. Additionally, placing a sand filter within the groundwater table may give rise to infiltration, thus flooding the filter and rendering it inoperable during periods of inflow. When it is deemed feasible and desirable to employ an intermittent sand filter on a site exhibiting a shallow groundwater table, the effects of infiltration and flotation must be accounted for. The liner or concrete shell of the filter must be waterproofed.

Stormwater sand filters provide an attractive BMP option on high profile sites where visually obtrusive BMPs such as extended dry detention facilities and other basins are undesirable. Typically, sand filtration BMPs are visually unobtrusive and may be located on sites where aesthetic considerations and/or the preservation of open space is deemed a priority.

Sand filters are capable of receiving hydrocarbon-laden runoff. However, the facility owner must realize that such loading conditions will inevitably lead to rapid clogging of the filter media. When the presence of hydrocarbons is anticipated in the runoff entering a sand filter, the filter's pre-treatment chamber should be designed to remove unemulsified hydrocarbons prior to their entrance into the primary filter chamber. An alternative option is to provide an upstream "treatment train" comprised of a BMP(s) capable of reducing the level of hydrocarbons present in the runoff entering the sand filter.

The following table presents the relative stormwater management function of stormwater sand filters.

Table B.9 Relative Stormwater Management Function – Stormwater Sand Filters
Source: Pennsylvania Stormwater Best Management Practices Manual, (PA DEP, 2006)

Volume Reduction	Low
Groundwater Recharge	Low
Peak Rate Control	Low
Water Quality Improvement	High

Bioretention

Bioretention BMPs form a class of BMPs that improve the quality of stormwater runoff by means of adsorption, filtration, volitization, ion exchange, and microbial decomposition. In the most general sense, a bioretention BMP can be thought of as a modified infiltration area (such as those previously discussed) comprised of specific trees, plants, and shrubs intended to mimic the ecosystem of an upland forest floor. There are two categories of bioretention BMPs: off-line and on-line.


Bioretention Cell (DCR, 1999)

Off-Line Bioretention BMPs are areas comprised of sand and soil mixtures planted with native vegetation that are situated such that flow must be diverted into them. Runoff is directed to these areas either from overland flow sources or from concentrated discharge leaving an engineered drainage system. Off-line systems can be particularly useful in highly urbanized settings where the land available for stormwater management and treatment is limited. These BMPs can be located in parking lot islands, median strips, or open lawn areas. Off-line systems can be sized to hold a designated water volume. If a flow-splitter is employed to control the volume of runoff directed to the off-line practice, no emergency bypass is required.

The second category of bioretention BMPs, On-Line Systems, function in much the same manner as their off-line counterparts, but are located directly in drainage swales, filter strips, or other conveyance elements that comprise the main stormwater drainage network. Berms or check dams are employed to provide controlled ponding in these on-line bioretention areas. The use of check dams or other means of ponding runoff in a designated bioretention area is usually limited to drainage areas of no more than five acres. Furthermore, contrasting with off-line systems, the on-line system must be capable of safely passing larger, less frequent runoff producing events. This requirement may mandate an increased size of the bioretention area and provisions for potentially erosive velocities.

In essence, a bioretention facility is a specific type of infiltration practice, and as such is subject to many of the same restrictions as those discussed previously. Local and state ordinances often prohibit the construction of bioretention cells on sites exhibiting shallow water table or bedrock depths. Bioretention practices may further be restricted in the vicinity of water supply wells, septic drainfields, and structural foundations.

When a bioretention BMP is deemed feasible on a particular site, the first design element to consider is soil type. Two goals exist in developing a soil mixture for the bioretention area. First, the soil must be sufficiently permeable to allow infiltration. Secondly, the soil should be able to adsorb organic nitrogen and phosphorus. To achieve these goals, soil mixtures with a maximum of 10 percent clay are used. The permissible pH range of the soil is between 5.5 and 6.5, and will ideally consist of a loam, loam/sand mix, loamy sand, or sandy loam. In-situ soils may be amended with sand and/or organic material. A typical sand/organic amended soil is combined with 20-30% organic material (compost), and 50% construction (course grained) sand. A typical bioretention area will have a minimum planting soil depth of 24 inches or a minimum of four inches deeper than the bottom of the largest root ball. (PA DEP, 2006).

To ensure manageable sediment loading, rigorous guidelines exist in establishing the maximum drainage area that can be directed to a bioretention facility. In most instances, the ratio of contributing drainage area to bioretention surface area should be a maximum of 5:1. The Federal Highway Administration document, Evaluation and Management of Highway Runoff Water Quality, further recommends that the minimum size of an off-line bioretention area be 15 ft wide by 40 ft long. For bioretention areas to function optimally, the length-to-width ratio should be maintained as close to 2 to 1 as practically possible. The length and width of on-line bioretention areas is governed by the geometry and size of the swale or filter strip in which they are located.

Bioretention areas, relative to other BMP practices, are expensive to construct. However, much of this cost arises from the intensive planting schedule required in bioretention areas. The inclusion of a bioretention area on a developed site is often in an area that would be landscaped anyway. Therefore, the net cost is often considerably less than the actual construction cost. Furthermore, inclusion of bioretention areas on a site often reduces the number of surface inlets and conveyance piping that is required to accommodate runoff. The following table presents the relative stormwater management function of bioretention BMPs.

Table B.10 Relative Stormwater Management Function – Bioretention
Source: Pennsylvania Stormwater Best Management Practices Manual, (PA DEP, 2006)

Volume Reduction	Medium
Groundwater Recharge	Medium/High
Peak Rate Control	Low/Medium
Water Quality Improvement	Medium/High

Constructed Wetlands

Constructed stormwater wetlands are a structural BMP having the capacity to improve the quality of stormwater runoff in much the same manner as retention and enhanced extended detention basins. Like these impounding facilities, stormwater wetlands are seeded with a diverse mix of aquatic and emergent vegetation, which plays an integral role in the pollutant removal efficiency of the practice. Wetland BMPs improve the quality of runoff by physical, chemical, and biological means. The physical treatment of runoff occurs as a result of decreased flow velocities in the wetland, thus leading to evaporation, sedimentation, adsorption, and/or filtration. Chemical treatment arises in the form of chelation (bonding of heavy metal ions), precipitation, and chemical adsorption. The biological treatment processes occurring in wetlands include decomposition, plant uptake and removal of nutrients, and biological transformation and degradation. (FHWA, 1996)


Constructed Stormwater Wetlands (DCR, 1999)

Constructed stormwater wetlands should, generally, not be used for flood control or downstream channel control. When a BMP is employed as a quantity control practice, there is an inherent expectation of rapidly fluctuating water levels in the practice following runoff producing events. Rapid fluctuations in water level subject emergent wetland and upland vegetation to enormous stress, and many wetland species cannot survive such conditions. In addition to producing large surges of stormwater runoff, land use conversion resulting in a loss of pervious cover will often result in a decrease of perennial baseflow from a watershed. The decrease or absence of such baseflow is problematic for the establishment of a diverse and healthy mix of wetland vegetation.

Constructed stormwater wetlands are comprised of three distinct zones – “low marsh,” “high marsh,” and “deep pool.” These varying-depth zones introduce microtopography to the basin floor.

Constructed stormwater wetlands should generally not be considered when their contributing drainage area is less than 10 acres. Of critical concern is the presence of adequate baseflow to the facility. Many species of wetland vegetation cannot survive extreme drought conditions. Additionally, insufficient baseflow and the subsequent stagnation of wetland marsh areas can lead to the emergence of undesirable odors from the wetland. Regardless of drainage area, all proposed wetlands should be subjected to a low flow analysis to ensure that an adequate marsh volume is retained even during periods of dry weather when evaporation and/or infiltration are occurring at a high rate. The anticipated baseflow from a fixed drainage area can exhibit great variability, and insufficient baseflow may require consideration of alternate BMPs.

The presence of a shallow groundwater table may allow for the implementation of a constructed wetland whose contributing drainage area is very small. These circumstances are site-specific, and the groundwater elevation must be monitored closely to establish the design elevation of the wetland's permanent pool.

The maximum drainage area to a constructed stormwater wetland is not explicitly restricted. However, the designer must consider that, due to the needs of aquatic plant species, storage volume in the form of excessive pool depth (vertical storage) is typically not possible. Therefore, the land area required for constructed wetland may be two to three times the site area required of alternative BMPs. (MWCOG, 1992) The minimum surface area of the wetland marsh area is generally two percent of the contributing drainage area.

While stormwater wetlands should not be constructed within 50 feet of any slope steeper than 10%, the implementation of constructed stormwater wetlands can be successfully accomplished in the presence of a variety of soil types. To ensure the long-term success of a constructed wetland, it is essential that water inflows (baseflow, surface runoff, and groundwater) be greater than losses to evaporation and infiltration. Consequently, soils exhibiting high infiltration rates are generally not suited for the construction of stormwater wetlands. Often, soils of moderately high permeability are capable of supporting the shallow marsh areas of a stormwater wetland. However, the hydraulic head (pressure) generated from deeper regions, such as the wetland micro-pool, may increase the effective infiltration rate rendering similar soils unsuitable for wetland construction. A clay liner, geosynthetic membrane, or other material may be employed to combat excessively high infiltration rates.

When properly designed, landscaped, and maintained, constructed wetlands may be suitable for high visibility locations. However, when a constructed wetland is proposed in a high visibility location, ongoing maintenance of the facility is critical to its acceptance by neighboring landowners. Additionally, early in the project planning stages, careful attention should be given to the general characteristics of neighboring land uses. The landscape of a constructed wetland exhibits natural and sometimes rapid growth and vegetative colonization. This may be undesirable in the vicinity of an otherwise manicured landscape. The designer must also be aware of the significant land area requirements of a constructed stormwater wetland.

The following table presents the relative stormwater management function of bioretention BMPs.

Table B.11 Relative Stormwater Management Function – Constructed Stormwater Wetlands

Volume Reduction	Low
Groundwater Recharge	Low
Peak Rate Control	Low
Water Quality Improvement	High

Manufactured/Proprietary BMPs

Proprietary BMPs are a structural category of BMP using some form or combination of settling and filtration to remove particulate pollutants from turbulent flow. Manufactured practices vary widely in size and function. The most common types of proprietary BMP are hydrodynamic separators and catch basin inserts.

Hydrodynamic separation devices are designed to remove settleable solids, oil and grease, debris, and flotables from stormwater runoff through gravitational settling. Also termed oil / water separation devices, these BMPs are strictly for water quality benefit, and do not mitigate the peak rate of post-development runoff from their contributing watershed. Their implementation is most common in urban and ultra-urban areas where surface BMPs are not feasible. (VADCR, 1999) These manufactured systems are designed as flow-through structures, and do not provide significant detention volume. In contrast to conventional BMPs capable of storing a designated water quality volume, flow into a manufactured hydrodynamic separator is regulated by its inflow pipe or other structural hydraulic devices. When the maximum design inflow is exceeded, systems whose flow is regulated by the inflow pipe cause stormwater to back up into the upstream conveyance system or associated storage facility. When structural device(s) are employed to regulate flow into the hydrodynamic separator, flows in excess of the desired treatment volume either bypass the structure completely or bypass the separator's treatment chamber.

Hydrodynamic oil / water separators are best employed in commercial, industrial, and transportation land uses. Usually more economically attractive options exist than hydrodynamic separators for residential BMP needs. Often, hydrodynamic separators are employed as pretreatment measures for high-density or ultra urban sites, or in hydrocarbon hotspots, such as gas stations and areas with exceptionally high vehicular traffic.

Hydrodynamic separation devices are generally categorized as Chambered Separation Structures or Swirl Concentration Structures.

Chambered separation devices rely on gravitational settling of particles and, to a lesser degree, centrifugal forces to remove pollutants from stormwater. Chambered systems exhibit an upper bypass chamber and a lower storage / separation chamber. Runoff enters the structure in the upper bypass chamber and is channeled through a downpipe into the lower storage / separation, or treatment chamber. The system is designed such that when inflow exceeds the operating capacity, flow “jumps” the downpipe and completely bypasses the lower treatment chamber. (VADCR, 1999)

Swirl separation structures are characterized by an internal mechanism that creates a swirling motion. This motion results in the settling of solids to the bottom of the chamber. Additional chambers serve to trap oil and other floating pollutants. Swirl separators do not exhibit a means for treating large runoff producing events. Larger flows simply pass through the structure untreated. However, because of the swirling motion within the structure, large flow events do not resuspend previously trapped particulates. (VADCR, 1999)

The specific design criteria among hydrodynamic separation devices vary considerably. Proprietary separation devices are watertight and thus particularly useful in areas exhibiting shallow water table depths or in close proximity to water supply wells. Manufactured separation systems can be used in almost any soil or terrain. Additionally, since located underground, aesthetics and public safety are rarely considerations in their implementation.
Hydrodynamic separators require a much more intensive maintenance schedule than other BMP measures to ensure desirable performance levels.

Catch basins are chambers or sumps which provide the entrance point for surface runoff into a stormwater conveyance system. Catch basin inserts are employed to intercept coarse sediments, oils, grease, litter, and debris from the runoff prior to its entrance into the storm sewer. Catch basin inserts are well suited to parking lots, maintenance yards, and other locations where runoff travels directly from an impervious surface into the stormwater conveyance system. (VTRC, 2004) Water quality inlets encompass a broad spectrum of BMPs designed to remove non point source pollutants from runoff. These structural BMPs vary in size and treatment capacity, but typically employ some form of settling and filtration to remove particulate pollutants. Water quality inlets exist as a wide array of proprietary products discussed later in this section. However, these different configurations generally exhibit similar strengths and shortcomings. The most common types of catch basin inserts are tray type, bag type, basket type, and sumps constructed in inlets.

Tray type filters function by passing stormwater through a filter media situated in a tray located around the perimeter of an inlet. Runoff enters the tray and exits via weir flow under design conditions. Runoff from large storms simply passes over the tray into the inlet unobstructed and untreated. (PADEP, 2006) Bag type inserts are made of fabric and placed in the drain inlet around the perimeter of the grate. Runoff entering the drain must pass through the bag prior to exiting through the drain pipe outlet. The system is usually equipped with overflow holes to prevent backwater conditions during heavy runoff producing events. (PADEP, 2006) Basket type inserts set inside of an inlet and can be removed for periodic maintenance. Small orifices permit small storm events to weep through, while larger storms overflow the basket. Basket type inserts are useful for filtering trash, debris, and large sediment, but require consistent maintenance. (PADEP,

2006) Inlets may also be designed such that space is created below the invert of the outlet pipe(s) for sediment and debris to deposit. Generally, this space will be 6 to 12 inches deep. When an inlet is equipped with a sediment deposition sump, small weep holes are drilled into the bottom of the inlet to prevent standing water for long periods of time. In areas with carbonate geology, weep holes in inlets are not permitted and may preclude the use of an inlet sump altogether. Inlets equipped with a sump require intense maintenance and sediment removal.

Much like hydrodynamic separators, sediment loading is a primary concern when catch basin media inserts are employed. In addition to potentially clogging or otherwise affecting the insert's pollutant removal performance, the re-suspension of particles and sediment is of concern. To avoid such re-suspension, the drainage area to each water quality inlet or catch basin should be restricted to no more than one acre of impervious cover. Regular maintenance and removal of accumulated debris is essential to ensuring the continued functioning of water quality inlet systems. Studies have shown that water quality inlets storing in excess of 60% of their total sediment capacity may resuspend the stored sediments into the runoff entering the inlet. (PADEP, 2006) The manufacturer's guidelines for maintenance must be strictly followed for any proprietary system. The expected pollutant type and loading rate for the specific site of interest must also be considered.

Appendix C. Other BMPs Included in the VT BMP DSS

Fundamental to the Analytic Hierarchy Process (AHP) decision support algorithm is the construction of pairwise comparison matrices. Within the context of this application of the AHP, these pairwise comparison matrices serve to compare and rank the various BMP alternatives in terms of each selection criteria. Appendix D of this report describes in detail the construction of these BMP comparison matrices. The following is a description of the non-structural, low impact development BMPs available in the VT BMP DSS, including the performance characteristics and implementation guidelines used in constructing the pairwise comparison matrices described in Appendix D.

Vegetated Roofs

A vegetated roof cover is a veneer of vegetation that is grown on and completely covers an otherwise conventional roof, thus more closely matching native surface vegetation than that of the impervious roof. (PADEP, 2006) The vegetated roof veneer may range between two and six inches in thickness, and may be comprised of multiple layers including waterproofing membranes, synthetic insulation, engineered and non-engineered soil media. With proper installation and selection of materials, even thin vegetated covers are capable of providing significant rainfall retention, runoff reduction, and water quality improvement. (PADEP, 2006) In the United States, vegetated roofs are applied in residential, commercial, ultra urban, and industrial settings, as well as in retrofit applications.

Various types of vegetated roof systems exist. Broadly categorized, vegetated roof systems that exceed 10 inches in depth are termed intensive roof covers while shallower roof assemblies are termed extensive designs. Intensive assemblies are intended primarily to achieve aesthetic and architectural objectives, with only secondary consideration of stormwater management function. Extensive roof covers, by contrast, are usually 6 inches or less in depth and have a well-defined stormwater management objective as their primary function. Extensive BMP roof systems are further classified as single media, dual media, or dual media with a synthetic detention layer.

Single media assemblies are most often used in pitched roof applications, and when a thin and lightweight application is desired, such as a residential setting. The plant species are selected from very drought-tolerant species, and the engineered media is of very high permeability. The profile of a single media vegetated roof assembly typically consists of a waterproofing membrane, root barrier, synthetic geotextile drain mat, engineered growth media, and a foliage layer. Single media vegetated roof assemblies installed on pitched roofs often require the use of slope bars, rigid slope stabilization panels, cribbing, reinforcing mesh, or other provisions to prevent sliding and instability. These assemblies, when used on flat roofs, typically require a network of perforated internal drainage conduits to effectively convey percolated rainfall to deck drains and scuppers.

In contrast to single media assemblies, dual media vegetated roof assemblies utilize two types of non-soil drainage media. Fine-grained media with some organic content is placed over a basal layer of coarse lightweight mineral aggregate. Dual media assemblies do not include a geocomposite drain. The objective of a dual media assembly is to improve the drought resistance of the system by attempting to replicate a natural growth environment in which sandy topsoil overlies gravelly subsoil. These assemblies are typically 4 to 6 inches thick and are comprised of a waterproofing membrane, root barrier, coarse-grained drainage media, separation geotextile, fine-grained growth media layer, and a foliage layer. Dual media assemblies are less versatile than their single media counterparts, and their implementation is restricted to roof pitches of 1.5:12 or less. Large dual media assemblies must incorporate a network of perforated internal drainage piping to convey percolated rainfall.

Dual media assemblies equipped with a synthetic detention layer employ plastic panels (geocomposite drain sheets) with cup-like receptacles on their upper surfaces. These sheets are then filled with coarse lightweight mineral aggregate. The cups trap and retain precipitation thus reducing the observed runoff rate and volume from the roof. The profile of a dual media system implementing a synthetic holding layer consists of a waterproofing membrane, felt baric, retention / detention layer, coarse-grained drainage media, separation geotextile, fine-grained growth media, and a foliage layer. The complexity of the dual media synthetic assembly typically results in a total BMP depth of five inches or greater. These assemblies are only feasible on roof pitches less than or equal to 1:12.

When vegetated roof assemblies are implemented on rooftops with pitches steeper than 2V:12H, structural measures must be included to ensure against sliding. Additionally, the structural design of the building for which a vegetated roof practice is planned must be evaluated for compatibility with the anticipated maximum dead and live loads. Typical dead loads for wet vegetated covers range from 8 to 36 pounds per square foot. Live loading values can vary considerably and are a function of rainfall retention. Due to this variability, actual design weights must be established using laboratory procedures. Internal building drainage, including provisions to cover and protect deck drains or scuppers (small openings to permit the drainage of water from a floor or rooftop), must anticipate the need to manage large rainfall events without inundating the cover. In all application scenarios, the roof system must be equipped with a premium waterproofing system. When the waterproofing membrane used is not root-fast, a supplemental root-barrier must be installed.

The vegetation selected for a rooftop assembly must create a vigorous, drought-tolerant cover and be suited for the climate in which it is installed. Vegetated roof installations intended to serve as water quality BMPs must not be fertilized. Furthermore, non-irrigated assemblies are strongly preferred, even though they preclude the use of certain, otherwise acceptable, plant species. Strict guidelines also govern selection of the various drainage media used in a vegetated roof assembly. The engineered media employed should have a maximum moisture capacity of between 30 and 40 percent, and must contain no clay particles. Additionally, the engineered media should exhibit no more than 15% organic matter.

Adequate drainage is essential to the proper functioning of a vegetated roof. Failure of the roof drainage system can lead to loss of vegetation as well as penetration of water into surrounding structures. (Osmundson, 1999) Adequate drainage is a product of two key elements – the drainage medium and the drainage piping. The drainage medium must consist of rot-proof material through which water can percolate and eventually enter the roof drains. In the United States, as early as the 1930's, pebbles and broken rock were being applied in rooftop gardens as a drainage medium. Modern advances in rooftop garden technology now provide synthetic drainage assemblies which provide much greater storage volume at much lower weight than aggregate medium. Drainage media void space and underdrain piping should typically provide sufficient volume such that surface runoff from the roof is only observed when storm events exceed a 2-year return frequency intensity.

Compared to many other structural BMPs, vegetated roof assemblies are relatively low maintenance. During the initial plant establishment period, periodic irrigation and weeding is required. Upon establishment of a healthy foliage layer, only two annual inspections and light weeding operations are typically required. Though discouraged, irrigated assemblies are occasionally used, and do require more intensive maintenance operations.

Many factors influence the construction of a vegetated roof assembly, making cost quantification difficult. Building height, rooftop accessibility, type of assembly, and overall project size greatly impact the costs associated with this type of BMP practice. While implementation costs vary considerably, when compared to other BMP practices, the long-term maintenance cost of a vegetated roof assembly often make it an attractive BMP option.

While various claims for pollutant removal performance of rooftop gardens have been made, it is not clear at this point that there is a sufficient database to support them. What is clear is that the opportunity of this BMP to intercept overland flow with its associated load of suspended sediment and phosphorus does not exist. The only true source of pollutants on the rooftop garden will be atmospheric deposition, assuming there is no fertilizer application, as recommended in virtually all guidance documents. There has been little to no investigation of the removal process in the case of atmospheric deposition.

The following table presents the relative stormwater management function of vegetated roofs.

Table C.1 Relative Stormwater Management Function – Vegetated Roofs
Source: Pennsylvania Stormwater Best Management Practices Manual, (PA DEP, 2006)

Volume Reduction	Medium / High
Groundwater Recharge	None
Peak Rate Control	Low
Water Quality Improvement	Medium

Rainwater Harvesting
Rainwater harvesting measures include a number of devices intended to intercept precipitation, store it for a period of time, and provide a means for reuse of the water. These capture devices include cisterns, rain barrels, and vertical storage or "fat downspouts." The capture and reuse approach to stormwater management can be applied in residential, commercial, urban, industrial, and retrofit applications. Use of rainwater harvesting systems is typically not found in highway settings. In addition to reducing stormwater runoff, the intercepted water is ideal for fire protection and irrigation. In urban areas employing combined sewer systems, the runoff volume reduction arising from the use of precipitation capture systems are of tremendous benefit in reducing the frequency of surcharge events. The use of stored rainwater in potable applications is not advised in the absence of treatment. However, a number of non-potable needs may be addressed by a capture and reuse approach. These include:

- Irrigation of landscaped areas and gardens
- Storage for fire protection needs
- "Greywater" needs such as flushing toilets
- Athletic field irrigation

Cisterns are containers designed to hold large volumes of water (by definition, cistern volumes are typically 500 gallons or more). Cisterns may be located underground or on the surface, and are available in a variety of sizes and materials, including fiberglass, concrete, plastic, and brick. Rain Barrels are containers designed exclusively to capture runoff from roof leaders and downspouts. Rain barrels vary in volume, and are sized based on the roof area from which they are receiving runoff or as a minimum volume computed by a water budget design approach. Vertical Storage units or "fat downspouts" function in the same manner as cisterns and rain barrels, but are typically much larger and usually rest against the building from which they are intercepting runoff. Often, the water stored in these vertical storage units is used to provide fire protection. When employ

The first step when considering implementation of a rainwater harvesting system is to determine the water demand for the proposed reuse application. The demand is critical in determining the feasibility and size of the harvesting system. The volume of water harvested and stored, at a minimum, must equal the computed demand. Additionally, the capture and storage system must provide drawdown between storm events such that the required stormwater storage volume is available. The location of the rain harvesting device has a significant impact on evaporation losses from the device. Rainfall storage units should be protected from direct sunlight by positioning and landscaping. Often the system must be disconnected during winter months to avoid freezing and subsequent damage to the storage container.

The employment of capture and reuse systems exhibits a positive impact on the volume, peak rate, and quality of stormwater runoff from a site. The volume reduction is simply the volume of runoff from a single storm event that is captured and stored by the harvesting system. If the cistern or barrel is empty at the start of the precipitation event, the maximum volume reduction is the actual volume of the capture device. Because rainwater harvesting devices take a volume of water out of the total runoff from a site, the reduced volume may result in a reduced rate of runoff from the site. The removal of pollutants from stormwater entering a capture device takes place through filtration of the recycled primary storage, and natural filtration through soil and vegetation of any overflow discharge. A number of factors influence the pollutant removal performance of a rainwater harvesting system. These include the volume below the outlet of the system dedicated to sediment accumulation, the hydraulic residence time, and the frequency of maintenance.

Appendix D. Construction of BMP Pairwise Comparison Matrices

Fundamental to the AHP decision support algorithm is the construction of pairwise comparison matrices. For theory and methodology regarding the construction of these matrices, the reader is referred to section 4.2 of this report. Within the context of this application of the AHP, pairwise comparison matrices serve to compare and rank the various BMP alternatives in terms of each individual selection criterion. Table D.1 shows the BMP selection criteria available within the VT BMP DSS. This appendix presents the BMP comparison matrices constructed for each of these criteria. Appendices B and C of this report describe the BMP performance characteristics and implementation guidelines used in constructing these pairwise comparison matrices.

Table D.1 Available Selection Criteria in the Virginia Tech BMP Decision Support Software

Contributing Drainage Area (CDA) < 1 ac	CDA Impervious Fraction < 21%
CDA 1-5 ac	CDA Impervious Fraction 21-37%
CDA 5-10 ac	CDA Impervious Fraction 38-66%
CDA 10-25 ac	CDA Impervious Fraction > 66%
CDA > 25 ac	Presence of Hotspot Runoff
Presence of Shallow Groundwater	Peak Runoff Rate Attenuation Ability
Presence of Shallow Bedrock	Aesthetic Benefit/Liability
Presence of Hydrologic Soil Group A	Public Safety
Presence of Hydrologic Soil Group D	Site Slopes/Topography
Ability to Recharge Groundwater	Total Suspended Sediment Removal
Implementation Cost	Total Phosphorus Removal
Annual Maintenance Costs	Total Nitrogen Removal

Contributing Drainage Area

The first physical site constraint available as a BMP selection criterion is that of contributing drainage area (CDA). The installation of most BMPs is influenced greatly by the total area contributing runoff to the practice. For example, small, source control practices such as bioretention cells are generally not recommended for the treatment of runoff from areas greater than one acre. By contrast, practices such as retention ponds and constructed wetlands require much larger drainage areas capable of providing baseflow to maintain their permanent pools. Regardless, it is essential that the BMP chosen for a particular application is adequately suited to receive the runoff from its CDA. Table D.2 illustrates the contributing drainage area, in acres, generally recommended for each available BMP in the VT BMP DSS. This information is compiled and interpreted from various sources, and serves only as a broad recommendation.

Table 6.2 Recommended Contributing Drainage Area (Acres) By BMP

BMP	Recommended Contributing Drainage Area (acres)
Dry Extended Detention Basins	>10
Extended Detention Basins - Enhanced	10 Minimum*
Retention Basins	10 Minimum*
Infiltration Trenches	<10
Infiltration Basins	>10
Porous Pavement	<10
Vegetated Filter Strip	<1
Vegetated Water Quality Swale	<10
Sand Filters	<5
Bioretention	<1
Constructed Wetlands	10 Minimum*
Manufactured BMPs	Function of flow rate; generally suited to smaller areas
Vegetated Roofs	N/A
Rainwater Harvesting Systems	N/A

*In order to ensure adequate baseflow to support the permanent pool volume, a contributing drainage area of greater than 25 acres is often required.

As shown in Table D.1, during a BMP selection scenario the VT BMP DSS allows its user to specify CDA from one of five ranges. This enables the user to apply a BMP comparison template which reflects site-specific characteristics. Based on the information shown in Table D.2, and employing the scale of relative importances described in Chapter 4 of this report, these BMP comparison templates are presented on the following pages.

Table D.3 BMP Pairwise Comparison Matrix – CDA Less Than One Acre

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	2.00	3.00	2.00	0.17	0.14	0.17	1.00	0.14	0.14	0.14	0.14	0.14	0.14
Enhanced ED Basin (B)	0.50	***1.00***	2.00	1.00	0.14	0.13	0.14	0.50	0.13	0.13	0.13	0.13	0.13	0.13
Retention Basin (C)	0.33	0.50	***1.00***	0.50	0.13	0.11	0.13	0.33	0.11	0.11	0.11	0.11	0.11	0.11
Constructed Wetlands (D)	0.50	1.00	2.00	***1.00***	0.14	0.13	0.14	0.50	0.13	0.13	0.13	0.13	0.13	0.13
Vegetated WQ Swale (E)	6.00	7.00	8.00	7.00	***1.00***	0.50	1.00	6.00	0.50	0.50	0.50	0.50	0.50	0.50
Vegetated Filter Strip (F)	7.00	8.00	9.00	8.00	2.00	***1.00***	2.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00
Infiltration Trench (G)	6.00	7.00	8.00	7.00	1.00	0.50	***1.00***	6.00	0.50	0.50	0.50	0.50	0.50	0.50
Infiltration Basin (H)	1.00	2.00	3.00	2.00	0.17	0.14	0.17	***1.00***	0.14	0.14	0.14	0.14	0.14	0.14
Porous Pavement (I)	7.00	8.00	9.00	8.00	2.00	1.00	2.00	7.00	***1.00***	1.00	1.00	1.00	1.00	1.00
Bioretention (J)	7.00	8.00	9.00	8.00	2.00	1.00	2.00	7.00	1.00	***1.00***	1.00	1.00	1.00	1.00
Sand Filters (K)	7.00	8.00	9.00	8.00	2.00	1.00	2.00	7.00	1.00	1.00	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	7.00	8.00	9.00	8.00	2.00	1.00	2.00	7.00	1.00	1.00	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	7.00	8.00	9.00	8.00	2.00	1.00	2.00	7.00	1.00	1.00	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	7.00	8.00	9.00	8.00	2.00	1.00	2.00	7.00	1.00	1.00	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Vegetated Filter Strip	0.1125
Porous Pavement	0.1125
Bioretention	0.1125
Sand Filters	0.1125
Vegetated Roof	0.1125
Rainwater Harvesting	0.1125
Manufactured BMPs	0.1125
Vegetated WQ Swale	0.0702
Infiltration Trench	0.0702
Dry ED Basin	0.0180
Infiltration Basin	0.0180
Enhanced ED Basin	0.0130
Constructed Wetlands	0.0130
Retention Basin	0.0100

Consistency Ratio = 0.01

Table D.4 BMP Pairwise Comparison Matrix – CDA Between One and Five Acres

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	2.00	3.00	2.00	0.17	0.14	0.17	1.00	0.14	6.00	0.14	6.00	6.00	0.14
Enhanced ED Basin (B)	0.50	***1.00***	2.00	1.00	0.14	0.13	0.14	0.50	0.13	6.00	0.13	6.00	6.00	0.13
Retention Basin (C)	0.33	0.50	***1.00***	0.50	0.13	0.11	0.13	0.33	0.11	6.00	0.11	6.00	6.00	0.11
Constructed Wetlands (D)	0.50	1.00	2.00	***1.00***	0.14	0.13	0.14	0.50	0.13	6.00	0.13	6.00	6.00	0.13
Vegetated WQ Swale (E)	6.00	7.00	8.00	7.00	***1.00***	0.50	1.00	6.00	0.50	9.00	0.50	9.00	9.00	0.50
Vegetated Filter Strip (F)	7.00	8.00	9.00	8.00	2.00	***1.00***	2.00	7.00	1.00	9.00	1.00	9.00	9.00	1.00
Infiltration Trench (G)	6.00	7.00	8.00	7.00	1.00	0.50	***1.00***	6.00	0.50	9.00	0.50	9.00	9.00	0.50
Infiltration Basin (H)	1.00	2.00	3.00	2.00	0.17	0.14	0.17	***1.00***	0.14	6.00	0.14	6.00	6.00	0.14
Porous Pavement (I)	7.00	8.00	9.00	8.00	2.00	1.00	2.00	7.00	***1.00***	9.00	1.00	9.00	9.00	1.00
Bioretention (J)	0.17	0.17	0.17	0.17	0.11	0.11	0.11	0.17	0.11	***1.00***	0.11	1.00	1.00	0.11
Sand Filters (K)	7.00	8.00	9.00	8.00	2.00	1.00	2.00	7.00	1.00	9.00	***1.00***	9.00	9.00	1.00
Vegetated Roof (L)	0.17	0.17	0.17	0.17	0.11	0.11	0.11	0.17	0.11	1.00	0.11	***1.00***	1.00	0.11
Rainwater Harvesting (M)	0.17	0.17	0.17	0.17	0.11	0.11	0.11	0.17	0.11	1.00	0.11	1.00	***1.00***	0.11
Manufactured BMPs (N)	7.00	8.00	9.00	8.00	2.00	1.00	2.00	7.00	1.00	9.00	1.00	9.00	9.00	***1.00***

BMP	Matrix Priority Vector
Vegetated Filter Strip	0.1502
Porous Pavement	0.1502
Sand Filters	0.1502
Manufactured BMPs	0.1502
Vegetated WQ Swale	0.1064
Infiltration Trench	0.1064
Dry ED Basin	0.0358
Infiltration Basin	0.0358
Enhanced ED Basin	0.0292
Constructed Wetlands	0.0292
Retention Basin	0.0253
Bioretention	0.0104
Vegetated Roof	0.0104
Rainwater Harvesting	0.0104

Consistency Ratio = 0.08

Table D.5 BMP Pairwise Comparison Matrix – CDA Between Five and 10 Acres

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	2.00	3.00	2.00	5.00	5.00	5.00	1.00	0.14	6.00	5.00	6.00	6.00	0.14
Enhanced ED Basin (B)	0.50	***1.00***	2.00	1.00	5.00	5.00	5.00	0.50	0.13	6.00	5.00	6.00	6.00	0.13
Retention Basin (C)	0.33	0.50	***1.00***	0.50	5.00	5.00	5.00	0.33	0.11	6.00	5.00	6.00	6.00	0.11
Constructed Wetlands (D)	0.50	1.00	2.00	***1.00***	5.00	5.00	5.00	0.50	0.13	6.00	5.00	6.00	6.00	0.13
Vegetated WQ Swale (E)	0.20	0.20	0.20	0.20	***1.00***	1.00	1.00	0.20	0.13	2.00	1.00	2.00	2.00	0.13
Vegetated Filter Strip (F)	0.20	0.20	0.20	0.20	1.00	***1.00***	1.00	0.20	0.13	2.00	1.00	2.00	2.00	0.13
Infiltration Trench (G)	0.20	0.20	0.20	0.20	1.00	1.00	***1.00***	0.20	0.13	2.00	1.00	2.00	2.00	0.13
Infiltration Basin (H)	1.00	2.00	3.00	2.00	5.00	5.00	5.00	***1.00***	0.14	6.00	5.00	6.00	6.00	0.14
Porous Pavement (I)	7.00	8.00	9.00	8.00	8.00	8.00	8.00	7.00	***1.00***	9.00	8.00	9.00	9.00	1.00
Bioretention (J)	0.17	0.17	0.17	0.17	0.50	0.50	0.50	0.17	0.11	***1.00***	0.50	1.00	1.00	0.11
Sand Filters (K)	0.20	0.20	0.20	0.20	1.00	1.00	1.00	0.20	0.13	2.00	***1.00***	2.00	2.00	0.13
Vegetated Roof (L)	0.17	0.17	0.17	0.17	0.50	0.50	0.50	0.17	0.11	1.00	0.50	***1.00***	1.00	0.11
Rainwater Harvesting (M)	0.17	0.17	0.17	0.17	0.50	0.50	0.50	0.17	0.11	1.00	0.50	1.00	***1.00***	0.11
Manufactured BMPs (N)	7.00	8.00	9.00	8.00	8.00	8.00	8.00	7.00	1.00	9.00	8.00	9.00	9.00	***1.00***

BMP	Matrix Priority Vector
Porous Pavement	0.2458
Manufactured BMPs	0.2458
Dry ED Basin	0.0851
Infiltration Basin	0.0851
Enhanced ED Basin	0.0722
Constructed Wetlands	0.0722
Retention Basin	0.0650
Vegetated WQ Swale	0.0217
Vegetated Filter Strip	0.0217
Infiltration Trench	0.0217
Sand Filters	0.0217
Bioretention	0.0139
Vegetated Roof	0.0139
Rainwater Harvesting	0.0139

Consistency Ratio = 0.07

Table D.6 BMP Pairwise Comparison Matrix – CDA Between 10 and 25 Acres

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	2.00	3.00	2.00	7.00	7.00	7.00	1.00	7.00	9.00	7.00	9.00	9.00	7.00
Enhanced ED Basin (B)	0.50	***1.00***	2.00	1.00	6.00	6.00	6.00	0.50	6.00	8.00	6.00	8.00	8.00	6.00
Retention Basin (C)	0.33	0.50	***1.00***	0.50	5.00	5.00	5.00	0.33	5.00	7.00	5.00	7.00	7.00	5.00
Constructed Wetlands (D)	0.50	1.00	2.00	***1.00***	6.00	6.00	6.00	0.50	6.00	8.00	6.00	8.00	8.00	6.00
Vegetated WQ Swale (E)	0.14	0.17	0.20	0.17	***1.00***	1.00	1.00	0.14	0.50	2.00	1.00	2.00	2.00	0.50
Vegetated Filter Strip (F)	0.14	0.17	0.20	0.17	1.00	***1.00***	1.00	0.14	0.50	2.00	1.00	2.00	2.00	0.50
Infiltration Trench (G)	0.14	0.17	0.20	0.17	1.00	1.00	***1.00***	0.14	0.50	2.00	1.00	2.00	2.00	0.50
Infiltration Basin (H)	1.00	2.00	3.00	2.00	7.00	7.00	7.00	***1.00***	7.00	9.00	7.00	9.00	9.00	7.00
Porous Pavement (I)	0.14	0.17	0.20	0.17	2.00	2.00	2.00	0.14	***1.00***	3.00	2.00	3.00	3.00	1.00
Bioretention (J)	0.11	0.13	0.14	0.13	0.50	0.50	0.50	0.11	0.33	***1.00***	0.50	1.00	1.00	0.33
Sand Filters (K)	0.14	0.17	0.20	0.17	1.00	1.00	1.00	0.14	0.50	2.00	***1.00***	2.00	2.00	0.50
Vegetated Roof (L)	0.11	0.13	0.14	0.13	0.50	0.50	0.50	0.11	0.33	1.00	0.50	***1.00***	1.00	0.33
Rainwater Harvesting (M)	0.11	0.13	0.14	0.13	0.50	0.50	0.50	0.11	0.33	1.00	0.50	1.00	***1.00***	0.33
Manufactured BMPs (N)	0.14	0.17	0.20	0.17	2.00	2.00	2.00	0.14	1.00	3.00	2.00	3.00	3.00	***1.00***

BMP	Matrix Priority Vector
Dry ED Basin	0.1952
Infiltration Basin	0.1952
Enhanced ED Basin	0.1409
Constructed Wetlands	0.1409
Retention Basin	0.1062
Porous Pavement	0.0378
Manufactured BMPs	0.0378
Vegetated WQ Swale	0.0251
Vegetated Filter Strip	0.0251
Infiltration Trench	0.0251
Sand Filters	0.0251
Bioretention	0.0151
Vegetated Roof	0.0151
Rainwater Harvesting	0.0151

Consistency Ratio = 0.02

Table D.7 BMP Pairwise Comparison Matrix – CDA Greater than 25 Acres

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	0.50	0.33	0.50	6.00	6.00	6.00	2.00	4.00	7.00	6.00	7.00	7.00	4.00
Enhanced ED Basin (B)	2.00	***1.00***	0.50	1.00	7.00	7.00	7.00	3.00	5.00	8.00	7.00	8.00	8.00	5.00
Retention Basin (C)	3.00	2.00	***1.00***	2.00	8.00	8.00	8.00	4.00	6.00	9.00	8.00	9.00	9.00	6.00
Constructed Wetlands (D)	2.00	1.00	0.50	***1.00***	7.00	7.00	7.00	3.00	5.00	8.00	7.00	8.00	8.00	5.00
Vegetated WQ Swale (E)	0.17	0.14	0.13	0.14	***1.00***	1.00	1.00	0.20	0.33	2.00	1.00	2.00	2.00	0.33
Vegetated Filter Strip (F)	0.17	0.14	0.13	0.14	1.00	***1.00***	1.00	0.20	0.33	2.00	1.00	2.00	2.00	0.33
Infiltration Trench (G)	0.17	0.14	0.13	0.14	1.00	1.00	***1.00***	0.20	0.33	2.00	1.00	2.00	2.00	0.33
Infiltration Basin (H)	0.50	0.33	0.25	0.33	5.00	5.00	5.00	***1.00***	5.00	7.00	6.00	7.00	7.00	5.00
Porous Pavement (I)	0.25	0.20	0.17	0.20	3.00	3.00	3.00	0.20	***1.00***	4.00	3.00	4.00	4.00	1.00
Bioretention (J)	0.14	0.13	0.11	0.13	0.50	0.50	0.50	0.14	0.25	***1.00***	0.50	1.00	1.00	0.33
Sand Filters (K)	0.17	0.14	0.13	0.14	1.00	1.00	1.00	0.17	0.33	2.00	***1.00***	2.00	2.00	0.33
Vegetated Roof (L)	0.14	0.13	0.11	0.13	0.50	0.50	0.50	0.14	0.25	1.00	0.50	***1.00***	1.00	0.33
Rainwater Harvesting (M)	0.14	0.13	0.11	0.13	0.50	0.50	0.50	0.14	0.25	1.00	0.50	1.00	***1.00***	0.33
Manufactured BMPs (N)	0.25	0.20	0.17	0.20	3.00	3.00	3.00	0.20	1.00	3.00	3.00	3.00	3.00	***1.00***

BMP	Matrix Priority Vector
Retention Basin	0.2203
Enhanced ED Basin	0.1607
Constructed Wetlands	0.1607
Dry ED Basin	0.1190
Infiltration Basin	0.1052
Porous Pavement	0.0496
Manufactured BMPs	0.0459
Vegetated WQ Swale	0.0234
Vegetated Filter Strip	0.0234
Infiltration Trench	0.0234
Sand Filters	0.0232
Bioretention	0.0151
Vegetated Roof	0.0151
Rainwater Harvesting	0.0151

Consistency Ratio = 0.02

Presence of Shallow Groundwater
The presence of shallow or seasonally shallow groundwater depths (typically defined as less than two feet below a site's finished grade) generally precludes the use of all infiltration practices. Practices which infiltrate little or no runoff into the subsurface are favored as treatment options in the presence of a shallow groundwater table. These practices include vegetated filter strips, manufactured BMP systems, and rainwater harvesting systems. Enhanced detention basins, retention ponds, and constructed wetlands may be designed to utilize the presence of shallow groundwater as a source of baseflow, and thus such a site characteristic may be considered beneficial to their implementation.

Table D.8 shows the BMP pairwise comparison matrix reflecting the presence of shallow groundwater depths.

Table D.8 BMP Pairwise Comparison Matrix – Presence of Shallow Groundwater Depths

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	0.20	0.20	0.20	5.00	0.20	5.00	5.00	5.00	1.00	1.00	0.20	0.20	0.20
Enhanced ED Basin (B)	5.00	***1.00***	1.00	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Retention Basin (C)	5.00	1.00	***1.00***	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Constructed Wetlands (D)	5.00	1.00	1.00	***1.00***	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Vegetated WQ Swale (E)	0.20	0.11	0.11	0.11	***1.00***	0.11	1.00	1.00	1.00	0.20	0.20	0.11	0.11	0.11
Vegetated Filter Strip (F)	5.00	1.00	1.00	1.00	9.00	***1.00***	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Infiltration Trench (G)	0.20	0.11	0.11	0.11	1.00	0.11	***1.00***	1.00	1.00	0.20	0.20	0.11	0.11	0.11
Infiltration Basin (H)	0.20	0.11	0.11	0.11	1.00	0.11	1.00	***1.00***	1.00	0.20	0.20	0.11	0.11	0.11
Porous Pavement (I)	0.20	0.11	0.11	0.11	1.00	0.11	1.00	1.00	***1.00***	0.20	0.20	0.11	0.11	0.11
Bioretention (J)	1.00	0.20	0.20	0.20	5.00	0.20	5.00	5.00	5.00	***1.00***	1.00	0.20	0.20	0.20
Sand Filters (K)	1.00	0.20	0.20	0.20	5.00	0.20	5.00	5.00	5.00	1.00	***1.00***	0.20	0.20	0.20
Vegetated Roof (L)	5.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	5.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	5.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Enhanced ED Basin	0.1211
Retention Basin	0.1211
Constructed Wetlands	0.1211
Vegetated Filter Strip	0.1211
Vegetated Roof	0.1211
Rainwater Harvesting	0.1211
Manufactured BMPs	0.1211
Dry ED Basin	0.0354
Bioretention	0.0354
Sand Filters	0.0354
Vegetated WQ Swale	0.0115
Infiltration Trench	0.0115
Infiltration Basin	0.0115
Porous Pavement	0.0115

Consistency Ratio = 0.02

Presence of Shallow Bedrock
Much like the presence of a shallow groundwater table, the presence of shallow bedrock depths on a site greatly restricts the BMP options at the designer's disposal. Infiltration practices and other BMPs which operate by employing subsurface filter beds are generally prohibited. As in the case of shallow groundwater depths, practices which infiltrate little or no runoff into the subsurface are favored as treatment options. However, unlike the presence of a shallow groundwater table, the presence of shallow bedrock depths provides no benefit for the implementation of retention ponds and constructed wetlands, and in fact may preclude their installation without a liner to minimize infiltration.

Table D.9 shows the BMP pairwise comparison matrix reflecting the presence of shallow bedrock depths.

Table D.9 BMP Pairwise Comparison Matrix – Presence of Shallow Bedrock Depths

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	0.20	0.20	0.20	5.00	0.20	5.00	5.00	5.00	1.00	1.00	0.20	0.20	0.20
Enhanced ED Basin (B)	5.00	***1.00***	1.00	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Retention Basin (C)	5.00	1.00	***1.00***	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Constructed Wetlands (D)	5.00	1.00	1.00	***1.00***	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Vegetated WQ Swale (E)	0.20	0.11	0.11	0.11	***1.00***	0.11	1.00	1.00	1.00	0.20	0.20	0.11	0.11	0.11
Vegetated Filter Strip (F)	5.00	1.00	1.00	1.00	9.00	***1.00***	9.00	9.00	9.00	5.00	5.00	1.00	1.00	1.00
Infiltration Trench (G)	0.20	0.11	0.11	0.11	1.00	0.11	***1.00***	1.00	1.00	0.20	0.20	0.11	0.11	0.11
Infiltration Basin (H)	0.20	0.11	0.11	0.11	1.00	0.11	1.00	***1.00***	1.00	0.20	0.20	0.11	0.11	0.11
Porous Pavement (I)	0.20	0.11	0.11	0.11	1.00	0.11	1.00	1.00	***1.00***	0.20	0.20	0.11	0.11	0.11
Bioretention (J)	1.00	0.20	0.20	0.20	5.00	0.20	5.00	5.00	5.00	***1.00***	1.00	0.20	0.20	0.20
Sand Filters (K)	1.00	0.20	0.20	0.20	5.00	0.20	5.00	5.00	5.00	1.00	***1.00***	0.20	0.20	0.20
Vegetated Roof (L)	5.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	5.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	5.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	5.00	5.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Vegetated Filter Strip	0.1665
Vegetated Roof	0.1665
Rainwater Harvesting	0.1665
Manufactured BMPs	0.1665
Dry ED Basin	0.0426
Enhanced ED Basin	0.0426
Retention Basin	0.0426
Constructed Wetlands	0.0426
Vegetated WQ Swale	0.0426
Bioretention	0.0426
Sand Filters	0.0426
Infiltration Trench	0.0121
Infiltration Basin	0.0121
Porous Pavement	0.0121

Consistency Ratio = 0.02

Presence of Hydrologic Soil Group A

Hydrologic soil group (HSG) A consists of sand, loamy sand, or sandy loam types of soils. These soils exhibit low runoff potential and high infiltration rates even when thoroughly wetted. The presence of HSG A on a site restricts the BMP options from which a designer can choose. Generally, this soil group exhibits infiltration rates beyond what is recommended for infiltration practices. Similarly, these excessively high infiltration rates may present difficulties in achieving acceptable hydraulic residence times in detention facilities, vegetated swales and filters, and wetlands. In the absence of synthetic liners, the presence of HSG A generally precludes the use of these practices.

Table D.10 shows the BMP pairwise comparison matrix reflecting the presence of HSG A.

Table D.10 BMP Pairwise Comparison Matrix – Presence of HSG A

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	1.00	1.00	1.00	1.00	5.00	5.00	5.00	0.20	0.20	0.20	0.20	0.20
Enhanced ED Basin (B)	1.00	***1.00***	1.00	1.00	1.00	1.00	5.00	5.00	5.00	0.20	0.20	0.20	0.20	0.20
Retention Basin (C)	1.00	1.00	***1.00***	1.00	1.00	1.00	5.00	5.00	5.00	0.20	0.20	0.20	0.20	0.20
Constructed Wetlands (D)	1.00	1.00	1.00	***1.00***	1.00	1.00	5.00	5.00	5.00	0.20	0.20	0.20	0.20	0.20
Vegetated WQ Swale (E)	1.00	1.00	1.00	1.00	***1.00***	1.00	5.00	5.00	5.00	0.20	0.20	0.20	0.20	0.20
Vegetated Filter Strip (F)	1.00	1.00	1.00	1.00	1.00	***1.00***	5.00	5.00	5.00	0.20	0.20	0.20	0.20	0.20
Infiltration Trench (G)	0.20	0.20	0.20	0.20	0.20	0.20	***1.00***	1.00	1.00	0.11	0.11	0.11	0.11	0.11
Infiltration Basin (H)	0.20	0.20	0.20	0.20	0.20	0.20	1.00	***1.00***	1.00	0.11	0.11	0.11	0.11	0.11
Porous Pavement (I)	0.20	0.20	0.20	0.20	0.20	0.20	1.00	1.00	***1.00***	0.11	0.11	0.11	0.11	0.11
Bioretention (J)	5.00	5.00	5.00	5.00	5.00	5.00	9.00	9.00	9.00	***1.00***	1.00	1.00	1.00	1.00
Sand Filters (K)	5.00	5.00	5.00	5.00	5.00	5.00	9.00	9.00	9.00	1.00	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	5.00	5.00	5.00	5.00	5.00	5.00	9.00	9.00	9.00	1.00	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	5.00	5.00	5.00	5.00	5.00	5.00	9.00	9.00	9.00	1.00	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	5.00	5.00	5.00	5.00	5.00	5.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Bioretention	0.1472
Sand Filters	0.1472
Vegetated Roof	0.1472
Rainwater Harvesting	0.1472
Manufactured BMPs	0.1472
Dry ED Basin	0.0382
Enhanced ED Basin	0.0382
Retention Basin	0.0382
Constructed Wetlands	0.0382
Vegetated WQ Swale	0.0382
Vegetated Filter Strip	0.0382
Infiltration Trench	0.0115
Infiltration Basin	0.0115
Porous Pavement	0.0115

Consistency Ratio = 0.02

Presence of Hydrologic Soil Group D
HSG D consists primarily of clay loam, silty clay loam, sandy clay, silty clay, or clay. This HSG has the highest runoff potential among all soil groups. Characteristics of HSG D are high swelling potential and very low infiltration rates when thoroughly wetted. In terms of surface runoff potential, HSG D behaves analogously to an impervious surface. Typically, soils classified as HSG D do not exhibit the minimum infiltration rates required of infiltration practices. Consequently, the implementation of infiltration practices, and those practices exhibiting similar physical processes, is restricted in the presence of these soil groups. While this criterion impacts the selection of infiltration practices in much the same manner as the shallow groundwater or shallow bedrock criteria, it impacts the selection of basin practices in a considerably different manner. The presence of HSG D is considered beneficial to the implementation of basin practices because it significantly reduces the undesired exfiltration loss of detained runoff.

Table D.11 shows the BMP pairwise comparison matrix reflecting the presence of HSG D.

Table D.11 BMP Pairwise Comparison Matrix – Presence of HSG D

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	1.00	1.00	5.00	1.00	9.00	9.00	9.00	3.00	1.00	1.00	1.00	1.00
Enhanced ED Basin (B)	1.00	***1.00***	1.00	1.00	5.00	1.00	9.00	9.00	9.00	3.00	1.00	1.00	1.00	1.00
Retention Basin (C)	1.00	1.00	***1.00***	1.00	5.00	1.00	9.00	9.00	9.00	3.00	1.00	1.00	1.00	1.00
Constructed Wetlands (D)	1.00	1.00	1.00	***1.00***	5.00	1.00	9.00	9.00	9.00	3.00	1.00	1.00	1.00	1.00
Vegetated WQ Swale (E)	0.20	0.20	0.20	0.20	***1.00***	0.20	5.00	5.00	5.00	0.33	0.20	0.20	0.20	0.20
Vegetated Filter Strip (F)	1.00	1.00	1.00	1.00	5.00	***1.00***	9.00	9.00	9.00	3.00	1.00	1.00	1.00	1.00
Infiltration Trench (G)	0.11	0.11	0.11	0.11	0.20	0.11	***1.00***	1.00	1.00	0.14	0.11	0.11	0.11	0.11
Infiltration Basin (H)	0.11	0.11	0.11	0.11	0.20	0.11	1.00	***1.00***	1.00	0.14	0.11	0.11	0.11	0.11
Porous Pavement (I)	0.11	0.11	0.11	0.11	0.20	0.11	1.00	1.00	***1.00***	0.14	0.11	0.11	0.11	0.11
Bioretention (J)	0.33	0.33	0.33	0.33	3.00	0.33	7.00	7.00	7.00	***1.00***	0.33	0.33	0.33	0.33
Sand Filters (K)	1.00	1.00	1.00	1.00	5.00	1.00	9.00	9.00	9.00	3.00	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	1.00	1.00	1.00	1.00	5.00	1.00	9.00	9.00	9.00	3.00	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	1.00	1.00	1.00	1.00	5.00	1.00	9.00	9.00	9.00	3.00	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	1.00	1.00	1.00	1.00	5.00	1.00	9.00	9.00	9.00	3.00	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Dry ED Basin	0.0999
Enhanced ED Basin	0.0999
Retention Basin	0.0999
Constructed Wetlands	0.0999
Vegetated Filter Strip	0.0999
Sand Filters	0.0999
Vegetated Roof	0.0999
Rainwater Harvesting	0.0999
Manufactured BMPs	0.0999
Bioretention	0.0441
Vegetated WQ Swale	0.0265
Infiltration Trench	0.0101
Infiltration Basin	0.0101
Porous Pavement	0.0101

Consistency Ratio = 0.02

Ability to Recharge Groundwater

Groundwater recharge is the hydrologic process by which precipitation migrates downward from the land surface, eventually entering the groundwater table. This natural process is critical to the long-term sustainability of groundwater supplies where aquifer extraction rates must not exceed recharge rates. Groundwater recharge is often impeded by land use intensification and the resulting increase in imperviousness. Numerous locations in the United States now require land development projects to provide some minimum level of post-development groundwater recharge through the use of BMPs.

Table D.12 shows the pairwise comparison matrix reflecting the ability of the BMPs to provide groundwater recharge. As shown by this matrix, all BMPs capable of providing groundwater recharge are ranked equally with one another. Similarly, those practices unable to provide groundwater recharge are ranked equally with one another, but lower than practices which can provide groundwater recharge.

Table D.12 BMP Pairwise Comparison Matrix – Ability to Provide Groundwater Recharge

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	0.11	1.00	0.11	0.11	1.00	0.11	0.11	0.11	0.11	1.00	1.00	1.00	1.00
Enhanced ED Basin (B)	9.00	***1.00***	9.00	1.00	1.00	9.00	1.00	1.00	1.00	1.00	9.00	9.00	9.00	9.00
Retention Basin (C)	1.00	0.11	***1.00***	0.11	0.11	1.00	0.11	0.11	0.11	0.11	1.00	1.00	1.00	1.00
Constructed Wetlands (D)	9.00	1.00	9.00	***1.00***	1.00	9.00	1.00	1.00	1.00	1.00	9.00	9.00	9.00	9.00
Vegetated WQ Swale (E)	9.00	1.00	9.00	1.00	***1.00***	9.00	1.00	1.00	1.00	1.00	9.00	9.00	9.00	9.00
Vegetated Filter Strip (F)	1.00	0.11	1.00	0.11	0.11	***1.00***	0.11	0.11	0.11	0.11	1.00	1.00	1.00	1.00
Infiltration Trench (G)	9.00	1.00	9.00	1.00	1.00	9.00	***1.00***	1.00	1.00	1.00	9.00	9.00	9.00	9.00
Infiltration Basin (H)	9.00	1.00	9.00	1.00	1.00	9.00	1.00	***1.00***	1.00	1.00	9.00	9.00	9.00	9.00
Porous Pavement (I)	9.00	1.00	9.00	1.00	1.00	9.00	1.00	1.00	***1.00***	1.00	9.00	9.00	9.00	9.00
Bioretention (J)	9.00	1.00	9.00	1.00	1.00	9.00	1.00	1.00	1.00	***1.00***	9.00	9.00	9.00	9.00
Sand Filters (K)	1.00	0.11	1.00	0.11	0.11	1.00	0.11	0.11	0.11	0.11	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	1.00	0.11	1.00	0.11	0.11	1.00	0.11	0.11	0.11	0.11	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	1.00	0.11	1.00	0.11	0.11	1.00	0.11	0.11	0.11	0.11	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	1.00	0.11	1.00	0.11	0.11	1.00	0.11	0.11	0.11	0.11	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Enhanced ED Basin	0.1286
Constructed Wetlands	0.1286
Vegetated WQ Swale	0.1286
Infiltration Trench	0.1286
Infiltration Basin	0.1286
Porous Pavement	0.1286
Bioretention	0.1286
Dry ED Basin	0.0143
Retention Basin	0.0143
Vegetated Filter Strip	0.0143
Sand Filters	0.0143
Vegetated Roof	0.0143
Rainwater Harvesting	0.0143
Manufactured BMPs	0.0143

Consistency Ratio = 0.00

Implementation and Annual Operations and Maintenance (O&M) Costs

BMP construction and maintenance costs vary considerably on a site-by-site basis. With any number of physical, site-specific parameters influencing the size and design of an individual BMP it becomes impractical, if not impossible to confidently predict material and labor costs associated with a given BMP type. In addition to the aforementioned physical site factors, there are issues such as land acquisition costs, contractor availability, seasonal impacts on construction activities, and non-essential BMP amenities that must be considered when preparing a detailed cost estimate for a proposed BMP installation. All of these factors, as well as many more, vary immensely both geographically and climatically. The VT BMP DSS allows its user to consider both installation and annual maintenance costs during the BMP selection process. However, these are only relative cost comparisons between the competing BMP options and do not reflect detailed construction cost estimates, nor do they address unforeseen, non-routine maintenance activities. The reader is referred to Young, K. D. (2006) for additional details on the development on these relative cost comparisons.

Tables D.13 and D.1 4 are the pairwise comparison matrices depicting the relative comparison of BMPs for both installation and O&M costs respectively.

Table D.13 BMP Pairwise Comparison Matrix – Installation Cost

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	2.00	1.00	2.00	1.00	0.25	5.00	2.00	1.00	5.00	5.00	1.00	0.25	1.00
Enhanced ED Basin (B)	0.50	***1.00***	0.50	1.00	0.50	0.17	3.00	1.00	0.50	3.00	3.00	0.50	0.17	0.50
Retention Basin (C)	1.00	2.00	***1.00***	2.00	1.00	0.25	5.00	2.00	1.00	5.00	5.00	1.00	0.25	1.00
Constructed Wetlands (D)	0.50	1.00	0.50	***1.00***	0.50	0.17	3.00	1.00	0.50	3.00	3.00	0.50	0.17	0.50
Vegetated WQ Swale (E)	1.00	2.00	1.00	2.00	***1.00***	0.25	5.00	2.00	1.00	5.00	5.00	1.00	0.25	1.00
Vegetated Filter Strip (F)	4.00	6.00	4.00	6.00	4.00	***1.00***	9.00	6.00	4.00	9.00	9.00	4.00	1.00	4.00
Infiltration Trench (G)	0.20	0.33	0.20	0.33	0.20	0.11	***1.00***	0.33	0.20	1.00	1.00	0.20	0.11	0.20
Infiltration Basin (H)	0.50	1.00	0.50	1.00	0.50	0.17	3.00	***1.00***	0.50	3.00	3.00	0.50	0.17	0.50
Porous Pavement (I)	1.00	2.00	1.00	2.00	1.00	0.25	5.00	2.00	***1.00***	5.00	5.00	1.00	0.25	1.00
Bioretention (J)	0.20	0.33	0.20	0.33	0.20	0.11	1.00	0.33	0.20	***1.00***	1.00	0.20	0.11	0.20
Sand Filters (K)	0.20	0.33	0.20	0.33	0.20	0.11	1.00	0.33	0.20	1.00	***1.00***	0.20	0.11	0.20
Vegetated Roof (L)	1.00	2.00	1.00	2.00	1.00	0.25	5.00	2.00	1.00	5.00	5.00	***1.00***	0.25	1.00
Rainwater Harvesting (M)	4.00	6.00	4.00	6.00	4.00	1.00	9.00	6.00	4.00	9.00	9.00	4.00	***1.00***	4.00
Manufactured BMPs (N)	1.00	2.00	1.00	2.00	1.00	0.25	5.00	2.00	1.00	5.00	5.00	1.00	0.25	***1.00***

BMP	Matrix Priority Vector
Vegetated Filter Strip	0.2175
Rainwater Harvesting	0.2175
Dry ED Basin	0.0680
Retention Basin	0.0680
Vegetated WQ Swale	0.0680
Porous Pavement	0.0680
Vegetated Roof	0.0680
Manufactured BMPs	0.0680
Enhanced ED Basin	0.0372
Constructed Wetlands	0.0372
Infiltration Basin	0.0372
Infiltration Trench	0.0151
Bioretention	0.0151
Sand Filters	0.0151

Consistency Ratio = 0.01

Table D.14 BMP Pairwise Comparison Matrix – Annual O&M Cost

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	1.00	1.00	1.00	0.25	5.00	1.00	0.25	5.00	0.25	0.25	0.25	1.00
Enhanced ED Basin (B)	1.00	***1.00***	1.00	1.00	1.00	0.25	5.00	1.00	0.25	5.00	0.25	0.25	0.25	1.00
Retention Basin (C)	1.00	1.00	***1.00***	1.00	1.00	0.25	5.00	1.00	0.25	5.00	0.25	0.25	0.25	1.00
Constructed Wetlands (D)	1.00	1.00	1.00	***1.00***	1.00	0.25	5.00	1.00	0.25	5.00	0.25	0.25	0.25	1.00
Vegetated WQ Swale (E)	1.00	1.00	1.00	1.00	***1.00***	0.25	5.00	1.00	0.25	5.00	0.25	0.25	0.25	1.00
Vegetated Filter Strip (F)	4.00	4.00	4.00	4.00	4.00	***1.00***	9.00	4.00	1.00	9.00	1.00	1.00	1.00	4.00
Infiltration Trench (G)	0.20	0.20	0.20	0.20	0.20	0.11	***1.00***	0.20	0.11	1.00	0.11	0.11	0.11	0.20
Infiltration Basin (H)	1.00	1.00	1.00	1.00	1.00	0.25	5.00	***1.00***	0.25	5.00	0.25	0.25	0.25	1.00
Porous Pavement (I)	4.00	4.00	4.00	4.00	4.00	1.00	9.00	4.00	***1.00***	9.00	1.00	1.00	1.00	4.00
Bioretention (J)	0.20	0.20	0.20	0.20	0.20	0.11	1.00	0.20	0.11	***1.00***	0.11	0.11	0.11	0.20
Sand Filters (K)	4.00	4.00	4.00	4.00	4.00	1.00	9.00	4.00	1.00	9.00	***1.00***	1.00	1.00	4.00
Vegetated Roof (L)	4.00	4.00	4.00	4.00	4.00	1.00	9.00	4.00	1.00	9.00	1.00	***1.00***	1.00	4.00
Rainwater Harvesting (M)	4.00	4.00	4.00	4.00	4.00	1.00	9.00	4.00	1.00	9.00	1.00	1.00	***1.00***	4.00
Manufactured BMPs (N)	1.00	1.00	1.00	1.00	1.00	0.25	5.00	1.00	0.25	5.00	0.25	0.25	0.25	***1.00***

BMP	Matrix Priority Vector
Vegetated Filter Strip	0.1399
Porous Pavement	0.1399
Sand Filters	0.1399
Vegetated Roof	0.1399
Rainwater Harvesting	0.1399
Dry ED Basin	0.0398
Enhanced ED Basin	0.0398
Retention Basin	0.0398
Constructed Wetlands	0.0398
Vegetated WQ Swale	0.0398
Infiltration Basin	0.0398
Manufactured BMPs	0.0398
Infiltration Trench	0.0111
Bioretention	0.0111

Consistency Ratio = 0.01

CDA Impervious Fraction

Described in Chapter 2 of the Virginia Stormwater Management Handbook (DCR, 1999), one approach to BMP selection is defined as "technology-based." This approach requires the designer to compute the amount of new impervious area arising from a land development project, and then make the BMP selection on the basis of the overall impervious fraction of the BMP's contributing drainage shed. This approach does not presume a specific pollutant removal target or efficiency and therefore contrasts a "performance-based" BMP selection procedure. Table D.15 is the Virginia technology-based BMP selection table.

Table D.15 Technology-Based BMP Selection Table (DCR, 1999)

Water Quality BMP	Target Phosphorus Removal Efficiency (%)	Percent Impervious Cover Cover (%)
Vegetated Filter Strip Grassed Swale	10 15	16-21
Constructed Wetlands Extended Detention (2xWQV) Retention Basin I (3xWQV)	30 35 40	22-37
Bioretention Basin Bioretention Filter Extended Detention - Enhanced Retention Basin II (4xWQV) Infiltration (1xWQV)	50 50 50 50 50	38-66
Sand Filter Infiltration (2xWQV) Retention Basin III (4xWQV with aquatic bench)	65 65 65	67-100

During a BMP selection scenario, the VT BMP DSS allows its user to choose from four impervious fraction ranges: less than 21%, 21-37%, 38-66%, and greater than 66%. This enables the user to apply a BMP comparison template which reflects site-specific characteristics. Based on the information shown in Table D.15, and employing the scale of relative importances described in Chapter 4 of this report, these BMP comparison templates are presented on the following pages.

Table D.16 BMP Pairwise Comparison Matrix – Impervious Cover < 21%

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	3.00	3.00	1.00	0.33	0.33	3.00	3.00	3.00	3.00	5.00	0.33	0.33	5.00
Enhanced ED Basin (B)	0.33	***1.00***	1.00	0.33	0.17	0.17	1.00	1.00	1.00	1.00	2.00	0.17	0.17	2.00
Retention Basin (C)	0.33	1.00	***1.00***	0.33	0.17	0.17	1.00	1.00	1.00	1.00	2.00	0.17	0.17	2.00
Constructed Wetlands (D)	1.00	3.00	3.00	***1.00***	0.33	0.33	3.00	3.00	3.00	3.00	5.00	0.33	0.33	5.00
Vegetated WQ Swale (E)	3.00	6.00	6.00	3.00	***1.00***	1.00	6.00	6.00	6.00	6.00	8.00	1.00	1.00	8.00
Vegetated Filter Strip (F)	3.00	6.00	6.00	3.00	1.00	***1.00***	6.00	6.00	6.00	6.00	8.00	1.00	1.00	8.00
Infiltration Trench (G)	0.33	1.00	1.00	0.33	0.17	0.17	***1.00***	1.00	1.00	1.00	2.00	0.17	0.17	2.00
Infiltration Basin (H)	0.33	1.00	1.00	0.33	0.17	0.17	1.00	***1.00***	1.00	1.00	2.00	0.17	0.17	2.00
Porous Pavement (I)	0.33	1.00	1.00	0.33	0.17	0.17	1.00	1.00	***1.00***	1.00	2.00	0.17	0.17	2.00
Bioretention (J)	0.33	1.00	1.00	0.33	0.17	0.17	1.00	1.00	1.00	***1.00***	2.00	0.17	0.17	2.00
Sand Filters (K)	0.20	0.50	0.50	0.20	0.13	0.13	0.50	0.50	0.50	0.50	***1.00***	0.13	0.13	1.00
Vegetated Roof (L)	3.00	6.00	6.00	3.00	1.00	1.00	6.00	6.00	6.00	6.00	8.00	***1.00***	1.00	8.00
Rainwater Harvesting (M)	3.00	6.00	6.00	3.00	1.00	1.00	6.00	6.00	6.00	6.00	8.00	1.00	***1.00***	8.00
Manufactured BMPs (N)	0.20	0.50	0.50	0.20	0.13	0.13	0.50	0.50	0.50	0.50	1.00	0.13	0.13	***1.00***

BMP	Matrix Priority Vector
Vegetated WQ Swale	0.1643
Vegetated Filter Strip	0.1643
Vegetated Roof	0.1643
Rainwater Harvesting	0.1643
Dry ED Basin	0.0723
Constructed Wetlands	0.0723
Enhanced ED Basin	0.0276
Retention Basin	0.0276
Infiltration Trench	0.0276
Infiltration Basin	0.0276
Porous Pavement	0.0276
Bioretention	0.0276
Sand Filters	0.0161
Manufactured BMPs	0.0161

Consistency Ratio = 0.01

Table D.17 BMP Pairwise Comparison Matrix – Impervious Cover 22-37%

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	4.00	4.00	1.00	9.00	9.00	4.00	4.00	4.00	4.00	6.00	1.00	1.00	6.00
Enhanced ED Basin (B)	0.25	***1.00***	1.00	0.25	5.00	5.00	1.00	1.00	1.00	1.00	2.00	0.25	0.25	2.00
Retention Basin (C)	0.25	1.00	***1.00***	0.25	5.00	5.00	1.00	1.00	1.00	1.00	2.00	0.25	0.25	2.00
Constructed Wetlands (D)	1.00	4.00	4.00	***1.00***	9.00	9.00	4.00	4.00	4.00	4.00	6.00	1.00	1.00	6.00
Vegetated WQ Swale (E)	0.11	0.20	0.20	0.11	***1.00***	1.00	0.20	0.20	0.20	0.20	0.33	0.11	0.11	0.33
Vegetated Filter Strip (F)	0.11	0.20	0.20	0.11	1.00	***1.00***	0.20	0.20	0.20	0.20	0.33	0.11	0.11	0.33
Infiltration Trench (G)	0.25	1.00	1.00	0.25	5.00	5.00	***1.00***	1.00	1.00	1.00	2.00	0.25	0.25	2.00
Infiltration Basin (H)	0.25	1.00	1.00	0.25	5.00	5.00	1.00	***1.00***	1.00	1.00	2.00	0.25	0.25	2.00
Porous Pavement (I)	0.25	1.00	1.00	0.25	5.00	5.00	1.00	1.00	***1.00***	1.00	2.00	0.25	0.25	2.00
Bioretention (J)	0.25	1.00	1.00	0.25	5.00	5.00	1.00	1.00	1.00	***1.00***	2.00	0.25	0.25	2.00
Sand Filters (K)	0.17	0.50	0.50	0.17	3.00	3.00	0.50	0.50	0.50	0.50	***1.00***	0.17	0.17	1.00
Vegetated Roof (L)	1.00	4.00	4.00	1.00	9.00	9.00	4.00	4.00	4.00	4.00	6.00	***1.00***	1.00	6.00
Rainwater Harvesting (M)	1.00	4.00	4.00	1.00	9.00	9.00	4.00	4.00	4.00	4.00	6.00	1.00	***1.00***	6.00
Manufactured BMPs (N)	0.17	0.50	0.50	0.17	3.00	3.00	0.50	0.50	0.50	0.50	1.00	0.17	0.17	***1.00***

BMP	Matrix Priority Vector
Dry ED Basin	0.1600
Constructed Wetlands	0.1600
Vegetated Roof	0.1600
Rainwater Harvesting	0.1600
Enhanced ED Basin	0.0472
Retention Basin	0.0472
Infiltration Trench	0.0472
Infiltration Basin	0.0472
Porous Pavement	0.0472
Bioretention	0.0472
Sand Filters	0.0265
Manufactured BMPs	0.0265
Vegetated WQ Swale	0.0121
Vegetated Filter Strip	0.0121

Consistency Ratio = 0.02

Table D.18 BMP Pairwise Comparison Matrix – Impervious Cover 38-66%

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	0.11	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.20	0.11	0.11	0.20
Enhanced ED Basin (B)	9.00	***1.00***	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	4.00	1.00	1.00	4.00
Retention Basin (C)	9.00	1.00	***1.00***	9.00	9.00	9.00	1.00	1.00	1.00	1.00	4.00	1.00	1.00	4.00
Constructed Wetlands (D)	1.00	0.11	0.11	***1.00***	1.00	1.00	0.11	0.11	0.11	0.11	0.20	0.11	0.11	0.20
Vegetated WQ Swale (E)	1.00	0.11	0.11	1.00	***1.00***	1.00	0.11	0.11	0.11	0.11	0.20	0.11	0.11	0.20
Vegetated Filter Strip (F)	1.00	0.11	0.11	1.00	1.00	***1.00***	0.11	0.11	0.11	0.11	0.20	0.11	0.11	0.20
Infiltration Trench (G)	9.00	1.00	1.00	9.00	9.00	9.00	***1.00***	1.00	1.00	1.00	4.00	1.00	1.00	4.00
Infiltration Basin (H)	9.00	1.00	1.00	9.00	9.00	9.00	1.00	***1.00***	1.00	1.00	4.00	1.00	1.00	4.00
Porous Pavement (I)	9.00	1.00	1.00	9.00	9.00	9.00	1.00	1.00	***1.00***	1.00	4.00	1.00	1.00	4.00
Bioretention (J)	9.00	1.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	***1.00***	4.00	1.00	1.00	4.00
Sand Filters (K)	5.00	0.25	0.25	5.00	5.00	5.00	0.25	0.25	0.25	0.25	***1.00***	0.25	0.25	1.00
Vegetated Roof (L)	9.00	1.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	4.00	***1.00***	1.00	4.00
Rainwater Harvesting (M)	9.00	1.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	4.00	1.00	***1.00***	4.00
Manufactured BMPs (N)	5.00	0.25	0.25	5.00	5.00	5.00	0.25	0.25	0.25	0.25	1.00	0.25	0.25	***1.00***

BMP	Matrix Priority Vector
Enhanced ED Basin	0.1102
Retention Basin	0.1102
Infiltration Trench	0.1102
Infiltration Basin	0.1102
Porous Pavement	0.1102
Bioretention	0.1102
Vegetated Roof	0.1102
Rainwater Harvesting	0.1102
Sand Filters	0.0367
Manufactured BMPs	0.0367
Dry ED Basin	0.0112
Constructed Wetlands	0.0112
Vegetated WQ Swale	0.0112
Vegetated Filter Strip	0.0112

Consistency Ratio = 0.02

Table D.19 BMP Pairwise Comparison Matrix – Impervious Cover >66%

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	0.25	1.00	1.00	1.00	0.25	0.25	0.25	1.00	0.11	0.11	0.11	0.11
Enhanced ED Basin (B)	1.00	***1.00***	0.25	1.00	1.00	1.00	0.25	0.25	0.25	1.00	0.11	0.11	0.11	0.11
Retention Basin (C)	4.00	4.00	***1.00***	4.00	4.00	4.00	1.00	1.00	1.00	4.00	0.20	0.20	0.20	0.20
Constructed Wetlands (D)	1.00	1.00	0.25	***1.00***	1.00	1.00	0.25	0.25	0.25	1.00	0.11	0.11	0.11	0.11
Vegetated WQ Swale (E)	1.00	1.00	0.25	1.00	***1.00***	1.00	0.25	0.25	0.25	1.00	0.11	0.11	0.11	0.11
Vegetated Filter Strip (F)	1.00	1.00	0.25	1.00	1.00	***1.00***	0.25	0.25	0.25	1.00	0.11	0.11	0.11	0.11
Infiltration Trench (G)	4.00	4.00	1.00	4.00	4.00	4.00	***1.00***	1.00	1.00	4.00	0.20	0.20	0.20	0.20
Infiltration Basin (H)	4.00	4.00	1.00	4.00	4.00	4.00	1.00	***1.00***	1.00	4.00	0.20	0.20	0.20	0.20
Porous Pavement (I)	4.00	4.00	1.00	4.00	4.00	4.00	1.00	1.00	***1.00***	4.00	0.20	0.20	0.20	0.20
Bioretention (J)	1.00	1.00	0.25	1.00	1.00	1.00	0.25	0.25	0.25	***1.00***	0.11	0.11	0.11	0.11
Sand Filters (K)	9.00	9.00	5.00	9.00	9.00	9.00	5.00	5.00	5.00	9.00	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	9.00	9.00	5.00	9.00	9.00	9.00	5.00	5.00	5.00	9.00	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	9.00	9.00	5.00	9.00	9.00	9.00	5.00	5.00	5.00	9.00	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	9.00	9.00	5.00	9.00	9.00	9.00	5.00	5.00	5.00	9.00	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Sand Filters	0.1748
Vegetated Roof	0.1748
Rainwater Harvesting	0.1748
Manufactured BMPs	0.1748
Retention Basin	0.0512
Infiltration Trench	0.0512
Infiltration Basin	0.0512
Porous Pavement	0.0512
Dry ED Basin	0.0160
Enhanced ED Basin	0.0160
Constructed Wetlands	0.0160
Vegetated WQ Swale	0.0160
Vegetated Filter Strip	0.0160
Bioretention	0.0160

Consistency Ratio = 0.02

Presence of Hotspot Runoff

Stormwater hotspots are defined as generating sites from which the runoff exhibits pollutant concentrations greatly in excess of those typically found in stormwater. More often than not, this definition is further extended to reflect the presence of hydrocarbons in the runoff. The Maryland Department of the Environment, 2000, cites all BMPs capable of accepting hotspot runoff, with the exception of infiltration practices and wet vegetative water quality swales. The VT BMP DSS permits its user to consider the presence of hotspot runoff in the BMP selection process. Within the software, all BMPs capable of receiving hotspot runoff are ranked equally, while those practices to which hotspot runoff cannot be directed are ranked very low for this criterion.

Table D.20 shows the BMP pairwise comparison matrix reflecting the ability of the BMPs to receive runoff from hotspot generating sites.

Table D.20 BMP Pairwise Comparison Matrix – Ability to Receive Hotspot Runoff

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Enhanced ED Basin (B)	1.00	***1.00***	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Retention Basin (C)	1.00	1.00	***1.00***	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Constructed Wetlands (D)	1.00	1.00	1.00	***1.00***	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Vegetated WQ Swale (E)	0.11	0.11	0.11	0.11	***1.00***	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11
Vegetated Filter Strip (F)	1.00	1.00	1.00	1.00	9.00	***1.00***	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Infiltration Trench (G)	0.11	0.11	0.11	0.11	1.00	0.11	***1.00***	1.00	1.00	0.11	0.11	0.11	0.11	0.11
Infiltration Basin (H)	0.11	0.11	0.11	0.11	1.00	0.11	1.00	***1.00***	1.00	0.11	0.11	0.11	0.11	0.11
Porous Pavement (I)	0.11	0.11	0.11	0.11	1.00	0.11	1.00	1.00	***1.00***	0.11	0.11	0.11	0.11	0.11
Bioretention (J)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	***1.00***	1.00	1.00	1.00	1.00
Sand Filters (K)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Dry ED Basin	0.0957
Enhanced ED Basin	0.0957
Retention Basin	0.0957
Constructed Wetlands	0.0957
Vegetated Filter Strip	0.0957
Bioretention	0.0957
Sand Filters	0.0957
Vegetated Roof	0.0957
Rainwater Harvesting	0.0957
Manufactured BMPs	0.0957
Vegetated WQ Swale	0.0106
Infiltration Trench	0.0106
Infiltration Basin	0.0106
Porous Pavement	0.0106

Consistency Ratio = 0.00

Peak Runoff Rate Attenuation Ability
Historically, the focus of stormwater management has been to reduce the peak rate of runoff from a developed site to pre-development (or other acceptable) levels. Providing flood control in the form of peak rate attenuation is still a highly prioritized goal in most stormwater management efforts. Generally the basin class of BMP is regarded as having the greatest ability to control the rate of runoff from a site. Rainwater harvesting systems and vegetated roofs can also provide significant runoff rate reduction for the volume of water that they are capable of intercepting (generally only from small catchments). Sand filters and other manufactured BMPs are primarily implemented as water quality BMPs, and provide little to no runoff rate reduction.

The Virginia Tech BMP Decision Support Software enables it user to consider runoff rate attenuation capability when choosing among competing BMP options. Table D.21 shows the BMP pairwise comparison matrix reflecting the ability of the BMPs to reduce the volumetric rate of runoff from a site.

Table D.21 BMP Pairwise Comparison Matrix – Ability to Reduce Volumetric Rate of Runoff

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Enhanced ED Basin (B)	1.00	***1.00***	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Retention Basin (C)	1.00	1.00	***1.00***	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Constructed Wetlands (D)	1.00	1.00	1.00	***1.00***	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Vegetated WQ Swale (E)	0.11	0.11	0.11	0.11	***1.00***	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11
Vegetated Filter Strip (F)	1.00	1.00	1.00	1.00	9.00	***1.00***	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00
Infiltration Trench (G)	0.11	0.11	0.11	0.11	1.00	0.11	***1.00***	1.00	1.00	0.11	0.11	0.11	0.11	0.11
Infiltration Basin (H)	0.11	0.11	0.11	0.11	1.00	0.11	1.00	***1.00***	1.00	0.11	0.11	0.11	0.11	0.11
Porous Pavement (I)	0.11	0.11	0.11	0.11	1.00	0.11	1.00	1.00	***1.00***	0.11	0.11	0.11	0.11	0.11
Bioretention (J)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	***1.00***	1.00	1.00	1.00	1.00
Sand Filters (K)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	1.00	1.00	1.00	1.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Dry ED Basin	0.1252
Enhanced ED Basin	0.1252
Retention Basin	0.1252
Infiltration Basin	0.1252
Rainwater Harvesting	0.1252
Porous Pavement	0.0779
Vegetated Roof	0.0779
Constructed Wetlands	0.0513
Infiltration Trench	0.0513
Bioretention	0.0513
Vegetated WQ Swale	0.0277
Vegetated Filter Strip	0.0166
Sand Filters	0.0101
Manufactured BMPs	0.0101

Consistency Ratio = 0.02

Aesthetic Benefit or Liability

When the proposed installation is in a high profile location, the public's perception of a BMP may become an essential selection consideration. Some BMPs, notably dry detention basins, offer very little potential to provide aesthetic benefit to a site and, in fact, may be an aesthetic liability. Other BMPs, such as sand filters, have little potential to provide aesthetic benefit to a site, but can be designed and located so as to minimize their obtrusiveness. Still other BMPs, such as retention basins and constructed wetlands, can be designed such that they become a desirable site amenity capable of providing recreational opportunities and wildlife habitat.

The aesthetic benefit or liability of the various BMP options is available as a selection criterion in Virginia Tech's BMP Decision Support Software. Table D.22 shows the BMP pairwise comparison matrix reflecting the ability of the BMPs to provide aesthetic benefit to a developed site.

Table D.22 BMP Pairwise Comparison Matrix – Ability to the BMP to Provide Aesthetic Benefit

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	0.11	0.11	0.50	0.11	0.50	1.00	0.14	0.11	0.14	0.14	0.14	0.14
Enhanced ED Basin (B)	1.00	***1.00***	0.11	0.11	0.50	0.11	0.50	1.00	0.14	0.11	0.14	0.14	0.14	0.14
Retention Basin (C)	9.00	9.00	***1.00***	1.00	7.00	1.00	7.00	9.00	2.00	1.00	2.00	2.00	2.00	2.00
Constructed Wetlands (D)	9.00	9.00	1.00	***1.00***	7.00	1.00	7.00	9.00	2.00	1.00	2.00	2.00	2.00	2.00
Vegetated WQ Swale (E)	2.00	2.00	0.14	0.14	***1.00***	0.14	1.00	2.00	0.20	0.14	0.20	0.20	0.20	0.20
Vegetated Filter Strip (F)	9.00	9.00	1.00	1.00	7.00	***1.00***	7.00	9.00	2.00	1.00	2.00	2.00	2.00	2.00
Infiltration Trench (G)	2.00	2.00	0.14	0.14	1.00	0.14	***1.00***	2.00	0.20	0.14	0.20	0.20	0.20	0.20
Infiltration Basin (H)	1.00	1.00	0.11	0.11	0.50	0.11	0.50	***1.00***	0.14	0.11	0.14	0.14	0.14	0.14
Porous Pavement (I)	7.00	7.00	0.50	0.50	5.00	0.50	5.00	7.00	***1.00***	0.50	1.00	1.00	1.00	1.00
Bioretention (J)	9.00	9.00	1.00	1.00	7.00	1.00	7.00	9.00	2.00	***1.00***	2.00	2.00	2.00	2.00
Sand Filters (K)	7.00	7.00	0.50	0.50	5.00	0.50	5.00	7.00	1.00	0.50	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	7.00	7.00	0.50	0.50	5.00	0.50	5.00	7.00	1.00	0.50	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	7.00	7.00	0.50	0.50	5.00	0.50	5.00	7.00	1.00	0.50	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	7.00	7.00	0.50	0.50	5.00	0.50	5.00	7.00	1.00	0.50	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Retention Basin	0.1342
Constructed Wetlands	0.1342
Vegetated Filter Strip	0.1342
Bioretention	0.1342
Porous Pavement	0.0778
Sand Filters	0.0778
Vegetated Roof	0.0778
Rainwater Harvesting	0.0778
Manufactured BMPs	0.0778
Vegetated WQ Swale	0.0189
Infiltration Trench	0.0189
Dry ED Basin	0.0122
Enhanced ED Basin	0.0122
Infiltration Basin	0.0122

Consistency Ratio = 0.01

Public Safety

Some BMPs have inherent public safety issues associated with their installation. The most notable safety concern arising from BMP implementation occurs when the practice exhibits a permanent pool, such as the case with enhanced detention basins, retention basins, and constructed stormwater wetlands. Practices exhibiting a permanent pool also have the potential to become marshy and stagnant, resulting in ideal habitat for mosquitoes and other disease carrying vectors. Vegetated water quality swales and infiltration trenches may also develop marshy conditions which are undesirable in populated areas.

The Virginia Tech BMP Decision Support Software permits its user to consider public safety during the BMP selection process. Table D.23 shows the BMP pairwise comparison matrix reflecting the public safety of the various BMP alternatives.

Table D.23 BMP Pairwise Comparison Matrix – Public Safety

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	3.00	3.00	3.00	0.50	0.17	0.50	1.00	0.17	0.17	0.17	0.17	0.17	0.17
Enhanced ED Basin (B)	0.33	***1.00***	1.00	1.00	0.20	0.11	0.20	0.33	0.11	0.11	0.11	0.11	0.11	0.11
Retention Basin (C)	0.33	1.00	***1.00***	1.00	0.20	0.11	0.20	0.33	0.11	0.11	0.11	0.11	0.11	0.11
Constructed Wetlands (D)	0.33	1.00	1.00	***1.00***	0.20	0.11	0.20	0.33	0.11	0.11	0.11	0.11	0.11	0.11
Vegetated WQ Swale (E)	2.00	5.00	5.00	5.00	***1.00***	0.25	1.00	2.00	0.25	0.25	0.25	0.25	0.25	0.25
Vegetated Filter Strip (F)	6.00	9.00	9.00	9.00	4.00	***1.00***	4.00	6.00	1.00	1.00	1.00	1.00	1.00	1.00
Infiltration Trench (G)	2.00	5.00	5.00	5.00	1.00	0.25	***1.00***	2.00	0.25	0.25	0.25	0.25	0.25	0.25
Infiltration Basin (H)	1.00	3.00	3.00	3.00	0.50	0.17	0.50	***1.00***	0.17	0.17	0.17	0.17	0.17	0.17
Porous Pavement (I)	6.00	9.00	9.00	9.00	4.00	1.00	4.00	6.00	***1.00***	1.00	1.00	1.00	1.00	1.00
Bioretention (J)	6.00	9.00	9.00	9.00	4.00	1.00	4.00	6.00	1.00	***1.00***	1.00	1.00	1.00	1.00
Sand Filters (K)	6.00	9.00	9.00	9.00	4.00	1.00	4.00	6.00	1.00	1.00	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	6.00	9.00	9.00	9.00	4.00	1.00	4.00	6.00	1.00	1.00	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	6.00	9.00	9.00	9.00	4.00	1.00	4.00	6.00	1.00	1.00	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	6.00	9.00	9.00	9.00	4.00	1.00	4.00	6.00	1.00	1.00	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Vegetated Filter Strip	0.1203
Porous Pavement	0.1203
Bioretention	0.1203
Sand Filters	0.1203
Vegetated Roof	0.1203
Rainwater Harvesting	0.1203
Manufactured BMPs	0.1203
Vegetated WQ Swale	0.0387
Infiltration Trench	0.0387
Dry ED Basin	0.0232
Infiltration Basin	0.0232
Enhanced ED Basin	0.0113
Retention Basin	0.0113
Constructed Wetlands	0.0113

Consistency Ratio = 0.01

Site Slopes/Topography

The topography of the site upon which a BMP installation is proposed is an important factor in choosing the appropriate practice. BMPs employing underground reservoirs and/or infiltration beds generally require site slopes to be less than 10 percent. Similarly, the use of filtering practices such as grassed swales and vegetated filter strips is restricted to slopes of less than 20 percent.

When the site of interest exhibits an average slope exceeding 10 percent, users of the Virginia Tech BMP Decision Support Software can introduce this as a BMP selection criterion. Table D.24 shows the BMP pairwise comparison matrix reflecting the presence of site slopes in excess of 10 percent.

Table D.24 BMP Pairwise Comparison Matrix – Presence of Slopes Exceeding 10%

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	1.00	5.00	9.00	9.00	1.00	1.00	9.00	1.00	1.00	1.00	1.00	1.00
Enhanced ED Basin (B)	1.00	***1.00***	1.00	5.00	9.00	9.00	1.00	1.00	9.00	1.00	1.00	1.00	1.00	1.00
Retention Basin (C)	1.00	1.00	***1.00***	5.00	9.00	9.00	1.00	1.00	9.00	1.00	1.00	1.00	1.00	1.00
Constructed Wetlands (D)	0.20	0.20	0.20	***1.00***	4.00	4.00	0.20	0.20	4.00	0.20	0.20	0.20	0.20	0.20
Vegetated WQ Swale (E)	0.11	0.11	0.11	0.25	***1.00***	1.00	0.11	0.11	1.00	0.11	0.11	0.11	0.11	0.11
Vegetated Filter Strip (F)	0.11	0.11	0.11	0.25	1.00	***1.00***	0.11	0.11	1.00	0.11	0.11	0.11	0.11	0.11
Infiltration Trench (G)	1.00	1.00	1.00	5.00	9.00	9.00	***1.00***	1.00	9.00	1.00	1.00	1.00	1.00	1.00
Infiltration Basin (H)	1.00	1.00	1.00	5.00	9.00	9.00	1.00	***1.00***	9.00	1.00	1.00	1.00	1.00	1.00
Porous Pavement (I)	0.11	0.11	0.11	0.25	1.00	1.00	0.11	0.11	***1.00***	0.11	0.11	0.11	0.11	0.11
Bioretention (J)	1.00	1.00	1.00	5.00	9.00	9.00	1.00	1.00	9.00	***1.00***	1.00	1.00	1.00	1.00
Sand Filters (K)	1.00	1.00	1.00	5.00	9.00	9.00	1.00	1.00	9.00	1.00	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	1.00	1.00	1.00	5.00	9.00	9.00	1.00	1.00	9.00	1.00	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	1.00	1.00	1.00	5.00	9.00	9.00	1.00	1.00	9.00	1.00	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	1.00	1.00	1.00	5.00	9.00	9.00	1.00	1.00	9.00	1.00	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Dry ED Basin	0.0946
Enhanced ED Basin	0.0946
Retention Basin	0.0946
Infiltration Trench	0.0946
Infiltration Basin	0.0946
Bioretention	0.0946
Sand Filters	0.0946
Vegetated Roof	0.0946
Rainwater Harvesting	0.0946
Manufactured BMPs	0.0946
Constructed Wetlands	0.0238
Vegetated WQ Swale	0.0101
Vegetated Filter Strip	0.0101
Porous Pavement	0.0101

Consistency Ratio = 0.01

Pollutant Removal Performance

The runoff from urbanized areas carries a variety of soluble and particulate pollutants, typically at levels much greater than those observed in the runoff from undisturbed, natural spaces. Many of these pollutants pose significant threats to the aquatic ecosystems of receiving waters. The state of Virginia defines phosphorus as its "keystone pollutant." Phosphorus was selected because of the unique manner in which it exhibits characteristics of both soluble and particulate pollutants. Nutrients such as phosphorus and nitrogen are of particular interest because of their potential to cause eutrophication of surface waters. Notable levels of suspended sediment are also found in the runoff generated from impervious surfaces, managed lawns, and sites whose surfaces have been denuded through construction processes. The VT BMP DSS allows its user to introduce the removal of total suspended sediment (TSS), total phosphorus (TP), and total nitrogen (TN) as selection criteria during a BMP selection scenario.

Within the VT BMP DSS, users can choose to consider the pollutant removal performance of competing BMP alternatives in one of two ways. First, for the pollutant of interest, BMPs can be evaluated by "threshold" pollutant removal efficiencies (80% for TSS, 35% for TP, and 30% for TN). Alternatively, the user can choose to introduce pollutant removal performance as a relative comparison of BMP alternatives. When the threshold pollutant removal criteria are employed in the algorithm, BMPs are rigidly evaluated on their ability to consistently achieve the threshold values. All BMPs capable of achieving the explicitly stated removal efficiency are ranked equally, while those practices unable to attain the expressed removal efficiency are given a very low ranking. When the relative pollutant removal criteria are selected, BMPs are ranked relatively against other competing BMP alternatives in terms of their ability to remove the pollutant of interest from stormwater runoff.

Data supporting the construction of the BMP pollutant removal comparison matrices is derived from the International Stormwater BMP Database (USEPA and ASCE) and the National Pollutant Removal Performance Database for Stormwater Treatment Practices 2nd Edition (CWP, 2000). The reader is referred to Young, K. D. (2006) for additional details on the development on these BMP pollutant removal data.

Tables D.25 through D.30 are the pairwise comparison matrices depicting the pollutant removal performance of the BMPs available in the VT BMP DSS.

Table D.25 BMP Pairwise Comparison Matrix – 80% TSS Removal

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Enhanced ED Basin (B)	1.00	***1.00***	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Retention Basin (C)	9.00	9.00	***1.00***	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Constructed Wetlands (D)	1.00	1.00	0.11	***1.00***	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Vegetated WQ Swale (E)	1.00	1.00	0.11	1.00	***1.00***	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Vegetated Filter Strip (F)	1.00	1.00	0.11	1.00	1.00	***1.00***	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Infiltration Trench (G)	9.00	9.00	1.00	9.00	9.00	9.00	***1.00***	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Infiltration Basin (H)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	***1.00***	1.00	1.00	1.00	1.00	1.00	9.00
Porous Pavement (I)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	***1.00***	1.00	1.00	1.00	1.00	9.00
Bioretention (J)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	***1.00***	1.00	1.00	1.00	9.00
Sand Filters (K)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	***1.00***	1.00	1.00	9.00
Vegetated Roof (L)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	***1.00***	1.00	9.00
Rainwater Harvesting (M)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	***1.00***	9.00
Manufactured BMPs (N)	1.00	1.00	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	***1.00***

BMP	Matrix Priority Vector
Retention Basin	0.1154
Infiltration Trench	0.1154
Infiltration Basin	0.1154
Porous Pavement	0.1154
Bioretention	0.1154
Sand Filters	0.1154
Vegetated Roof	0.1154
Rainwater Harvesting	0.1154
Dry ED Basin	0.0128
Enhanced ED Basin	0.0128
Constructed Wetlands	0.0128
Vegetated WQ Swale	0.0128
Vegetated Filter Strip	0.0128
Manufactured BMPs	0.0128

Consistency Ratio = 0.00

Table D.26 BMP Pairwise Comparison Matrix – 35% TP Removal

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Enhanced ED Basin (B)	1.00	***1.00***	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Retention Basin (C)	9.00	9.00	***1.00***	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Constructed Wetlands (D)	1.00	1.00	0.11	***1.00***	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Vegetated WQ Swale (E)	1.00	1.00	0.11	1.00	***1.00***	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Vegetated Filter Strip (F)	1.00	1.00	0.11	1.00	1.00	***1.00***	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Infiltration Trench (G)	9.00	9.00	1.00	9.00	9.00	9.00	***1.00***	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Infiltration Basin (H)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	***1.00***	1.00	1.00	1.00	1.00	1.00	9.00
Porous Pavement (I)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	***1.00***	1.00	1.00	1.00	1.00	9.00
Bioretention (J)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	***1.00***	1.00	1.00	1.00	9.00
Sand Filters (K)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	***1.00***	1.00	1.00	9.00
Vegetated Roof (L)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	***1.00***	1.00	9.00
Rainwater Harvesting (M)	9.00	9.00	1.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	***1.00***	9.00
Manufactured BMPs (N)	1.00	1.00	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	***1.00***

BMP	Matrix Priority Vector
Retention Basin	0.1154
Infiltration Trench	0.1154
Infiltration Basin	0.1154
Porous Pavement	0.1154
Bioretention	0.1154
Sand Filters	0.1154
Vegetated Roof	0.1154
Rainwater Harvesting	0.1154
Dry ED Basin	0.0128
Enhanced ED Basin	0.0128
Constructed Wetlands	0.0128
Vegetated WQ Swale	0.0128
Vegetated Filter Strip	0.0128
Manufactured BMPs	0.0128

Consistency Ratio = 0.00

Table D.27 BMP Pairwise Comparison Matrix – 30% TN Removal

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	1.00	1.00	1.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Enhanced ED Basin (B)	1.00	***1.00***	1.00	1.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Retention Basin (C)	1.00	1.00	***1.00***	1.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Constructed Wetlands (D)	1.00	1.00	1.00	***1.00***	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Vegetated WQ Swale (E)	0.11	0.11	0.11	0.11	***1.00***	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Vegetated Filter Strip (F)	0.11	0.11	0.11	0.11	1.00	***1.00***	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Infiltration Trench (G)	1.00	1.00	1.00	1.00	9.00	9.00	***1.00***	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Infiltration Basin (H)	1.00	1.00	1.00	1.00	9.00	9.00	1.00	***1.00***	1.00	1.00	1.00	1.00	1.00	9.00
Porous Pavement (I)	1.00	1.00	1.00	1.00	9.00	9.00	1.00	1.00	***1.00***	1.00	1.00	1.00	1.00	9.00
Bioretention (J)	1.00	1.00	1.00	1.00	9.00	9.00	1.00	1.00	1.00	***1.00***	1.00	1.00	1.00	9.00
Sand Filters (K)	1.00	1.00	1.00	1.00	9.00	9.00	1.00	1.00	1.00	1.00	***1.00***	1.00	1.00	9.00
Vegetated Roof (L)	1.00	1.00	1.00	1.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	***1.00***	1.00	9.00
Rainwater Harvesting (M)	1.00	1.00	1.00	1.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	***1.00***	9.00
Manufactured BMPs (N)	0.11	0.11	0.11	0.11	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	***1.00***

BMP	Matrix Priority Vector
Dry ED Basin	0.0882
Enhanced ED Basin	0.0882
Retention Basin	0.0882
Constructed Wetlands	0.0882
Infiltration Trench	0.0882
Infiltration Basin	0.0882
Porous Pavement	0.0882
Bioretention	0.0882
Sand Filters	0.0882
Vegetated Roof	0.0882
Rainwater Harvesting	0.0882
Vegetated WQ Swale	0.0098
Vegetated Filter Strip	0.0098
Manufactured BMPs	0.0098

Consistency Ratio = 0.00

Table D.28 BMP Pairwise Comparison Matrix – Relative TSS Removal

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	0.14	0.11	0.14	0.20	1.00	0.14	0.14	0.14	0.11	0.11	0.11	0.11	0.11
Enhanced ED Basin (B)	7.00	***1.00***	0.50	1.00	2.00	7.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50
Retention Basin (C)	9.00	2.00	***1.00***	2.00	4.00	9.00	2.00	2.00	2.00	1.00	1.00	1.00	1.00	1.00
Constructed Wetlands (D)	7.00	1.00	0.50	***1.00***	2.00	7.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50
Vegetated WQ Swale (E)	5.00	0.50	0.25	0.50	***1.00***	5.00	0.50	0.50	0.50	0.25	0.25	0.25	0.25	0.25
Vegetated Filter Strip (F)	1.00	0.14	0.11	0.14	0.20	***1.00***	0.14	0.14	0.14	0.11	0.11	0.11	0.11	0.11
Infiltration Trench (G)	7.00	1.00	0.50	1.00	2.00	7.00	***1.00***	1.00	1.00	0.50	0.50	0.50	0.50	0.50
Infiltration Basin (H)	7.00	1.00	0.50	1.00	2.00	7.00	1.00	***1.00***	1.00	0.50	0.50	0.50	0.50	0.50
Porous Pavement (I)	7.00	1.00	0.50	1.00	2.00	7.00	1.00	1.00	***1.00***	0.50	0.50	0.50	0.50	0.50
Bioretention (J)	9.00	2.00	1.00	2.00	4.00	9.00	2.00	2.00	2.00	***1.00***	1.00	1.00	1.00	1.00
Sand Filters (K)	9.00	2.00	1.00	2.00	4.00	9.00	2.00	2.00	2.00	1.00	***1.00***	1.00	1.00	1.00
Vegetated Roof (L)	9.00	2.00	1.00	2.00	4.00	9.00	2.00	2.00	2.00	1.00	1.00	***1.00***	1.00	1.00
Rainwater Harvesting (M)	9.00	2.00	1.00	2.00	4.00	9.00	2.00	2.00	2.00	1.00	1.00	1.00	***1.00***	1.00
Manufactured BMPs (N)	9.00	2.00	1.00	2.00	4.00	9.00	2.00	2.00	2.00	1.00	1.00	1.00	1.00	***1.00***

BMP	Matrix Priority Vector
Retention Basin	0.1094
Bioretention	0.1094
Sand Filters	0.1094
Vegetated Roof	0.1094
Rainwater Harvesting	0.1094
Manufactured BMPs	0.1094
Enhanced ED Basin	0.0584
Constructed Wetlands	0.0584
Infiltration Trench	0.0584
Infiltration Basin	0.0584
Porous Pavement	0.0584
Vegetated WQ Swale	0.0314
Dry ED Basin	0.0101
Vegetated Filter Strip	0.0101

Consistency Ratio = 0.01

Table D.29 BMP Pairwise Comparison Matrix – Relative TP Removal

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	0.50	0.25	0.50	5.00	5.00	0.25	0.25	0.25	0.25	0.25	0.25	0.25	5.00
Enhanced ED Basin (B)	2.00	***1.00***	0.50	1.00	7.00	7.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	7.00
Retention Basin (C)	4.00	2.00	***1.00***	2.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Constructed Wetlands (D)	2.00	1.00	0.50	***1.00***	7.00	7.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	7.00
Vegetated WQ Swale (E)	0.20	0.14	0.11	0.14	***1.00***	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Vegetated Filter Strip (F)	0.20	0.14	0.11	0.14	1.00	***1.00***	0.11	0.11	0.11	0.11	0.11	0.11	0.11	1.00
Infiltration Trench (G)	4.00	2.00	1.00	2.00	9.00	9.00	***1.00***	1.00	1.00	1.00	1.00	1.00	1.00	9.00
Infiltration Basin (H)	4.00	2.00	1.00	2.00	9.00	9.00	1.00	***1.00***	1.00	1.00	1.00	1.00	1.00	9.00
Porous Pavement (I)	4.00	2.00	1.00	2.00	9.00	9.00	1.00	1.00	***1.00***	1.00	1.00	1.00	1.00	9.00
Bioretention (J)	4.00	2.00	1.00	2.00	9.00	9.00	1.00	1.00	1.00	***1.00***	1.00	1.00	1.00	9.00
Sand Filters (K)	4.00	2.00	1.00	2.00	9.00	9.00	1.00	1.00	1.00	1.00	***1.00***	1.00	1.00	9.00
Vegetated Roof (L)	4.00	2.00	1.00	2.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	***1.00***	1.00	9.00
Rainwater Harvesting (M)	4.00	2.00	1.00	2.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	***1.00***	9.00
Manufactured BMPs (N)	0.20	0.14	0.11	0.14	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	***1.00***

BMP	Matrix Priority Vector
Retention Basin	0.1028
Infiltration Trench	0.1028
Infiltration Basin	0.1028
Porous Pavement	0.1028
Bioretention	0.1028
Sand Filters	0.1028
Vegetated Roof	0.1028
Rainwater Harvesting	0.1028
Enhanced ED Basin	0.0571
Constructed Wetlands	0.0571
Dry ED Basin	0.0320
Vegetated WQ Swale	0.0104
Vegetated Filter Strip	0.0104
Manufactured BMPs	0.0104

Consistency Ratio = 0.01

Table D.30 BMP Pairwise Comparison Matrix – Relative TN Removal

BMP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Dry ED Basin (A)	***1.00***	7.00	0.50	7.00	7.00	7.00	2.00	2.00	2.00	0.50	0.50	0.50	0.50	7.00
Enhanced ED Basin (B)	0.14	***1.00***	0.11	1.00	1.00	1.00	0.20	0.20	0.20	0.11	0.11	0.11	0.11	1.00
Retention Basin (C)	2.00	9.00	***1.00***	9.00	9.00	9.00	4.00	4.00	4.00	1.00	1.00	1.00	1.00	9.00
Constructed Wetlands (D)	0.14	1.00	0.11	***1.00***	1.00	1.00	0.20	0.20	0.20	0.11	0.11	0.11	0.11	1.00
Vegetated WQ Swale (E)	0.14	1.00	0.11	1.00	***1.00***	1.00	0.20	0.20	0.20	0.11	0.11	0.11	0.11	1.00
Vegetated Filter Strip (F)	0.14	1.00	0.11	1.00	1.00	***1.00***	0.20	0.20	0.20	0.11	0.11	0.11	0.11	1.00
Infiltration Trench (G)	0.50	5.00	0.25	5.00	5.00	5.00	***1.00***	1.00	1.00	0.25	0.25	0.25	0.25	5.00
Infiltration Basin (H)	0.50	5.00	0.25	5.00	5.00	5.00	1.00	***1.00***	1.00	0.25	0.25	0.25	0.25	5.00
Porous Pavement (I)	0.50	5.00	0.25	5.00	5.00	5.00	1.00	1.00	***1.00***	0.25	0.25	0.25	0.25	5.00
Bioretention (J)	2.00	9.00	1.00	9.00	9.00	9.00	4.00	4.00	4.00	***1.00***	1.00	1.00	1.00	9.00
Sand Filters (K)	2.00	9.00	1.00	9.00	9.00	9.00	4.00	4.00	4.00	1.00	***1.00***	1.00	1.00	9.00
Vegetated Roof (L)	2.00	9.00	1.00	9.00	9.00	9.00	4.00	4.00	4.00	1.00	1.00	***1.00***	1.00	9.00
Rainwater Harvesting (M)	2.00	9.00	1.00	9.00	9.00	9.00	4.00	4.00	4.00	1.00	1.00	1.00	***1.00***	9.00
Manufactured BMPs (N)	0.14	1.00	0.11	1.00	1.00	1.00	0.20	0.20	0.20	0.11	0.11	0.11	0.11	***1.00***

BMP	Matrix Priority Vector
Retention Basin	0.1409
Bioretention	0.1409
Sand Filters	0.1409
Vegetated Roof	0.1409
Rainwater Harvesting	0.1409
Dry ED Basin	0.0829
Infiltration Trench	0.0489
Infiltration Basin	0.0489
Porous Pavement	0.0489
Enhanced ED Basin	0.0132
Constructed Wetlands	0.0132
Vegetated WQ Swale	0.0132
Vegetated Filter Strip	0.0132
Manufactured BMPs	0.0132

Consistency Ratio = 0.01

Appendix E. Tutorial – Virginia Tech BMP Decision Support Software (VT BMP DSS)

The Virginia Tech BMP Decision Support Software (*VT BMP DSS)*

This document provides a basic tutorial on the use of the Virginia Tech Stormwater BMP Decision Support Software. For expanded discussion of the methodology behind this software, users are referred to Virginia's Stormwater Impact Evaluation Project: Developing an Optimization Tool for Improved Site Development, Selection and Placement of Stormwater Runoff BMPs – Final Report to the EPA (Young, et al., 2008).

The Virginia Tech BMP Decision Support Software applies the Analytic Hierarchy Process (AHP) decision-making algorithm to assist in the selection of Best Management Practices (BMPs) for the treatment of stormwater runoff. This software should be treated as "beta" software, in the sense that no long-term testing has been performed.

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The following people contributed to development of this software.

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Software Development

This version of the *VT BMP DSS* was written in Visual Basic 2005 to run on the Microsoft .NET 2.0 Framework.[1] The software should be treated as "beta" software, in the sense that no long-term testing has been performed. It is possible that use of the software may result in unforeseen errors.

The software consists of an executable file (*.exe), which contains the user interface and all of the computational logic of the program. To function, the software depends on a data file (*.xml) which contains lists of BMPs, selection criteria, and BMP performance vectors. This data file was kept separate from the actual program in order to permit future revisions to the lists of BMPs, selection criteria, or the BMP performance vectors. Users of the program should not open or alter this XML file in any way, as this could compromise the accuracy of the software's results, and could result in the program ceasing to function.

The software is capable of launching a PDF help document provided that, upon installation of the program, the PDF is stored in the same directory as the program executable.

Installation

The software currently does not have a Windows Installer application. Installing the software on a computer consists of two steps: checking for the appropriate .Net framework, and copying the program files.

The first step is to make sure that the computer has the Microsoft .NET 2.0 Framework installed; one way to check this is to go to **Control Panel>Add or Remove Programs**, and look to see if Microsoft .NET Framework 2.0 is listed as being currently installed. If it is not installed, then the easiest way to bring the computer up to date is to visit the Windows Update website (http://windowsupdate.microsoft.com/) using Internet Explorer, and scan for downloadable updates and service packs. In general, most computers should already have the .NET 2.0 Framework installed, as it is a common requirement for many Windows programs. Questions about Windows Update should be referred to your system administrator.

The second step is to copy the executable file (*.exe), the data file (*.xml), and the help file (*.pdf) into a folder on the computer's hard drive. It is critical that the three files are stored in the same folder.

[1] The .Net framework provides a base class library and a common language runtime, which offer a variety of advantages over previous Windows application development methods.

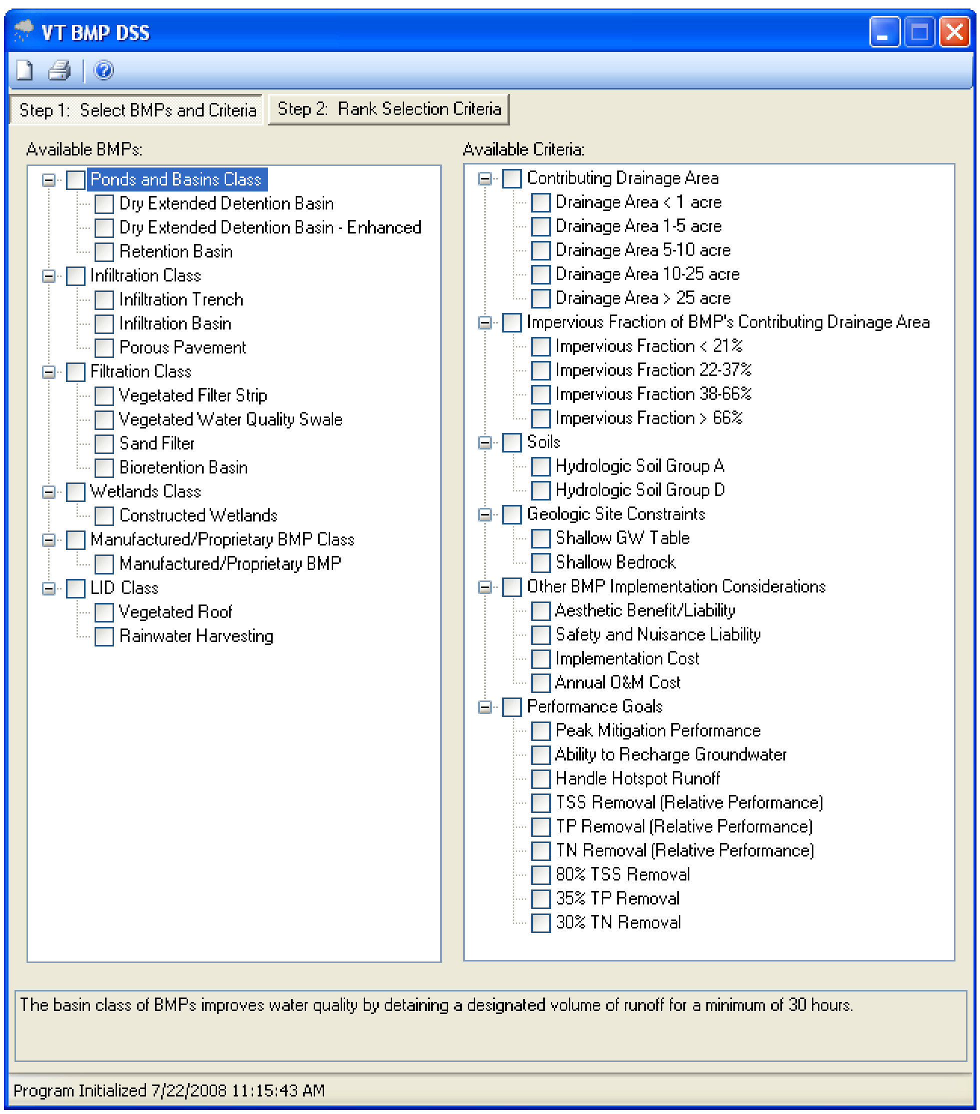
Getting Started

After installing the three separate files (*.exe, *.xml, and *.pdf) in a common folder, start the program by double-clicking the executable file.

If desired, users may also add a desktop shortcut by right-clicking on the executable file, and selecting **Send To>Desktop (create shortcut)**. Upon successfully creating a shortcut link, the following icon should appear on the desktop:

Double clicking this icon will initialize the program.

When the program initializes, users should see the following interface:



Starting a New BMP Selection Scenario

When the program is first started, all BMP alternatives and all selection criteria will be deselected. If, at any point during the application, the user wishes to return to this initial condition, simply click the **New** icon:

Upon clicking the **New** icon, users will be prompted to confirm your intent to reinitialize the program. Clicking "Yes" will deselect all BMP alternatives and selection criteria and also clear any previously completed criteria weighting.

Selecting BMPs for Consideration

In 1998, the Virginia Stormwater Management (SWM) regulations (4 VAC 3-20-10 et. seq.) were amended as a result of the evolutionary nature of effective stormwater management. One result of the amendments was the 1999 publication of the Virginia Stormwater Management Handbook, (DCR, 1999). The Handbook provides technical guidance for compliance with State SWM regulations and identifies each of the structural BMPs defined in section 4 VAC 3-20-10 of the Virginia Code. These BMPs are shown as follows:

Structural BMPs Recognized in the
Virginia Stormwater Management Regulations

Dry Extended Detention Basins	Porous Pavement
Extended Detention Basins - Enhanced	Bio-Retention
Retention Basins	Sand Filters
Constructed Wetlands	Grassed Swales
Infiltration Basins	Vegetated Filter Strips
Infiltration Trenches	Manufactured BMP Systems

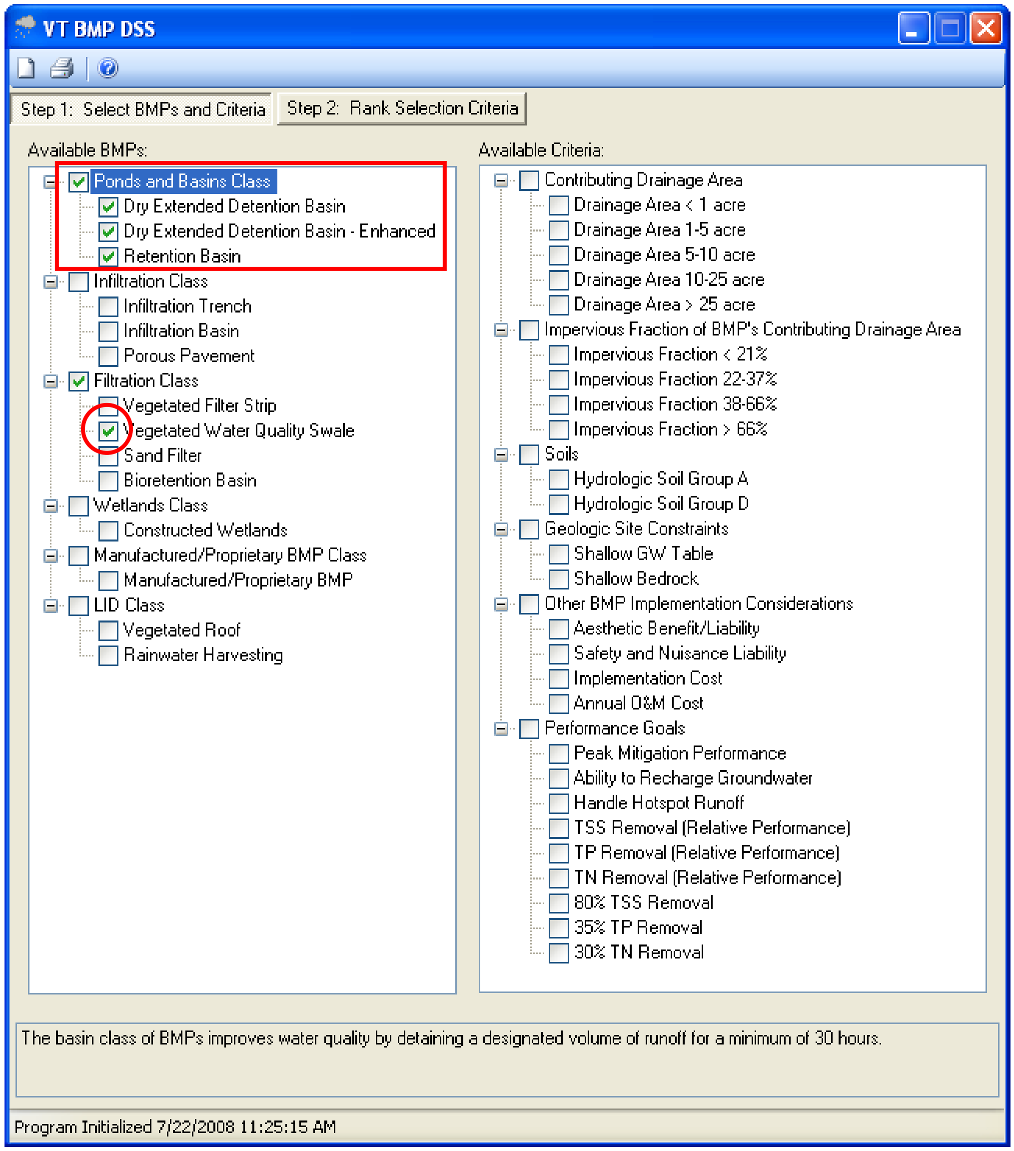
The Handbook states that additional BMPs, beyond those specifically named, may be implemented "*at the discretion of the local program administrator or the Department.*"

The *VT BMP DSS* allows the consideration of a total of 14 different BMP options for any given runoff management scenario. Comprising this list are those structural BMPs recognized by the State of Virginia Stormwater Management Program, as well as vegetated roofs and rainwater harvesting systems.

The available BMP options are grouped into different classes comprised of BMPs exhibiting similar physical processes. Upon initialization of the program all BMP options will, by default, be deselected. Users may choose which BMPs are to be included in the selection scenario by clicking the box beside each individual BMP, or they may select an entire class of BMP by clicking in the box beside the class name.

Clicking a class selects all BMPs within that class

Clicking an individual BMP type selects only that BMP



The fundamental objective in applying the AHP algorithm to the BMP selection process is to consider a wide array of BMP alternatives, and from those alternatives select the single practice that best simultaneously satisfies all user-chosen selection criteria. Therefore, in most applications it is advisable to consider all 14 BMP options. However, there may be instances when the user wishes to preclude from consideration certain BMPs or classes of BMP. For example, consider a stormwater management need arising from the construction of a road. In such a scenario, the user may choose to omit vegetated roofs from being included in the selection process.

Available BMP Selection Criteria

When attempting to choose a single practice from a pool of competing BMP options, numerous factors influence the decision making process. Most of these individual factors can be categorized as either a functional goal or a physical site constraint. Functional goals include reducing the peak rate of runoff from a site and the removal of targeted pollutants from the runoff. Physical site constraints encompass those factors that may preclude the use of certain BMPs or classes of BMPs. These constraints include the practice's contributing drainage area, site soil type(s), and other geologic factors. Yet other criteria exist that are neither a functional goal nor a physical site constraint. These criteria include the practice's aesthetic benefit or liability, the implementation and maintenance costs of the practice, and any public safety issues associated with the practice.

The *VT BMP DSS* allows the user to introduce up to a total of 16 different criteria to a given BMP selection scenario. The following is a description of the available selection criteria and how each specifically relates to BMP selection.

Contributing Drainage Area (CDA) Criterion

The first physical site constraint available as a BMP selection criterion is contributing drainage area (CDA). The installation of most BMPs is influenced greatly by the total area contributing runoff to the practice. For example, small, source control practices such as bioretention cells are generally not recommended for the treatment of runoff from areas greater than 5 acres. By contrast, practices such as retention ponds and constructed wetlands require much larger drainage areas capable of providing baseflow to maintain their permanent pools. Regardless, it is essential that the BMP chosen for a particular application is adequately suited to receive the runoff from its CDA. During a BMP selection scenario, the *VT BMP DSS* allows its user to choose from four CDA ranges: less than 1 acre, 5-10 acres, 10-25 acres, and greater than 25 acres. These CDA ranges are mutually exclusive, meaning that only one can be chosen for a given BMP selection scenario.

Impervious Fraction Criterion

Described in Chapter 2 of the Virginia Stormwater Management Handbook (DCR, 1999), one approach to BMP selection is defined as "technology-based." This approach requires the designer to compute the amount of new impervious area arising from a land development project, and then make the BMP selection on the basis of the overall impervious fraction of the BMP's contributing drainage shed. This approach does not presume a specific pollutant removal target or efficiency and therefore contrasts a "performance-based" BMP selection procedure. During a BMP selection scenario, the *VT BMP DSS* allows its user to choose from four impervious fraction ranges: less than 21%, 21-37%, 38-66%, and greater than 66%. The impervious fraction ranges are mutually exclusive, meaning that only one can be chosen for a given BMP selection scenario.

Soils Criterion

Hydrologic soil group (HSG) A consists of sand, loamy sand, or sandy loam types of soils. These soils exhibit low runoff potential and high infiltration rates even when thoroughly wetted. The presence of HSG A on a site restricts the BMP options from which a designer can choose. Generally, this soil group exhibits infiltration rates beyond what is recommended for infiltration practices. Similarly, these excessively high infiltration rates may present difficulties in achieving acceptable hydraulic residence times in detention facilities, vegetated swales and filters, and wetlands. In the absence of synthetic liners, the presence of HSG A generally precludes the use of these practices.

HSG D consists primarily of clay loam, silty clay loam, sandy clay, silty clay, or clay. This HSG has the highest runoff potential among all soil groups. Characteristics of HSG D are high swelling potential and very low infiltration rates when thoroughly wetted. In terms of surface runoff potential, HSG D behaves analogously to an impervious surface. Typically, soils classified as HSG D do not exhibit the minimum infiltration rates required of infiltration practices. Consequently, the implementation of infiltration practices, and those practices exhibiting similar physical processes, is restricted in the presence of these soil groups. The presence of HSG D is considered beneficial to the implementation of basin practices because it significantly reduces the undesired exfiltration loss of detained runoff.

HSG B and C are not available as selection criteria in the *VT BMP DSS* because their presence on a site does not typically preclude the installation of any BMPs.

The soil types are mutually exclusive, meaning that only one can be chosen for a given BMP selection scenario.

Geologic Site Constraints

The presence of shallow or seasonally shallow groundwater depths (typically defined as less than two feet below a site's finished grade) usually precludes the use of infiltration practices. In addition to infiltration basins and trenches, this restriction extends to bioretention basins and porous pavement. Practices which infiltrate little or no runoff into the subsurface are favored as treatment options in the presence of a shallow groundwater table. These practices include grassed swales, vegetated filter strips, manufactured BMP systems, and rainwater harvesting systems. Retention ponds and constructed wetlands may be designed to utilize the presence of shallow groundwater as a source of baseflow, and thus such a site characteristic is often considered beneficial to their implementation.

Much like the presence of a shallow groundwater table, the presence of shallow bedrock depths on a site greatly restricts the BMP options at the designer's disposal. Infiltration practices and other BMPs which operate by employing subsurface filter beds are generally prohibited. As in the case of shallow groundwater depths, practices which infiltrate little or no runoff into the subsurface are favored as treatment options. However, unlike the presence of a shallow groundwater table, the presence of shallow bedrock depths provides no benefit for the implementation of retention ponds and constructed wetlands, and in fact may preclude their installation without a liner to minimize infiltration.

Other BMP Implementation Considerations
The topography of a site upon which a BMP installation is proposed is an important factor in choosing the appropriate practice. BMPs employing underground reservoirs and/or infiltration beds, grassed swales, and vegetated filter strips are restricted to site slopes of less than 20 percent. When the site of interest exhibits steep slopes, users of the *VT BMP DSS* can introduce this as a BMP selection criterion.

Stormwater hotspots are defined as generating sites from which the runoff exhibits pollutant concentrations greatly in excess of those typically found in stormwater. More often than not, this definition is further extended to reflect the presence of hydrocarbons in the runoff. The Maryland Department of the Environment (MDE), 2000, cites all BMPs capable of accepting hotspot runoff, with the exception of infiltration practices and wet vegetative water quality swales. The *VT BMP DSS* permits its user to consider the presence of hotspot runoff in the BMP selection process.

When the proposed installation is in a high profile location, the public perception of a BMP may become an essential selection consideration. Some BMPs, notably dry detention basins, offer very little potential to provide aesthetic benefit to a site and, in fact, may be an aesthetic liability. Other BMPs, while having little potential to provide aesthetic benefit to a site, can be designed to minimize their obtrusiveness. Still other BMPs, such as retention basins and constructed wetlands, can be designed such that they become a desirable site amenity capable of providing recreational opportunities and wildlife habitat. The aesthetic benefit or liability of the various BMP options is available as a selection criterion in the *VT BMP DSS*.

Some BMPs have inherent public safety issues associated with their installation. The most notable safety concern arising from BMP implementation occurs when the practice exhibits a permanent pool, such as the case with enhanced detention basins, retention basins, and constructed stormwater wetlands. Practices exhibiting a permanent pool also have the potential to become marshy and stagnant, resulting in ideal habitat for mosquitoes and other disease carrying vectors. The *VT BMP DSS* permits its user to consider public safety during the BMP selection process.

BMP construction and maintenance costs vary considerably on a site-by-site basis. With any number of physical, site-specific parameters influencing the size and design of an individual BMP it becomes impractical, if not impossible to attempt to confidently predict all of the material and labor costs associated with a given BMP type. In addition to the aforementioned physical site factors, there are issues such as land acquisition costs, contractor availability, seasonal impacts on construction activities, and non-essential BMP amenities that must be considered when preparing a detailed cost estimate for a proposed BMP installation. All of these factors, as well as many more, vary immensely both geographically and climatically. The *VT BMP DSS* allows its user to consider both installation and annual maintenance costs during the BMP selection process. However, these cost comparisons are only relative comparisons among the competing BMP options and are not intended to replace the need for detailed construction cost estimates, nor do they address unforeseen, non-routine maintenance activities.

Performance Goals

Historically, the focus of stormwater management has been to reduce the peak rate of runoff from a developed site to pre-development (or other acceptable) levels. Providing flood control in the form of peak rate attenuation is still a highly prioritized goal in most stormwater management endeavors. In the state of Virginia, this functional stormwater management goal is required by "Minimum Standard 19"of the Virginia Erosion and Sediment Control Regulations (Section 4VAC50-30-40). The *VT BMP DSS* enables its user to consider runoff rate attenuation capability when choosing among competing BMP options.

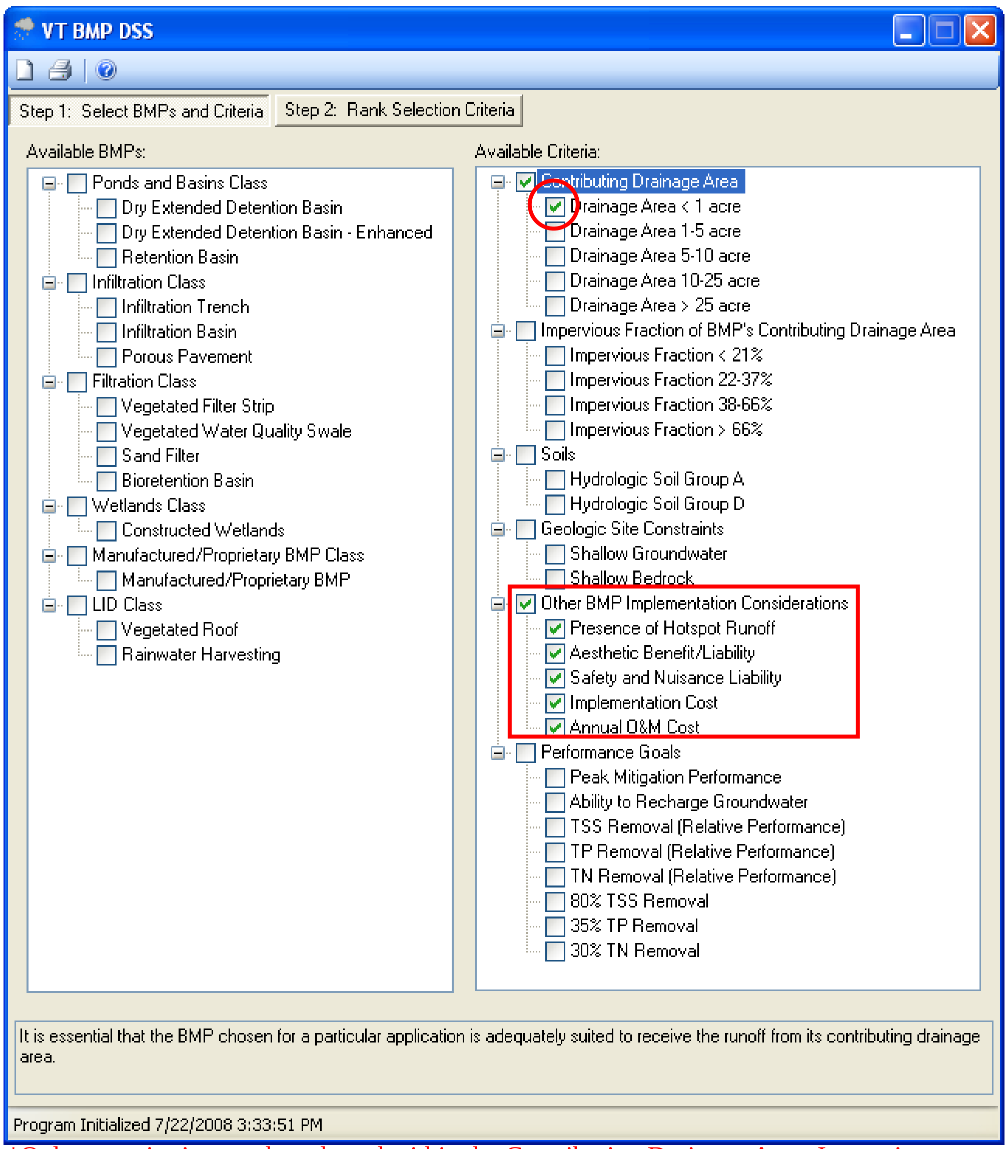
Groundwater recharge is the hydrologic process by which precipitation migrates downward from the land surface, eventually entering the groundwater table. This natural process is critical to the long-term sustainability of groundwater supplies where aquifer extraction rates must not exceed recharge rates. Groundwater recharge is often impeded by land use intensification and the resulting increase in imperviousness. Numerous locations in the United States now require land development projects to provide some minimum level of post-development groundwater recharge through the use of BMPs. The *VT BMP DSS* enables its user to consider groundwater recharge capability when choosing among competing BMP options.

The runoff from urbanized areas carries a variety of soluble and particulate pollutants, typically at levels much greater than those observed in the runoff from undisturbed, natural spaces. Many of these pollutants pose significant threats to the aquatic ecosystems to which they are introduced. The state of Virginia defines phosphorus as its "keystone pollutant." Phosphorus and other nutrients such as nitrogen are of concern because of their potential to cause eutrophication of the water bodies to which they are introduced. Notable levels of suspended sediment are also found in the runoff generated from impervious surfaces, managed lawns, and sites whose surfaces have been denuded through construction processes.

Within the *VT BMP DSS*, users can choose to introduce the pollutant removal performance of competing BMP alternatives as a selection criterion. For a given pollutant, this criterion can be expressed as a "threshold" pollutant removal efficiency (80% for TSS, 35% for TP, and 30% for TN) or as simply the relative pollutant removal efficiency of a given BMP when compared to other BMP options. When the threshold pollutant removal criteria are employed in the algorithm, BMPs are rigidly evaluated on their ability to achieve the threshold values. All BMPs capable of achieving the explicitly stated removal efficiency are ranked equally, while those practices unable to attain the expressed removal efficiency are given very low preference. When the relative pollutant removal criteria are selected, BMPs are ranked *relatively* against other competing BMP alternatives in terms of their ability to remove the pollutant of interest from stormwater runoff.

Choosing Influential Selection Criteria

The *VT BMP DSS* allows for the introduction of up to 16 different influential criteria in a given BMP selection scenario. The available individual criteria are grouped into six broad categories of criteria. Upon initialization of the program all selection criteria will, by default, be deselected. Users may choose which criteria to include in a BMP selection scenario by clicking the box beside each individual criterion, or by selecting an entire category of criteria. It is noted that the contributing drainage area, impervious fraction, and soils categories are mutually exclusive, meaning that only one criterion can be selected within each category.



Clicking an individual criterion selects only that criterion

Clicking a category selects all criteria within that category*

*Only one criterion can be selected within the Contributing Drainage Area, Impervious Fraction, and Soils Categories

User-Weighting of the Influential Selection Criteria

Upon identification of those influential criteria that are critical to the BMP selection process, the user must qualitatively define the relative importance of each criterion. This process is inherently subjective, and the relative importance of each individual criterion may be viewed differently by different users. However, certain guidelines do exist that will improve the reliability of results obtained from the *VT BMP DSS*.

First, it is recommended that any physical site constraints be given the highest degree of influence during the BMP selection process. The rationale behind this recommendation lies in the fact that the chosen BMP *must* be suited to the physical constraints of the site upon which it is to be installed. For example, consider a site whose in situ soils are primarily HSG D. These soils will not typically exhibit the minimum infiltration rate required for installation of the infiltration class of BMP. Consequently, if this physical site constraint was omitted or not prioritized during BMP selection, the algorithm could conceivably rank an infiltration BMP very favorably. Such a situation would require the user to manually override the BMP rankings obtained from the algorithm.

One possible exception to the inclusion and prioritization of physical site constraints is the Contributing Drainage Area (CDA) criterion. When stormwater management options are being evaluated at the planning stage of development, the user may wish to omit this criterion completely. Doing so will provide a ranking of candidate BMPs that is not influenced or limited by CDA, but that presumably meets other physical site constraints and functional goals.. This will allow the design engineer to approach runoff management in a distributed manner, with the site's grading being manipulated to ensure that the drainage area to the chosen BMP(s) does not exceed that which the BMP can accommodate. This situation contrasts application of the *VT BMP DSS* during the design stage of development when site grading is completed and the location of the proposed BMP has been identified. In this situation, the CDA to the BMP will be known, and the CDA criterion should be included and emphasized during the BMP selection process.

As with physical site constraints, it is generally advisable to provide any regulatory, or functional stormwater management objectives with a great deal of influence during the BMP selection process. More often than not, particularly on land development projects, the driving factor behind a BMP installation is meeting the stormwater management requirements imposed by the local review authority or the State. These regulatory requirements may include flood control in the form of peak runoff rate attenuation, providing groundwater recharge, or a reduction in pollutant loads found in the runoff. If a regulatory requirement, such as peak runoff rate reduction, was omitted or deprioritized during the BMP selection process, the algorithm may rank a particular BMP very favorably when, in reality, that BMP is not be capable of providing any runoff rate reduction.

Influential BMP selection criteria that are not categorized as a physical site constraint or a regulatory objective can be given the degree of influence deemed appropriate by the individual user or stakeholder group.

Upon qualitatively assessing each of the chosen selection criteria, the user may express these assessments in the *VT BMP DSS* by one of two entry methods – the Wizard method or by the manual Pairwise Comparison method. In order to ensure perfect consistency among the criteria weightings, the Wizard is the recommended method of criteria weighting. However, the Pairwise Comparison also yields reliable results, and more closely adheres to the AHP's foundational methodology.

Executing the Algorithm – Wizard Method of Criteria Ranking

The following example demonstrates the criteria ranking procedure by the Wizard method.

Consider the following, hypothetical stormwater runoff management scenario:

- An existing heavy equipment maintenance yard is releasing untreated runoff
- Runoff from the yard is believed to contain hydrocarbons (hotspot runoff)
- The total area discharging the untreated runoff is 0.75 acres
- The following pollutant removal targets are desired through installation of the BMP
    - 80% removal of total suspended sediment (TSS)
    - 35% removal of total phosphorus (TP)
    - 30% removal of total nitrogen (TN)
- The BMP installation will be in a high profile location visible to a neighboring residential neighborhood.
    - The chosen BMP should, if possible, provide aesthetic benefit
    - Public safety should be considered during selection of the BMP

Step 1. Qualitatively Assess the Influential Selection Criteria

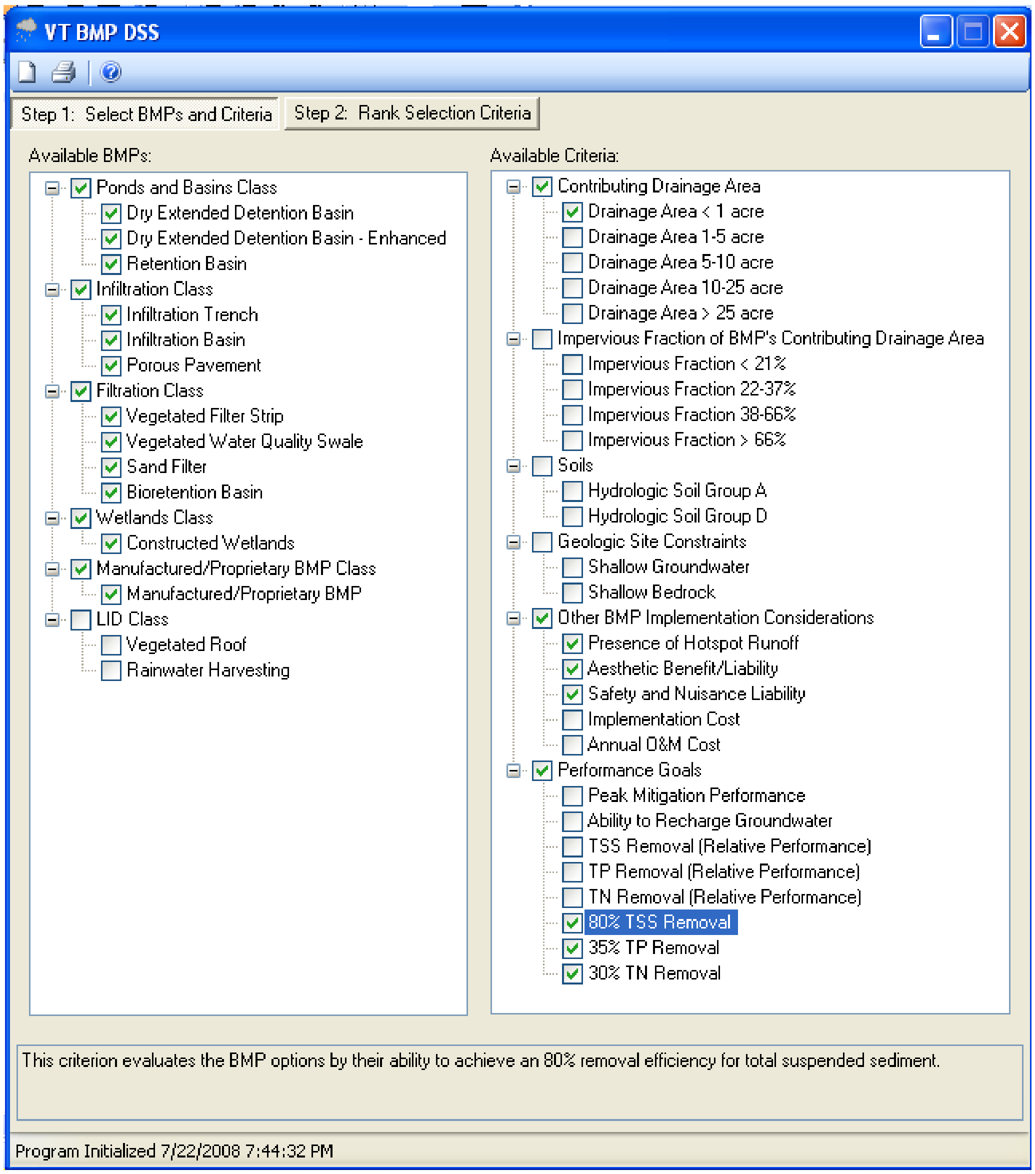
First, the user must qualitatively assess the relative importance of each of the identified influential selection criteria. In this example we will place the highest degree of influence on the presence of hotspot runoff and the three pollutant removal objectives. These four criteria will be weighted equally with one another, but assigned greater influence than the remaining selection criteria.

Aesthetic considerations and public safety concerns will be weighted equally with one another, but granted slightly less influence than the hotspot runoff and pollutant removal criteria. This qualitative assessment will enable the algorithm to compare and rank competing BMP alternatives in terms of their ability to provide aesthetic benefit while minimizing public safety concerns.

Finally, the least amount of influence will be given to the contributing drainage area criterion. Ideally, we would like to choose a BMP that is specifically targeted to a very small drainage shed, such as the 0.75 acres from which runoff is to be treated. However, achieving this objective should not compromise the pollutant removal objectives or any of the other criteria deemed more critical in this BMP selection scenario.

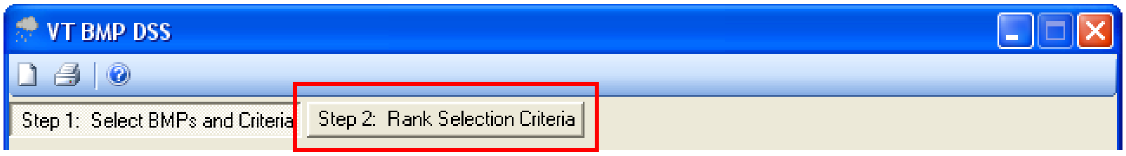
Step 2. Select the BMPs and Selection Criteria for Inclusion

Upon launching the *VT BMP DSS*, the user must choose which BMPs and which criteria to consider in the selection scenario. In this example, we will remove vegetated roofs and rainwater harvesting from consideration, as we are seeking to treat runoff from an existing maintenance yard. The previously identified selection criteria should be chosen, as shown in the following figure.

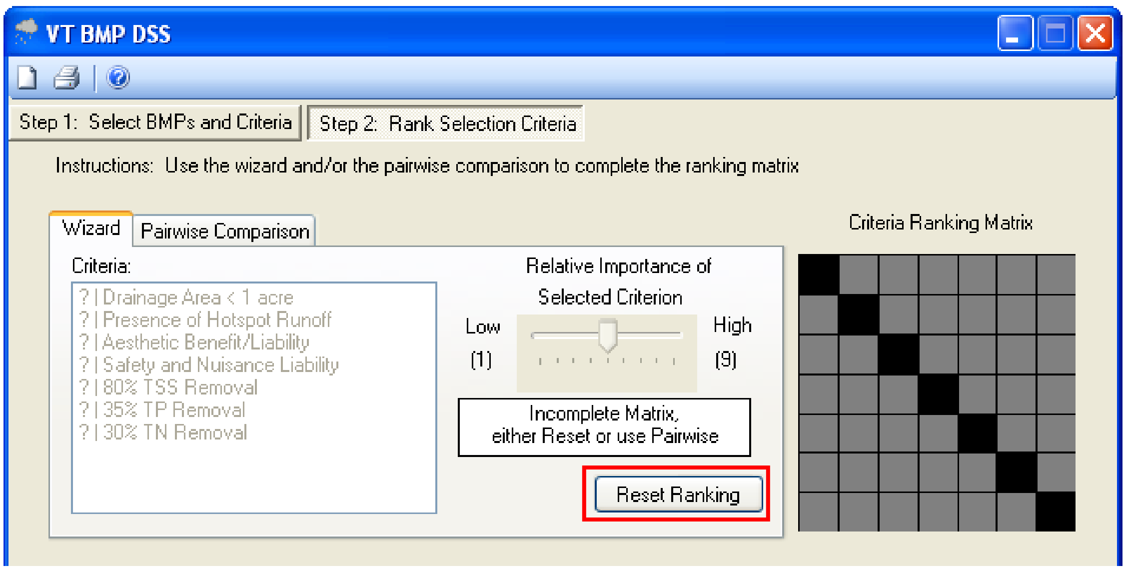


Step 3. Rank the Chosen Selection Criteria

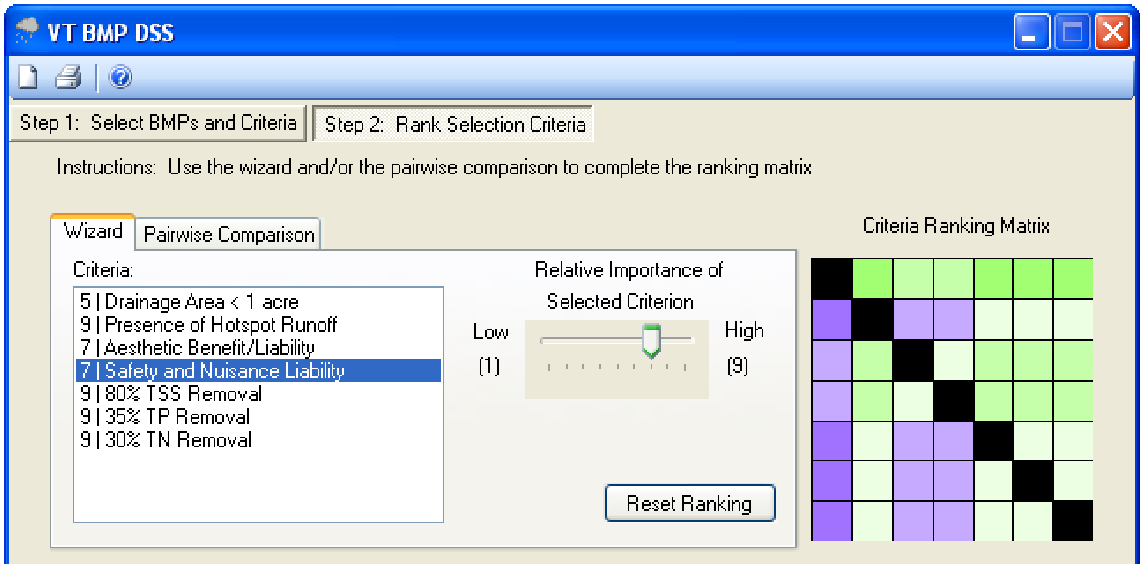
Next, the user should click the tab called "Step 2: Rank Selection Criteria."



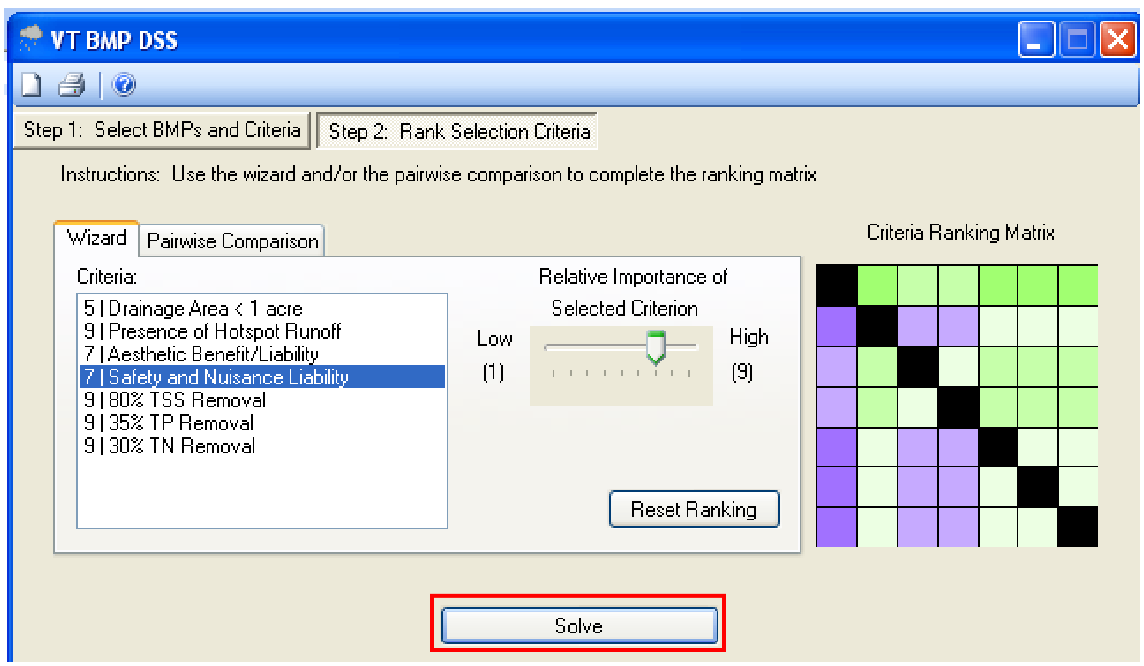
The user will then see the following interface. By default, the Wizard entry method will be selected. To begin ranking the criteria, click the "Reset Ranking" tab.



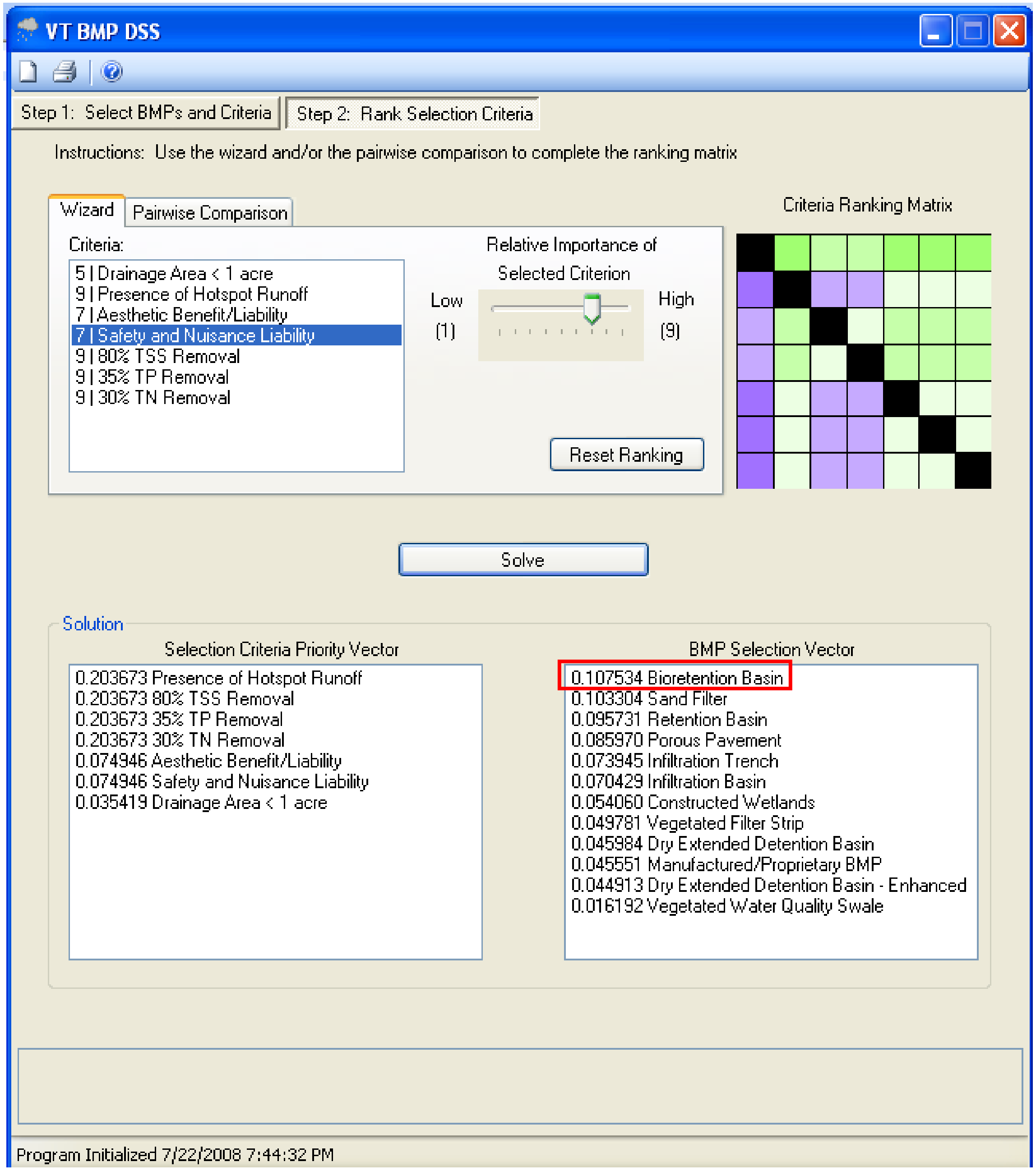
Once the criteria rankings are reset, each criteria will, by default, be assigned a relative ranking of 9 (highest degree of influence). To adjust the default rankings, the user must click on the criterion of interest and adjust the degree of influence by using the slider. This process is repeated until each criterion is ranked in agreement with the qualitative criteria assessments made in Step 1. Reflecting these assessments, the following figure shows the chosen criteria and their respective degree of influence in the BMP selection.



Next, the user clicks the "Solve" tab.



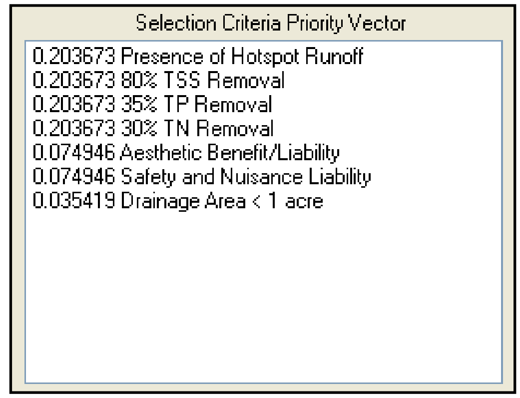
Upon clicking the "Solve" tab, the algorithm is executed and the BMP rankings are computed.



The computed results indicate that a bioretention basin is the BMP that best simultaneously satisfies each of the user-chosen and user-ranked criteria.

Step 4. Evaluate the Results

The final step is to scrutinize the results. First, the user should examine the "Selection Criteria Priority Vector." This vector expresses, quantitatively, the qualitative assessments made by the operator in Step 1.



Examining the "Selection Criteria Priority Vector" for this example reveals that the highest degree of influence was given to the presence of hotspot runoff and pollutant removal criteria. Furthermore, as desired by the user, these criteria are ranked equally with each other. Aesthetic benefit and public safety concerns are, again per user assessment, ranked equally with one another but given less influence than the hotspot runoff and pollutant removal criteria. Finally, as desired by the user, the contributing drainage area criterion is given the lowest degree of influence. Examination of this vector indicates that the qualitative user assessments of the influential selection criteria were suitably depicted quantitatively by the algorithm.

It is important to note that the AHP algorithm attempts to simultaneously satisfy all user-chosen weighted criteria. In attempting to do so, it is entirely possible that an individual criterion may be violated. Consequently, the user should critically scrutinize the results delivered by the algorithm. In this scenario, the algorithm ranked a bioretention basin as the BMP best suited to achieving the runoff management objectives previously described. The following is an evaluation of the reliability of this ranking.

Selection Criterion	Bioretention Basin Characteristics
80% Removal of TSS	Anticipated 86% Removal Efficiency*
35% Removal of TP	Anticipated 59% Removal Efficiency*
30% Removal of TN	Anticipated 38% Removal Efficiency*
Ability to Receive Hotspot Runoff	Yes
Aesthetic Benefit	Adds pervious cover to an otherwise impervious site, also provides water quality improvement very unobtrusively
Safety Concerns	Minimal safety concerns - 6" maximum ponding depth
Contributing Drainage Area < 1ac.	Ideally suited to very small drainage sheds

*Reflects values obtained during ongoing research efforts at Virginia Tech

<u>Executing the Algorithm – Pairwise Comparison Method of Criteria Ranking</u>

The following example demonstrates the criteria ranking procedure by the Pairwise Comparison method. The runoff management scenario described in this example is identical to that used in the example describing use of the criteria weighting Wizard.

Consider the following, hypothetical stormwater runoff management scenario:

- An existing heavy equipment maintenance yard is releasing untreated runoff
- Runoff from the yard is believed to contain hydrocarbons (hotspot runoff)
- The total area discharging the untreated runoff is 0.75 acres

- The following pollutant removal targets are desired through installation of the BMP
    - 80% removal of total suspended sediment (TSS)
    - 35% removal of total phosphorus (TP)
    - 30% removal of total nitrogen (TN)

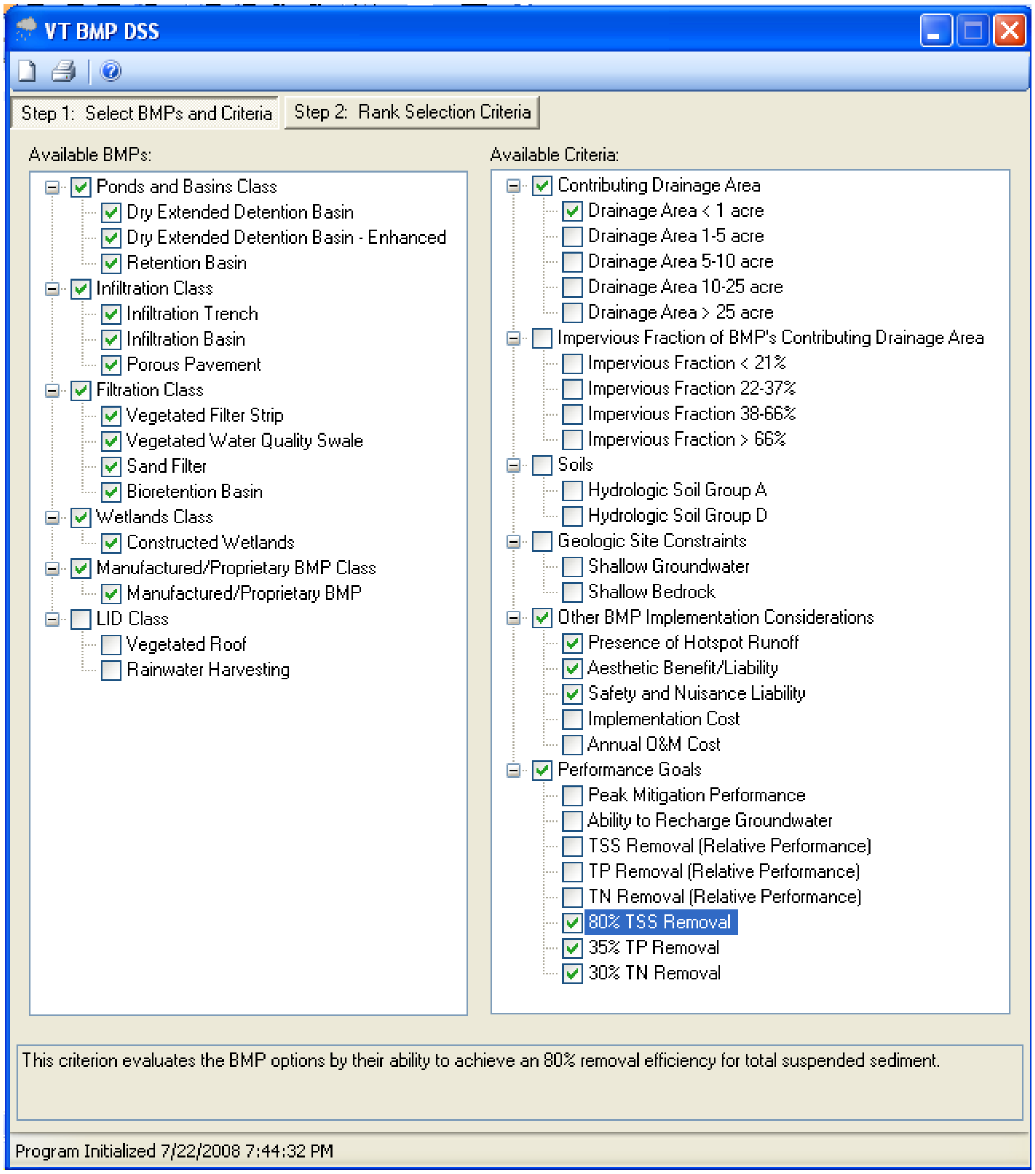
- The BMP installation will be in a high profile location visible to a neighboring residential neighborhood.
    - The chosen BMP should, if possible, provide aesthetic benefit
    - Public safety should be considered during selection of the BMP

Step 1. Qualitatively Assess the Influential Selection Criteria
First, the user must qualitatively assess the relative importance of each of the identified influential selection criteria. In this example we will place the highest degree of influence on the presence of hotspot runoff and the three pollutant removal objectives. These four criteria will be weighted equally with one another, but assigned greater influence than the remaining selection criteria.

Aesthetic considerations and public safety concerns will be weighted equally with one another, but granted slightly less influence than the hotspot runoff and pollutant removal criteria. This qualitative assessment will enable the algorithm to compare and rank competing BMP alternatives in terms of their ability to provide aesthetic benefit while minimizing public safety concerns.

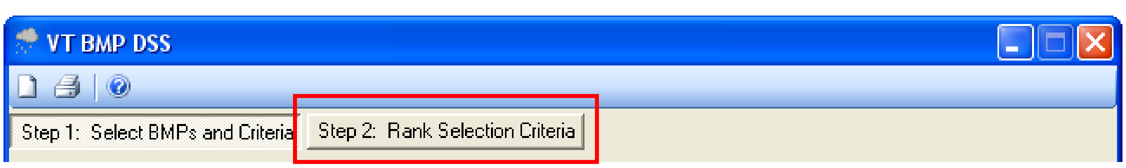
Finally, the least amount of influence will be given to the contributing drainage area criterion. Ideally, we would like to choose a BMP that is specifically targeted to a very small drainage shed, such as the 0.75 acres from which runoff is to be treated. However, achieving this objective should not compromise the pollutant removal objectives or any of the other criteria deemed more critical in this BMP selection scenario.

Step 2. Select the BMPs and Selection Criteria for Inclusion
Upon launching the *VT BMP DSS*, the user must choose which BMPs and which criteria to consider in the selection scenario. In this example, we will remove vegetated roofs and rainwater harvesting from consideration, as we are seeking to treat runoff from an existing maintenance yard. The previously identified selection criteria should be chosen, as shown in the following figure.

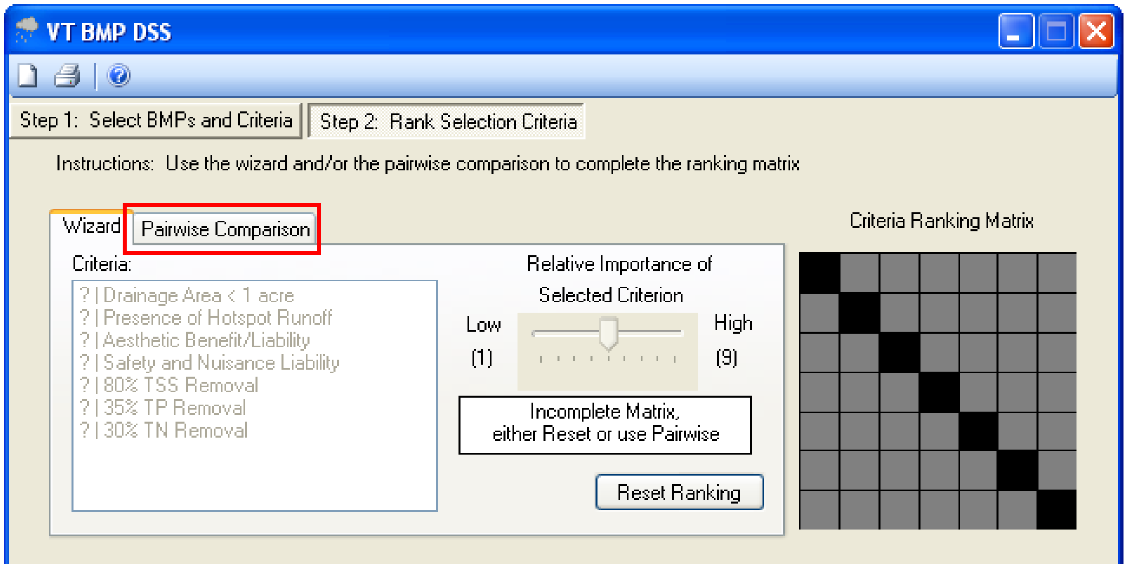


__Step 3. Rank the Chosen Selection Criteria__

Next, the user should click the tab called "Step 2: Rank Selection Criteria."

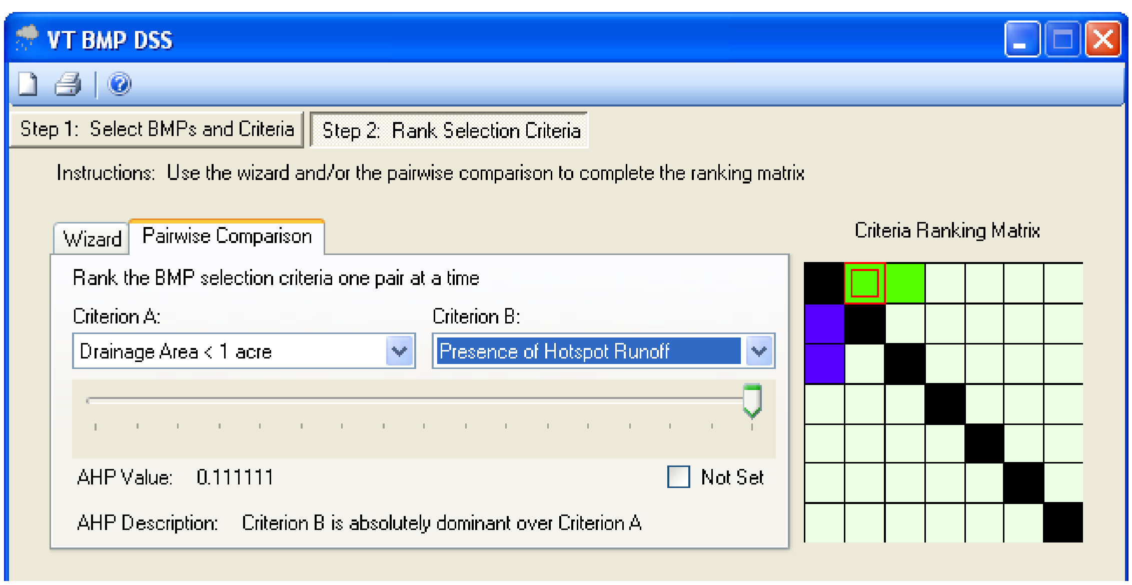


The user will then see the following interface. By default, the Wizard entry method will be selected. To begin ranking the criteria by the Pairwise Comparison method, click that tab.

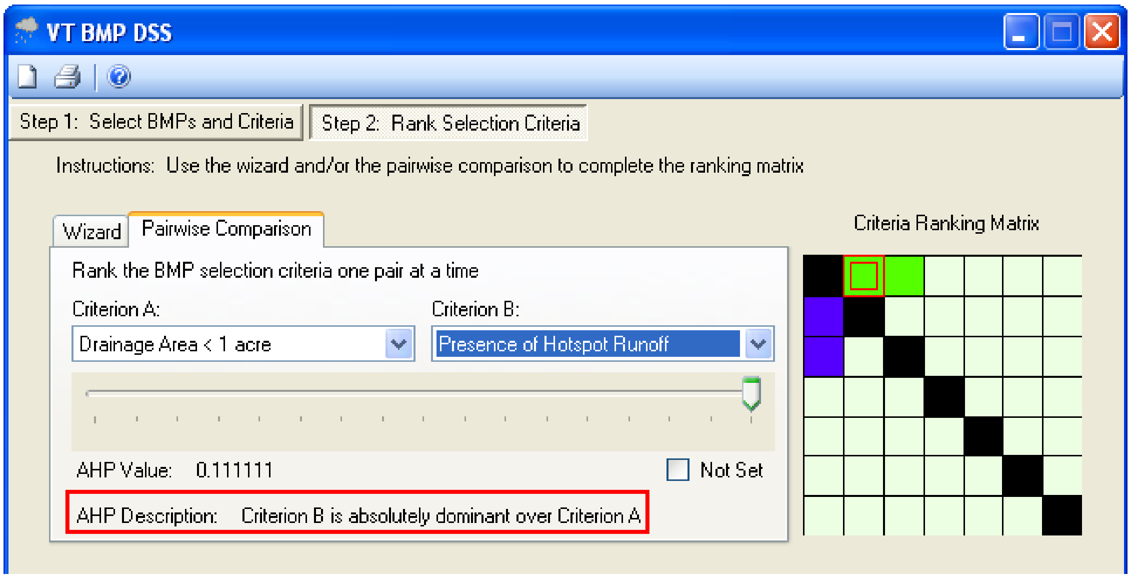


The Pairwise Comparison method of criteria ranking forces the user to compare and evaluate the importance of each criterion against every other criterion on a "cell-by-cell" basis. This method contrasts the Wizard method of entry, where the user simply defines the overall importance of each criterion and the software applies an algorithm to create the criterion-by-criterion comparisons.

Upon clicking the "Pairwise Comparison" tab, the user will see the following interface.

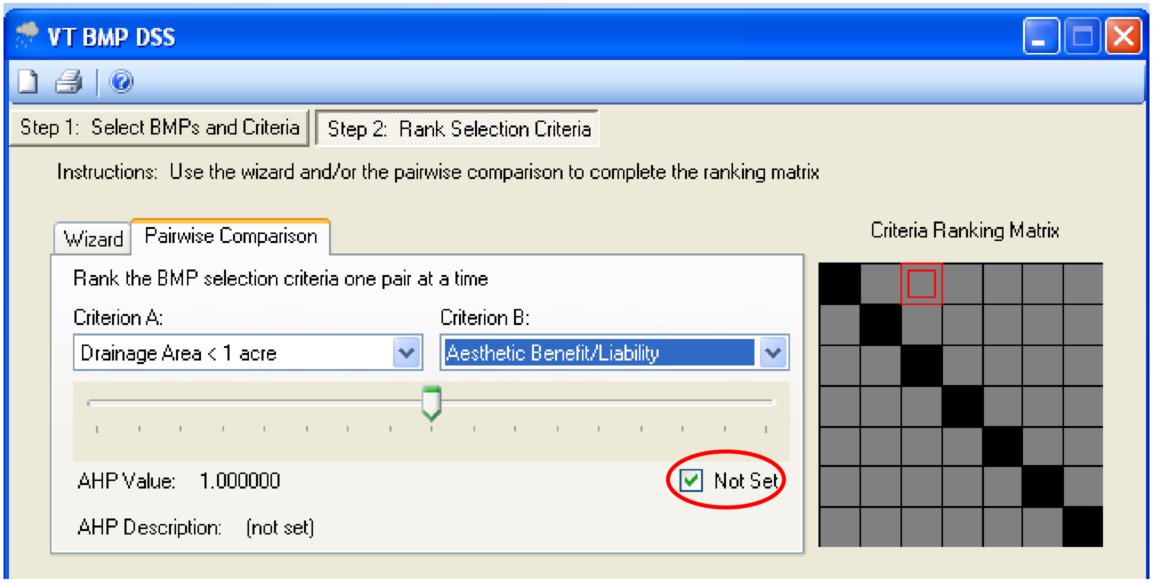


At this point, the user can begin making relative comparisons among the chosen criteria by using the slider to establish which criterion is more important, and to what degree. In the example shown, contributing drainage area (Criterion "A") is being compared against the presence of hotspot runoff (Criterion B). As expressed in Step 1, the hotspot runoff criterion is of absolute importance to the BMP selection, along with achieving the pollutant removal objectives. The contributing drainage area criterion, by contrast, was qualitatively determined to be the least influential of any criterion. Therefore, as shown, the slider has been moved to the extreme end of the scale under the criterion deemed most important. Note that the "AHP Description" is dynamic and expresses to the user which criterion is being emphasized and to what degree.



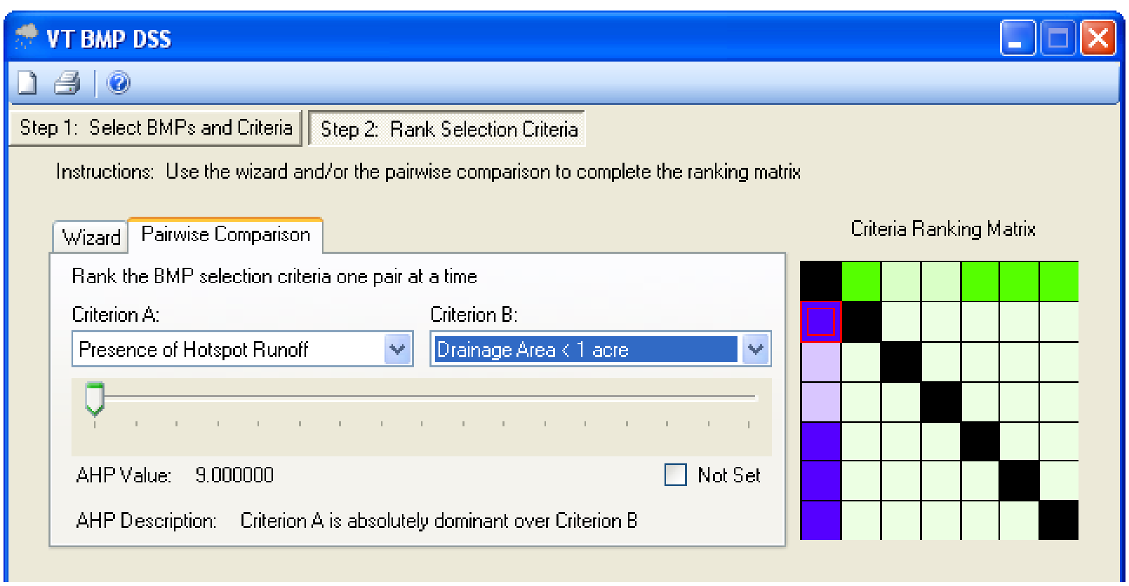
The "AHP Description" is dynamic and, as the slider is being adjusted, expresses to the user which criterion is being emphasized and to what degree.

The user continues to cycle through all of the criteria until a comparison has been made of each criterion against every other criterion. As shown in the following figure, the operator can easily track whether a comparison has already been made by viewing the status of the "Not Set" box. When a comparison has been made by adjusting the slider, this box will be deselected. If a user wishes to express that two criteria are of equal importance, they may manually deselect this box and leave the slider in the middle position.



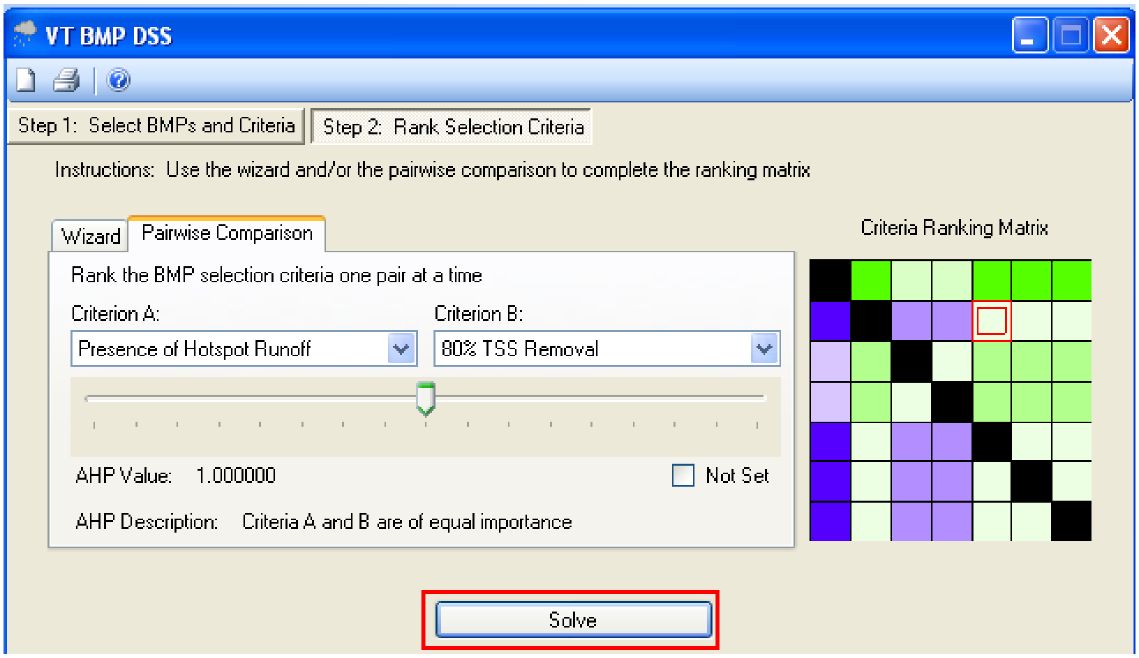
The "Not Set" box indicates to the user whether or not a pairwise comparison has already been made for the two criteria.

As the user continues to cycle through the pairwise comparisons, it is likely that they will encounter redundant comparisons, such as the one shown in the following figure.

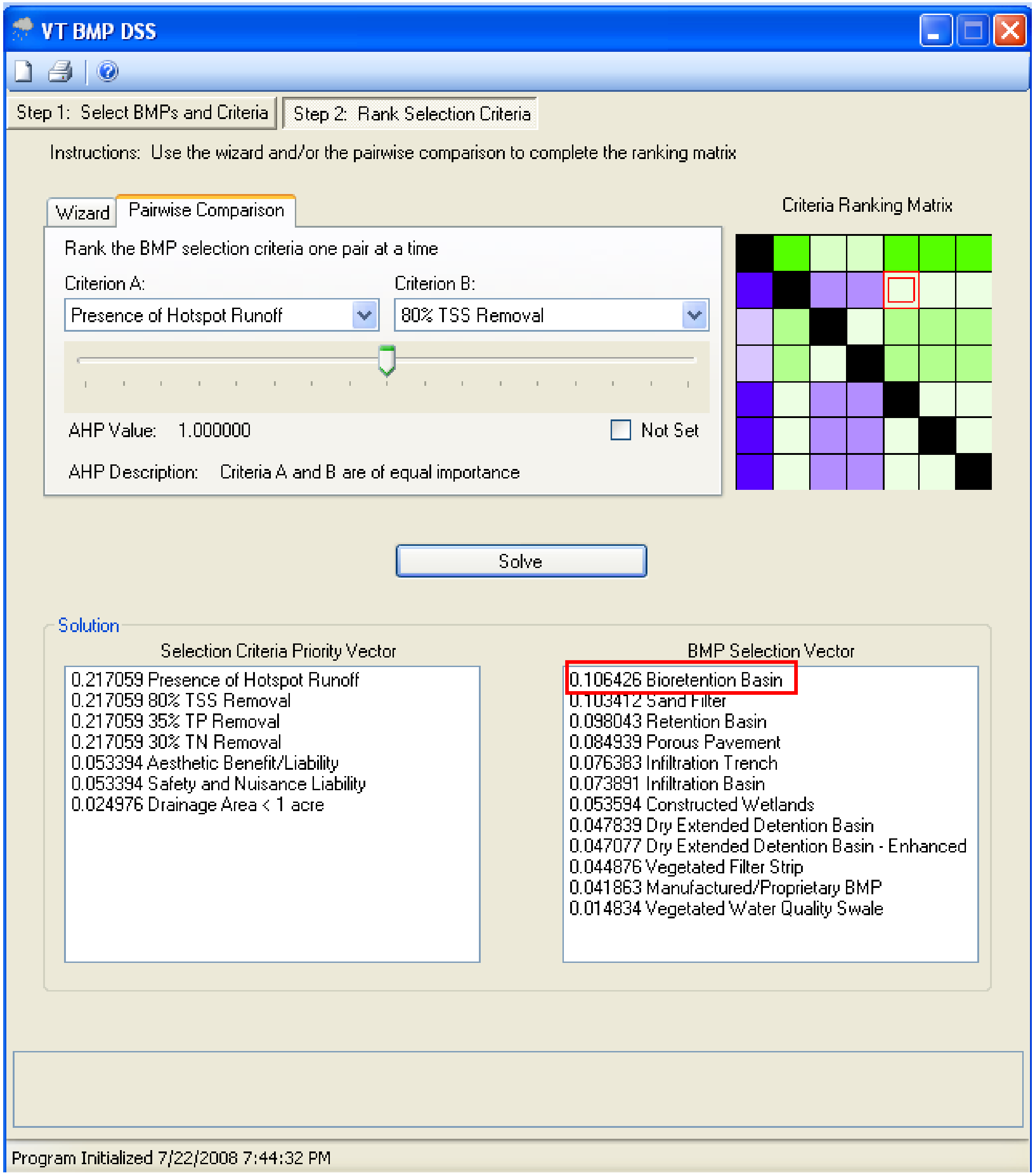


In this example, a pairwise comparison has already been made between these two criteria, but initially it was made with the drainage area as "Criterion A" and hotspot runoff as "Criterion B." Note that, despite the reversal of the two criteria, the influential preference is still given to the hotspot runoff criterion. The software is dynamic and once a comparison is made it is stored until a solution is computed or the matrix values are reset. When the user encounters a comparison that has previously been expressed, they may simply proceed to the next comparison.

The user should continue to cycle through all of the criteria until they have expressed a pairwise comparison of every criterion against every other criterion. Once these comparisons have been made and are reflective of the qualitative assessments made during Step 1, the user clicks the "Solve" tab.



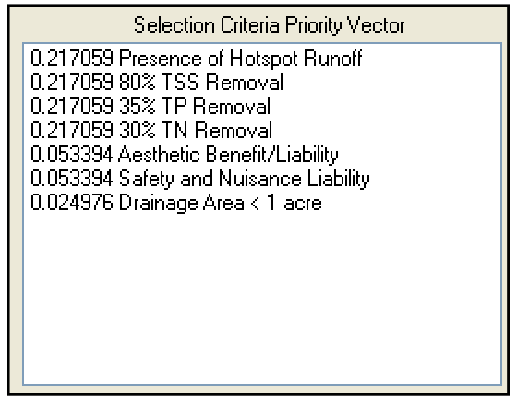
Upon clicking the "Solve" tab, the algorithm is executed and the BMP rankings are computed.



The computed results indicate that a bioretention basin is the BMP that best simultaneously satisfies each of the user-chosen and user-ranked criteria.

Step 4. Evaluate the Results

The final step is to scrutinize the results. First, the user should examine the "Selection Criteria Priority Vector." This vector expresses, quantitatively, the qualitative assessments made by the operator in Step 1.



Examining the "Selection Criteria Priority Vector" for this example reveals that the highest degree of influence was given to the presence of hotspot runoff and pollutant removal criteria. Furthermore, as desired by the user, these criteria are ranked equally with each other. Aesthetic benefit and public safety concerns are, again per user assessment, ranked equally with one another but given less influence than the hotspot runoff and pollutant removal criteria. Finally, as desired by the user, the contributing drainage area criterion is given the lowest degree of influence. Examination of this vector indicates that the qualitative user assessments of the influential selection criteria were suitably depicted quantitatively by the algorithm.

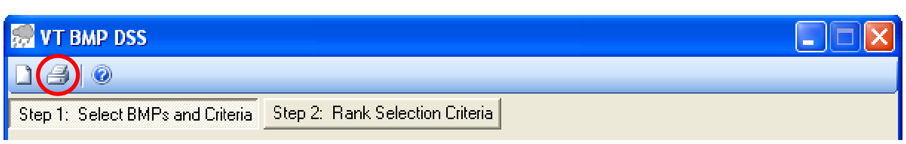
It is important to note that the AHP algorithm attempts to simultaneously satisfy all user-chosen weighted criteria. In attempting to do so, it is entirely possible that an individual criterion may be violated. Consequently, the user should critically scrutinize the results delivered by the algorithm. In this scenario, the algorithm ranked a bioretention basin as the BMP best suited to achieving the runoff management objectives previously described. The following is an evaluation of the reliability of this ranking.

Selection Criterion	**Bioretention Basin Characteristics**
80% Removal of TSS	Anticipated 86% Removal Efficiency*
35% Removal of TP	Anticipated 59% Removal Efficiency*
30% Removal of TN	Anticipated 38% Removal Efficiency*
Ability to Receive Hotspot Runoff	Yes
Aesthetic Benefit	Adds pervious cover to an otherwise impervious site, also provides water quality improvement very unobtrusively
Safety Concerns	Minimal safety concerns - 6" maximum ponding depth
Contributing Drainage Area < 1ac.	Ideally suited to very small drainage sheds

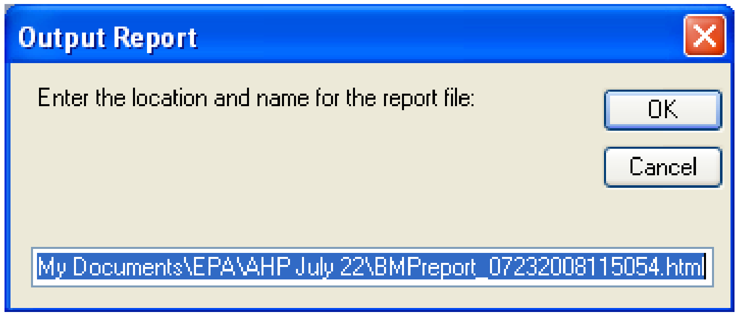
*Reflects values obtained during ongoing research efforts at Virginia Tech

Report Generation

After completing a BMP selection scenario, the user may generate a summary report by clicking the **Print** icon.



Upon clicking the **Print** icon, the user will be prompted to specify the name and destination of the summary report, which will be in *.html format. The default destination folder will be that in which the program executable is stored.



The summary report contains which BMPs were considered, which selection criteria were considered, the criteria priority vector, and the final BMP rankings.

Appendix F. Tutorial – Modeling of BMPs in EPA SWMM

The following appendix is a tutorial intended to guide the EPA SWMM user through the steps for creating model representations of several common stormwater BMPs. It is assumed that the user of this document is familiar with EPA SWMM elements, and is proficient in constructing hydrologic models in the EPA SWMM environment.

Most of the BMPs discussed in this tutorial are modeled using either a *treatment* model configuration or an *infiltration* model configuration. In addition to these two configurations, two alternative configurations were developed specifically for manufactured BMPs and rainwater harvesting systems respectively. The first step toward modeling a BMP in SWMM is choosing the appropriate model configuration.

Once the user has chosen a configuration, standardized procedures are used to assemble and size the SWMM elements that comprise the BMP model representation. Each BMP has an associated assembly/sizing procedure detailed in this tutorial. The sizing procedures described in this report are based on the BMP design guidelines provided in the Virginia Stormwater Management Handbook (DCR, 1999).

Initial Step: Choose BMP and Corresponding Model Configuration

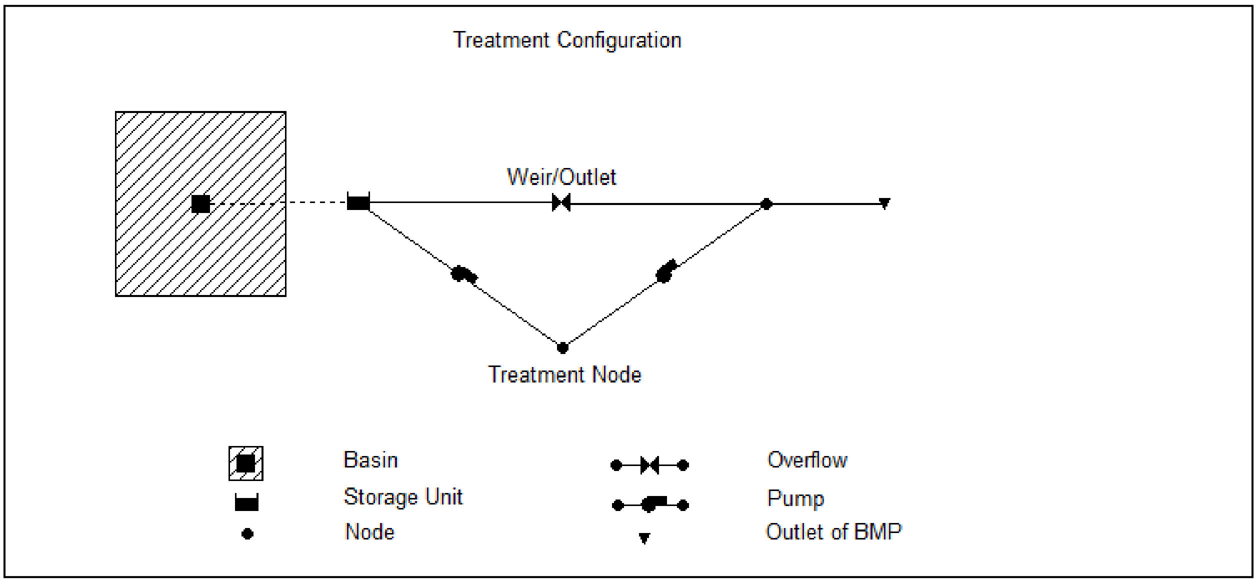


Figure F.1 – Treatment Configuration

The treatment configuration should be used to model the following BMPs:

- Basin Class BMPs
    - Extended and Enhanced Dry Detention
    - Retention Ponds
- Vegetated Buffer Strips
- Vegetated Swales
- Sand Filters
- Bioretention Filters
- Wetlands

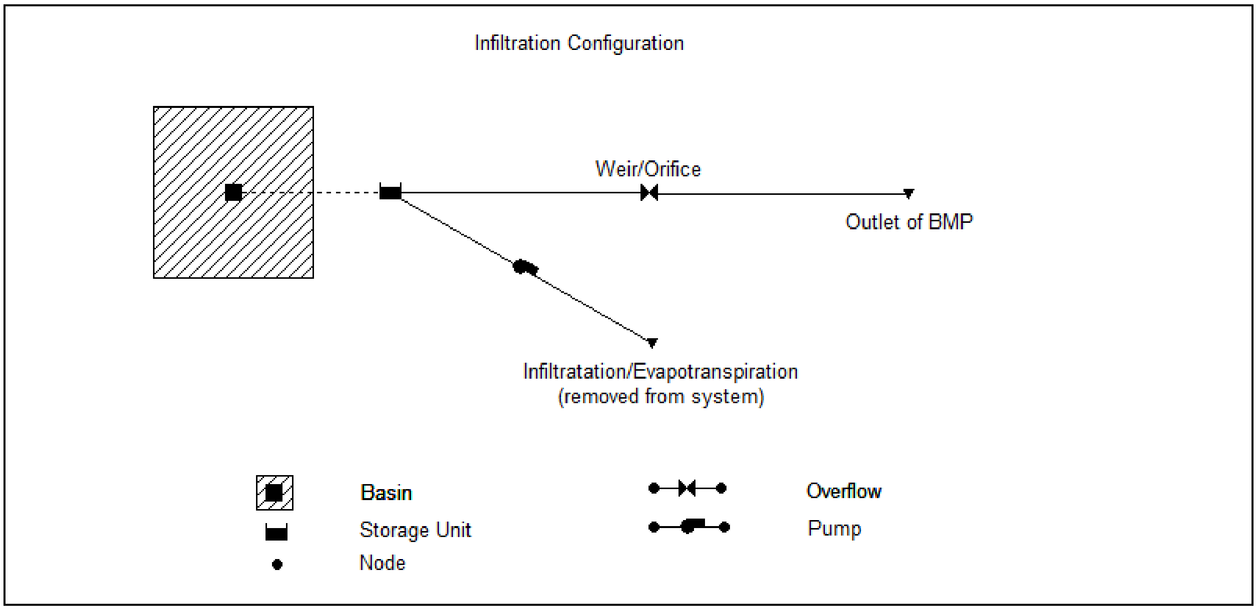


Figure F.2 – Infiltration Configuration

The treatment configuration should be used to model the following BMPs:

- Infiltration Basins/Trenches
- Porous Pavement
- Vegetated Roofs
- Bioretention Basins

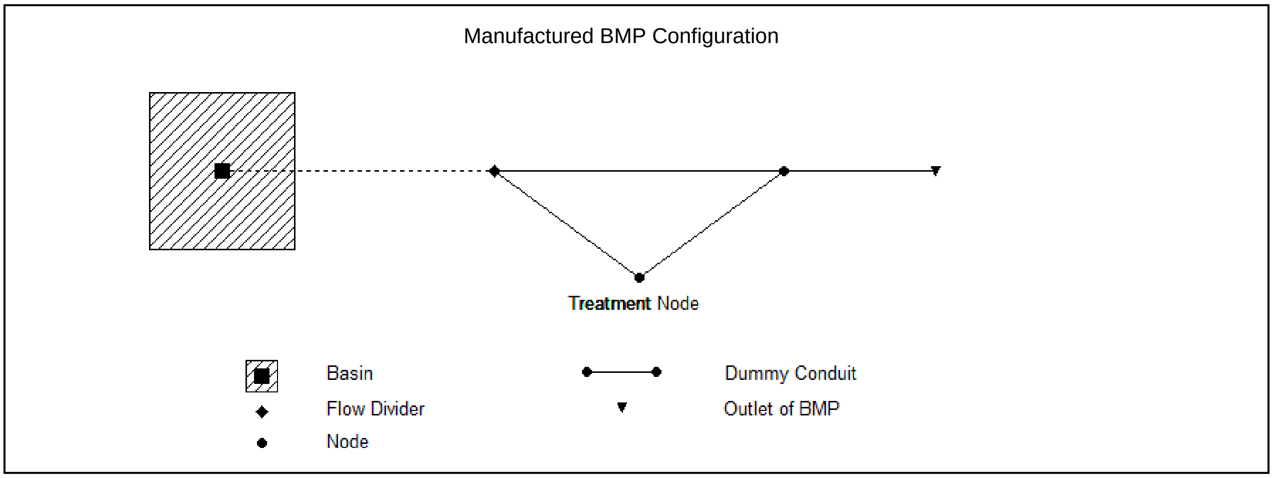


Figure F.3 – Manufactured BMP Configuration

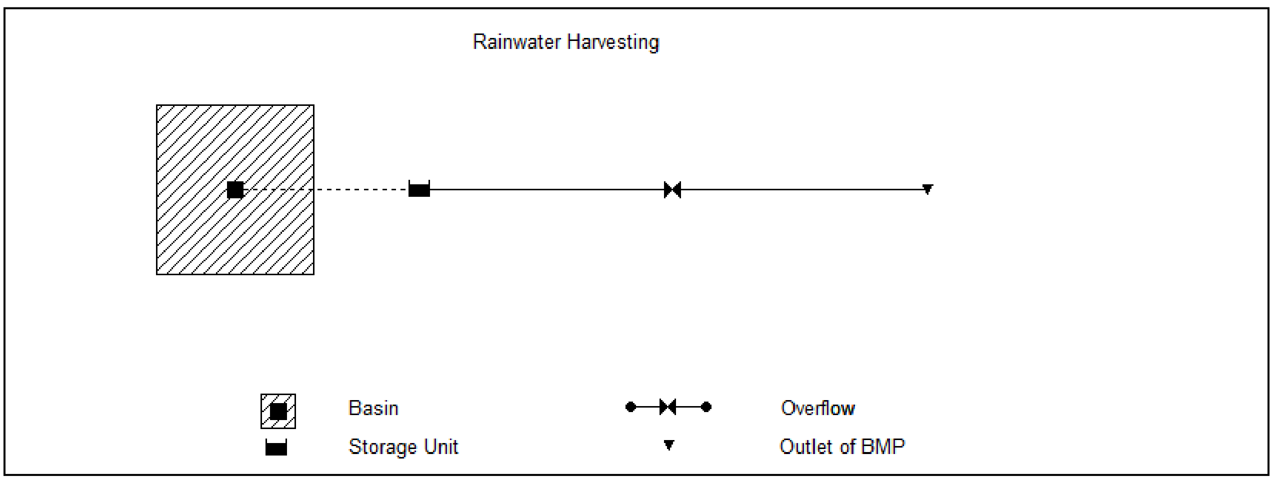


Figure F.4 – Rainwater Harvesting and Vegetative Roof Configuration

Assembly & Sizing Procedures

These assembly and sizing procedures assume that the BMP model representations are being used as planning tools, and that engineering drawings of the BMPs have not yet been developed. Consequently, the procedures described in this report enable the modeler to approximate a given BMP's performance very early in a project's planning stages. To model a BMP's performance prior to its detailed design, sizing of the BMP elements must be a function of basin characteristics such as area, geometry, impervious area, slope, etc. If BMP performance modeling is desired at the design stage, and detailed engineering drawings of the BMP *are* available, these modeling procedures can be adapted to incorporate actual design parameters such as outlet geometry and placement, water quality volume (WQV), and total storage volume.

None of the BMP assembly and sizing procedures described in this report are intended to model BMP performance for storms with a return frequency of greater than two years. This is because the primary objective of these model representations is to evaluate the water quality benefits of BMP installation. The majority of pollutant runoff from a given site is derived from small, frequently occurring storm events; therefore, the proposed model representations do not take exceedingly large storms into account. Even though water quantity control is not the primary concern of this research effort, the effects of the BMPs on water quantity can still be estimated for storm events equal to or below the 10-year event (i.e. most rainfall events).

Basin Class BMPs (Extended and Enhanced Detention, Retention, Wetlands)

1. Using the Object Toolbar and the treatment configuration as a template, recreate Figure F.1 in SWMM. Specify the created storage unit as the outlet for the desired basin. For the overflow element use an Outlet. Attach the downstream node to an outfall or connect to a downstream node that is part of a larger stormwater system.

2. Determine the approximate surface area corresponding to the necessary detention basin. A good estimate for this parameter is found by taking five (5) percent of the sub-catchment impervious area (DCR, 1999). Enter this value as the Ponded Area in the storage unit dialogue box. The basin geometry is approximated by a rectangular tank; therefore, the surface area in the corresponding Depth – Area relationship required by SWMM will be constant as depth increases.

3. Enter the basin outlet height as 0.833 feet. Enter the storage unit maximum depth as four (4) feet. The given depths for the approximated basins assume that the basin surface area was determined to be five (5) percent of the sub-catchment impervious area.

4. Make sure that the storage rating curve is set to “tabular”. Enter the Depth – Area relationship as a tabular curve within the storage unit dialogue box. Recall that the area is independent of depth.

5. Make sure the outlet rating curve is set to “tabular”. Enter the following generic rating curve for the basin outlet. For this step, the user must supply estimates of the pre-development peak flow rates for the 1-, 2-, and 10-year return period storms for the basin of interest.

Return Frequency (yrs)	Head (ft)	Outflow (cfs)
	0	0
1	0.833	-
2	1.833	-
10	3.167	-

6. Estimate the WQV:

$$WQV\ [ft^3] = \text{Basin Impervious Area}\ [ft^2] \quad X \quad \text{½” of Rainfall} / (12\ in/ft)$$

7. Determine the pump rate that represents the desired drawdown time for the estimated WQV. Note that the pump directs the WQV to a treatment node. In the pump curve dialogue box, select a Type II pump then enter this as a constant pump rate for head up to the depth of the basin for the pump leading to and away from the treatment node.

$$Q_{pump}\ [ft^3/s] = WQV \div \text{Hydraulic Residence Time (HRT)}$$

*For a basin class BMP, 24-48 hours is an appropriate HRT to treat the WQV

8. Determine the anticipated removal efficiencies for the pollutants of interest and enter these as removal equations in the treatment node dialogue box. Figure F.5 shows examples of removal equations entered into SWMM to represent 70% TSS removal and 60% TP removal in a retention basin.

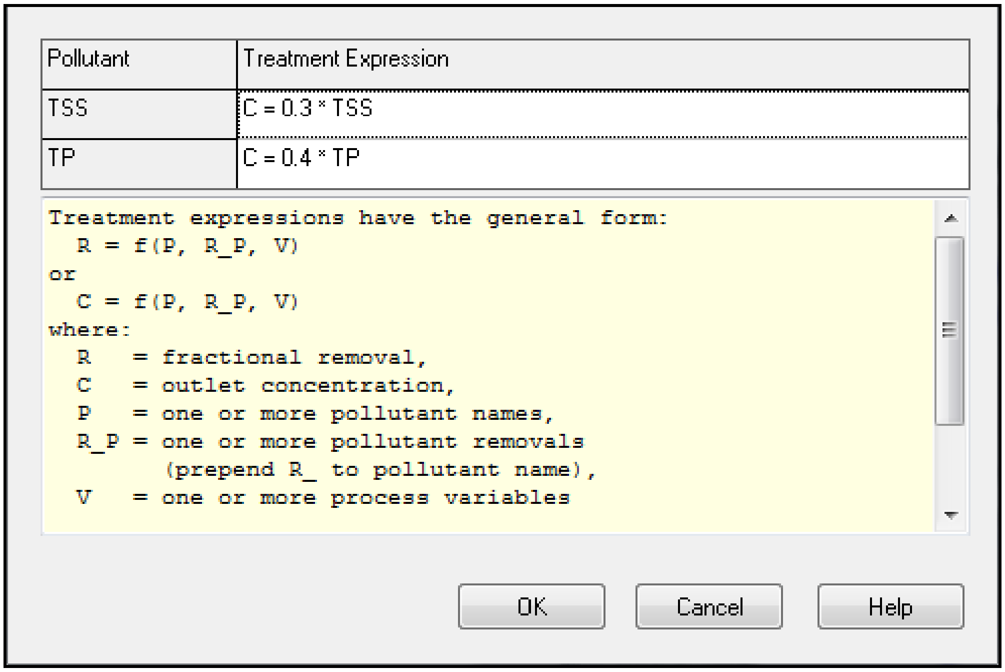


Figure F.5 – Entry of SWMM Pollutant Removal Equations

Sand Filters

1. Using the Object Toolbar and the treatment configuration as a template, recreate Figure F.1 in SWMM. Specify the created storage unit as the outlet for the desired basin. For the overflow element use a weir . Attach the weir to an outfall or connect to a downstream node that is part of a larger stormwater system.

2. Estimate the WQV:

   WQV [ft^3] = Basin Impervious Area [ft^2] X ½" of Rainfall / (12 in/ft)

3. Arbitrarily assign either the depth or surface area of the WQ storage portion of the filter and solve for the unknown variable. Note that the storage geometry is approximated by a rectangular tank; therefore, the surface area in the corresponding Depth – Area relationship required by SWMM will be constant as depth increases.

   WQV = Depth X Area

4. Assign the crest height of the overflow weir to the depth chosen in the previous step. Specify the geometry of the overflow weir. Overflow occurs when the filter is inundated with a storm larger than the design storm. The simplest way to model this situation is with a weir that represents the top of the filter; therefore, it

is easiest to choose a relatively long length for the weir and an arbitrary height. This way the weir will react similar to an inundated sand filter in that overflow will be nearly instantaneous once the WQV has been surpassed.

5. Enter the Depth – Area relationship as a tabular curve within the storage unit dialogue box. Recall that the area is independent of depth. The storage unit maximum depth corresponds to the depth calculated in Step 3 added to the weir height chosen in Step 4.

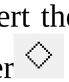
6. Determine the pump rate that represents the desired drawdown time for the estimated WQV. Note that the pump directs the WQV to a treatment node. In the pump curve dialogue box enter this as a constant pump rate for head up to the depth of the basin for the pump leading to and away from the treatment node.

$$Q_{pump}\ [ft^3/s] = WQV \div \text{Hydraulic Residence Time (HRT)}$$

7. Specify the desired removal efficiency associated with each pollutant within the treatment node dialogue box.

Proprietary Devices

1. In practice, proprietary devices are generally employed at a surface inlet or near the entry of a detention/retention basin. In the case of the former, the configuration represented in Figure F.3 is appropriate. In the case of the latter, Figure F.1 is appropriate. In either case, the device is represented by a treatment node in SWMM.

2. (a) For devices employed at a surface inlet, simply divert the design flowrate of the propriety device to the treatment node using a divider  element in SWMM. Ignore step 3 and proceed to step 4.

   (b) For devices employed in conjunction with storage facilities, estimate the WQV:

$$WQV\ [ft^3] = \text{Basin Impervious Area } [ft^2] \ \ X \ \ ½\text{” of Rainfall} / (12 \text{ in/ft})$$

3. Determine the pump rate that represents the desired drawdown time for the estimated WQV. Note that the pump directs the WQV to a treatment node. In the pump curve dialogue box, select a Type II pump then enter this as a constant pump rate for head up to the depth of the basin for the pump leading to and away from the treatment node.

$$Q_{pump}\ [ft^3/s] = WQV \div \text{Hydraulic Residence Time (HRT)}$$

4. Determine the expected removal efficiency and enter this as a removal equation within the treatment node dialogue box.

Infiltration Basins/Trenches

1. Using the Object Toolbar and the infiltration configuration as a template, recreate Figure F.2 in SWMM. Specify the created storage unit as the outlet for the desired basin. For the overflow element use a weir. Attach the weir to an outfall or connect to a downstream node that is part of a larger stormwater system.

2. Estimate the WQV:

   WQV [ft^3] = Basin Impervious Area [ft^2] X ½" of Rainfall / (12 in/ft)

3. Develop a *design* infiltration rate. Based on the existing soil conditions or upon proposed amended soil conditions, identify the appropriate *field* infiltration rate. The *design* rate is computed as half the *field* infiltration rate.

4. Determine the approximate surface area corresponding to the infiltration basin. Note that the basin geometry is approximated by a rectangular tank; therefore, the surface area in the corresponding Depth – Area relationship required by SWMM will be constant as depth increases.

   SA [ft^2] = WQV ÷ (Design Infiltration Rate [ft/hr] X Maximum Drawdown Time*

   *72 hours is a common *maximum* drawdown time for an infiltration facility.

5. Compute the basin depth. Enter this value as the crest height for the weir element. Note that the basin depth is designed in such a way that the infiltration facility is only capable of retaining the WQV. Runoff in excess of the WQV bypasses the infiltration practice.

   Depth [ft] = WQV ÷ SA

6. Specify the geometry of the overflow weir. Overflow occurs when the infiltration facility is inundated with a storm larger than the design storm. The simplest way to model this situation is with a weir that represents the crest of the infiltration facility; therefore, it is easiest to choose a relatively long length for the weir and an arbitrary height. This way the weir will react similar to an inundated infiltration practice in that overflow will be nearly instantaneous once the WQV has been surpassed.

7. Enter the Depth – Area relationship as a *tabular* curve within the storage unit dialogue box. Recall that the area is independent of depth. The storage unit maximum depth corresponds to the depth calculated in Step 5 added to the weir height chosen in Step 6.

8. Determine the pump rate that infiltrates the computed WQV. Note that the pump directs the WQV to an outfall, effectively removing this water from the overall system. This has an impact on both runoff quality and quantity. In the pump curve dialogue box, select a Type II pump then enter the calculated rate as a constant pump rate for head up to the depth of the basin.

$$Q_{pump}\ [ft^3/s] = \text{Infiltration rate [ft/hr]} \ \text{X} \ \text{SA} \ [ft^2] \ / \ (3600\ \text{sec/hr})$$

Porous Pavement

1. Using the Object Toolbar and the infiltration configuration as a template, recreate Figure F.2 in SWMM. Specify the created storage unit as the outlet for the desired basin. For the overflow element use a weir . Attach the weir to an outfall or connect to a downstream node that is part of a larger stormwater system.

2. Estimate the WQV. For many porous pavement systems the desired water quality volume is equivalent to the runoff associated with a 2-year return frequency storm. A simple, conservative estimate of this volume can be found using the 1-hour duration, 2-year rainfall depth found on an IDF graph for the location of interest:

   $$\text{WQV}\ [ft^3] = \text{1-hour, 2-year Rainfall Depth [ft]} \ \text{X} \ \text{Basin Impervious Area}\ [ft^2]$$

3. Arbitrarily assign either the depth or surface area of the storage portion of the facility and solve for the unknown variable. Note that the storage geometry is approximated by a rectangular tank; therefore, the surface area in the corresponding Depth – Area relationship required by SWMM will be constant as depth increases.

   $$\text{WQV} = \text{Depth X Area}$$

4. Assign the crest height of the overflow weir to the depth chosen in the previous step. Specify the geometry of the overflow weir. The simplest way is to choose a relatively long length for the weir and an arbitrary height. This way the weir will react similar to an inundated infiltration practice in that overflow will be nearly instantaneous once the WQV has been surpassed.

5. Enter the Depth – Area relationship as a tabular curve within the storage unit dialogue box. Recall that the area is independent of depth. The storage unit maximum depth corresponds to the depth calculated in Step 3 added to the weir height chosen in Step 4.

6. Develop a *design* infiltration rate. Based on the existing soil conditions or upon proposed amended soil conditions, identify the appropriate *field* infiltration rate. The *design* rate is computed as half the *field* infiltration rate.

7. Determine the pump rate that infiltrates the estimated WQV. Note that the pump directs the WQV to an outfall, effectively removing this water from the overall system. This has an impact on both runoff quality and quantity. In the pump curve dialogue box enter this as a constant pump rate for head up to the depth of the basin.

$$Q_{pump}\ [ft^3/s] = \text{Design Infiltration Rate [ft/hr]} \ \text{X} \ \text{SA} \ [ft^2] \ / \ (3600 \text{ sec/hr})$$

Bioretention

Bioretention BMPs may be modeled as filters or as basins. Bioretention filters discharge their treated runoff to a downstream receiving channel or storm sewer. By contrast, bioretention basins infiltrate their designated water quality volume, thus removing it completely from the system.

1. Using the Object Toolbar and the treatment configuration as a template, recreate Figure F.1 in SWMM for a bioretention filter or Figure F.2 for a bioretention basin. Specify the created storage unit as the outlet for the desired basin. For the overflow element use a weir . Attach the weir to an outfall or connect to a downstream node that is part of a larger stormwater system.

2. Estimate the WQV:

$$WQV\ [ft^3] = \text{Basin Impervious Area}\ [ft^2] \ \text{X} \ \text{½” of Rainfall} / (12 \text{ in/ft})$$

3. The surface ponding depth for a bioretention cell is generally restricted to a maximum of 0.5 feet; therefore, estimate the bioretention cell surface area as the WQV divided by 0.5 ft. Note that the basin geometry is approximated by a rectangular tank; therefore, the surface area in the corresponding Depth – Area relationship required by SWMM will be constant as depth increases.

4. Specify the geometry of the overflow weir. Overflow occurs when the bioretention cell is inundated with a storm larger than the design storm. The simplest way to model this situation is a weir that represents the bank elevation of the bioretention cell; therefore, it is easiest to choose a relatively long length for the weir and an arbitrary height. This way the weir will react similar to an

inundated bioretention practice in that overflow will be nearly instantaneous once the WQV has been surpassed and no additional storage will be achieved.

5. Enter the maximum depth of the storage unit as the maximum surface ponding depth of the bioretention cell plus the height of the weir (if the weir elevation differs from the maximum ponding elevation).

6. For a bioretention filter, determine the pump rate that represents the desired drawdown time for the estimated WQV. Note that the pump directs the WQV to a treatment node. In the pump curve dialogue box enter this as a constant pump rate for head up to the depth of the basin for the pump leading to and away from the treatment node.

$$Q_{pump}\ [ft^3/s] = WQV \div \text{Hydraulic Residence Time (HRT)}$$

   For a bioretention basin, determine the pump rate that infiltrates the computed WQV. Note that the pump directs the WQV to an outfall, effectively removing this water from the overall system. This has an impact on both runoff quality and quantity. In the pump curve dialogue box, select a Type II pump then enter the calculated rate as a constant pump rate for head up to the depth of the basin.

$$Q_{pump}\ [ft^3/s] = \text{Infiltration rate [ft/hr]} \ \text{X} \ \text{SA}\ [ft^2] \ / \ (3600\ \text{sec/hr})$$

7. Specify the desired removal efficiency associated with each pollutant within the treatment node dialogue box. Suggested removal efficiencies can be found at the conclusion of this manual.

Vegetated Buffers/Swales

1. Using the Object Toolbar and the treatment configuration as a template, recreate Figure F.1 in SWMM. Specify the created storage unit as the outlet for the desired basin. For the overflow element use a weir . Attach the weir to an outfall or connect to a downstream node that is part of a larger stormwater system.

2. Estimate the WQV:

$$WQV\ [ft^3] = \text{Basin Impervious Area}\ [ft^2] \ \ \text{X} \ \ \text{½” of Rainfall} / (12\ \text{in/ft})$$

3. Arbitrarily assign either the depth or surface area of the storage portion of the facility and solve for the unknown variable. Note that the storage geometry is approximated by a rectangular tank; therefore, the surface area in the

corresponding Depth – Area relationship required by SWMM will be constant as depth increases.

$$WQV = Depth \times Area$$

4. Assign the crest height of the overflow weir to the depth chosen in the previous step. Specify the geometry of the overflow weir. The simplest way is to choose a relatively long length for the weir and an arbitrary height. This way the weir will react similar to an inundated infiltration practice in that overflow will be nearly instantaneous once the WQV has been surpassed.

5. Enter the Depth – Area relationship as a tabular curve within the storage unit dialogue box. Recall that the area is independent of depth. The storage unit maximum depth corresponds to the depth calculated in Step 3 added to the weir height chosen in Step 4.

6. Determine the pump rate that represents the desired drawdown time for the estimated WQV. Note that the pump directs the WQV to a treatment node. In the pump curve dialogue box enter this as a constant pump rate for head up to the depth of the BMP for the pump leading to and away from the treatment node.

$$Q_{pump}\ [ft^3/s] = WQV \div \text{Hydraulic Residence Time (HRT)}$$

7. Specify the desired removal efficiency associated with each pollutant within the treatment node dialogue box. Suggested removal efficiencies can be found at the conclusion of this manual.

Rainwater Harvesting & Vegetated Roofs

1. Using the Object Toolbar and the treatment configuration as a template, recreate Figure F.4 in SWMM. Specify the created storage unit as the outlet for the desired basin. For the overflow element use a weir . Attach the weir to an outfall or connect to a downstream node that is part of a larger stormwater system.

2. Estimate the WQV. A conservative estimate for a design WQV for a rainwater harvesting system is based on one (1) inch of rainfall and an 80% capture rate:

$$WQV\ [ft^3] = 0.8 \times \text{Rooftop Area}\ [ft^2] \times 1\text{” of Rainfall} / (12\ in/ft)$$

For a vegetated roof:

$$WQV\ [ft^3] = \text{Rooftop Area}\ [ft] \times ½\text{” of Rainfall} / (12\ in/ft)$$

3. Arbitrarily size the storage element footprint. Determine the area of this footprint and enter this value as the Ponded Area within the storage element dialogue box.

4. Insert an appropriately sized overflow weir whose crest is located at the maximum depth of the WQV. This will store the WQV indefinitely, effectively removing it from the system. Enter a reasonable value for weir length and height. Make sure it is conservatively large in order to ensure instantaneous overflow during a large storm event.

$$\text{Weir Crest Height [ft]} = \text{WQV} \div \text{Area of Storage Element}$$

5. For the maximum depth of the storage element enter the weir crest height plus the height of the weir itself.

6. Enter the storage elevation curve as a tabular curve in the storage element dialogue box. Recall that area is constant with depth.

Appendix G. Tutorial – Development of a Decision Support GIS

Many of the criteria influencing the selection of a BMP for a particular runoff management application are functions of a site's physical characteristics. In order to optimally use the VT BMP decision support software it is essential to have readily available input data depicting the physical characteristics of the site upon which the BMP is to be located as well as any offsite areas contributing runoff to the BMP. While some of these physical site characteristics can only be adequately evaluated through the completion of a detailed site investigation, some can be sufficiently assessed through the use of GIS software. Among those physical site characteristics that can be readily evaluated through a GIS are hydrologic soil group (HSG), land cover imperviousness, and average land slope. This GIS-based desktop assessment is of particular value when stormwater management options are being evaluated at the planning stage of development. Table G.1 shows the GIS layers compiled under the scope of this project.

Table G.1 GIS Data Compiled Within the Scope of this Project

Data Category	Description	Data Source(s)
Parcel Boundaries	Tax parcel boundaries within the Town of Blacksburg	.shp file from Town of Blacksburg GIS
Sub-Watershed Boundaries	Sub-watershed delineations	.shp file of sub-watersheds developed during the Town of Blacksburg MS-4 permitting process
Land Cover	Identification of percentage imperviousness within parcel and sub-watershed boundaries.	Compilation of vector-format GIS data from various sources
Soil Type	Identification of area-weighted HSG within parcel and sub-watershed boundaries.	NRCS Soil Survey Geographic (SSURGO) Database
Site Slopes	Identification of average land slope within parcel and sub-watershed boundaries.	Town of Blacksburg LiDAR data

The Parcel Boundaries layer is a shapefile obtained from the Town of Blacksburg GIS (http://www.gis.lib.vt.edu/gis_data/Blacksburg/GISPage.html). This data layer depicts individual parcel boundaries as defined by the Montgomery County, Virginia tax maps. Many municipalities throughout the United States now maintain their tax map information in a GIS format, and this data is usually available from the locality.

The Sub-Watershed Boundaries layer is a shapefile developed during the first phase of the Town of Blacksburg Storm Water Management Research project by the Center for Geospatial Information and Technology (CGIT) in the fall of 2006. Completion of this research effort yielded a shapefile of the urban subwatersheds contributing runoff to the Town's storm sewer system. Most municipalities operating a Municipal Separate Storm Sewer System (MS 4) will have compiled similar data during their permitting process.

The Land Cover data set represents a compilation of vector-format GIS data that spans the Town of Blacksburg political boundary and discretely categorizes land cover as either pervious or impervious. This land cover/imperviousness dataset was developed by CGIT during its stormwater research work for the Town of Blacksburg.

The land cover data set employed within the scope of this project is rather detailed, based on local transportation and building inventory GIS data. The feasibility of developing land cover datasets at such a detailed level depends on the quality of existing GIS data available for the area, as well as the resources available for development and maintenance of the dataset. In instances when it is not possible to acquire local-level land cover data, less detailed land cover data may be obtained from a variety of sources. At a nationwide level, the Multi-Resolution Land Characteristics Consortium (MRLC) produces the National Land Cover Database (NLCD) line of products, derived from satellite imagery. The primary NLCD product is a land cover classification raster with a 30 meter cell size, but additional datasets of imperviousness and forest canopy have also been developed.

The Soil Type data set represents a compilation of soils data originating from the Soil Survey Geographic (SSURGO) database. SSURGO soils databases are typically published on a countywide basis and are available for free download (http://soils.usda.gov/survey/geography/ssurgo/). This data is often the most detailed soils information available for any given study area, short of undertaking a costly new soil survey. Upon download, the SSURGO data is delivered in two formats. One format is a shapefile and the other is a corresponding Microsoft® Access® database. The SSURGO shapefiles are comprised of "map unit polygons," and these polygons can be related to data held in the corresponding Access® database (although often the relationship between map unit polygons and records in a SSURGO table is not 1:1). Hydrologic Soil Group (HSG) data is reported in the "soil component table" of the SSURGO data, but many soil components may be present in any given map unit polygon. Therefore, to create a GIS dataset of HSG polygons, data aggregation within the SSURGO database is necessary.

The steps detailed in this tutorial are specific to creating Parcel and Watershed shapefiles that contain the HSG, average slope, and percentage of impervious cover for each parcel or watershed in the respective shapefile. The files in this tutorial were created in ESRI® ArcMap® version 9.2.0. This tutorial requires some basic knowledge of ArcMap®, but no more than a very simple understanding of the program. These steps can be applied to other overlay layers than parcels or watersheds.

GIS Procedure:

1. Open ArcMap and add data layers.
   a) In ArcMap click the Add Data button  and select the layers that are needed for the drawing.
   b) When the layers are added they need to all be in the same coordinate system for the calculations to work properly.
   c) To change a layer's coordinate system:
      - ➢ Open ArcToolbox (click on this button ). Select Data Management → Projections and Transformations → Feature (or Raster depending on your shapefile) → Project. Then select the file to be projected and a location for the new file and the new file's coordinate system.

2. Hydrologic Soil Calculations:
   a) Soil data characteristics layers can be found at the Soil Survey Geographic Database (SSURGO) website. The SSURGO data will be delivered in two formats. One format will be a shapefile that can be opened in ArcMap the other is a Microsoft Access Database. Be sure to read and understand the SSURGO manual before opening and manipulating the data. The ArcMap file does not contain the Hydrologic Soil Group (HSG) for the different soil types. This information is contained in the many tables of the Access Database. One of these tables is going to be opened in excel so it can be used with the shapefile.
      - ➢ Open the Access database and load the data tables that were provided by the Soil Data Mart.
      - ➢ In the "Tables" section, open the table named "component." This table will have many fields but one of them should be "Hydrologic Group" and another should be "Mapunit Key"
      - ➢ Export this table into excel by clicking File → Export. Save it as Excel format.
      - ➢ Close Access and open up the newly created Excel file.
      - ➢ Delete all of the columns except for:

Comp % - Low Value	Comp % - Representative Value
Comp % - High Value	Component Name
Major Component	Hydrologic Group
Mapunit Key	

      - ➢ Sort all the data based on Mapunit Key. (There will be some Mapunit Keys that repeat themselves. These keys are exclusive in the shapefile).
      - ➢ Now the user must use judgment and look at the major component field as well as the different percentages to decide the HSG for each Mapunit Key. Every Mapunit Key should have

only one HSG. In a new column next to the Mapunit Key write in the HSG assumed for each Mapunit Key. For example if there are two rows with Mapunit Key “51714” look at the Hydrologic Group column and the Major Component column to decide which HSG should be assigned to that Mapunit Key.

- Now create two new columns labeled “HSG” and “MUKey”. List each Mapunit Key and its assigned HSG. (This will help you to create a field for HSG in the SSURGO shapefile)

b) In ArcMap open the attribute table for the SSURGO shapefile. There is no field for the Hydrologic Soil Group (HSG) therefore it must be added manually based on the Mapunit Key. In order to find an average value for each parcel or subwatershed the HSG must be a number. The simplest way to label an HSG as a number is below:

A – 1 B – 2 C – 3 D – 4 W* – 0

*W stands for waterbody.

- Open the SSURGO shapefile’s attribute table in ArcMap.
- In the bottom right corner of the Attribute Table click on the button labeled “Options” and select “Add Field…” Name the field HSG_No and make the type a Short Integer. Then click “OK”.
- Right click on the header of the new field and select “Field Calculator…” Check the box labeled “Advanced” so that the program will accept VBA code.
- Each code will be different based on the Mapunit Keys and the HSGs for the area of interest. The best way to create VBA code to label the HSGs is to use a Case Select.
- There will need to be five different cases. One for each HSG: A, B, C, D, and W.
- Using the Excel table that contained the Mapunit Keys and corresponding HSGs the user can write the code. An example Excel table and VBA code is provided as follows:

Table G.2 HSG Excel example and VBA Code

MUKey	HSG
517083	A
517084	B
517085	B
517086	B
517087	B
517088	B
517089	B
517090	B
517091	B
517092	B
517093	B
517094	B
517095	B
517096	B
517097	C
517098	C
517099	B

MUKey	HSG
517100	C
517101	D
517102	D
517103	D
517104	D
517105	B
517106	B
517107	B
517108	B
517109	B
517110	B
517111	D
517112	D
517113	D
517114	D
517115	D
517116	D
517117	W

```
Dim Num as Integer
Select Case [MUKEY]
Case 517083
Num = 1
Case 517084 to 517096, 517099, 517105 to 517110
Num = 2
Case 517097 to 517098, 517100
Num = 3
Case 517101 to 517104, 517111 to 517116
Num = 4
Case 517117
Num = 0
End Select
```

- In the bottom line of the code underneath the text "HSG_No =" enter Num. This is the variable for the HSG.
- Each Case Select will be different based on Mapunit Keys and corresponding HSG values. Notice the HSG is a number instead of a letter A-D. This will be utilized later when the HSG will be averaged for a parcel (or subwatershed).
- If problems are encountered with the VBA code the user can try actually clicking the field [MUKey] instead of typing it in.
- Click "OK" in the bottom right and ArcMap will populate the field for HSG Number based on the Mapunit Key. A screen shot of the VBA code is provided as follows:

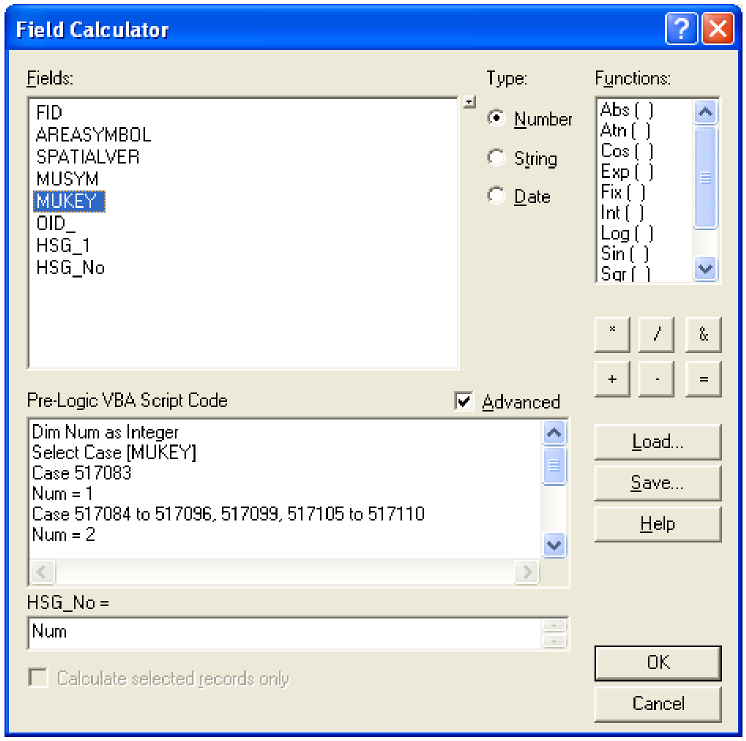
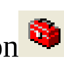


Figure G.1 Label and Mapunit Key VBA Code

c) Now that the HSG has been added to the attribute table the shapefile must be converted into a raster before it can be analyzed based on parcel or subwatershed.

- ➢ Open the ArcToolbox by clicking on the toolbox icon  in ArcMap.
- ➢ Select Conversion Tools → To Raster → Polygon to Raster.
- ➢ Under Input Features click the drop down arrow and select the SSURGO shapefile.
- ➢ Under Value Field click the drop down arrow and select HSG_No
- ➢ In the Output Raster Dataset select a file name and drive to clearly identify the new shapefile.
- ➢ The cell size should be chosen based on the user's judgment. The smaller the cell size the more accurate the raster will be. The cell size should certainly not be larger than the area of the smallest parcel. (The cell size used for this example was 5 ft).
- ➢ Click OK and the raster will be created in ArcMap.

d) The raster should have five discrete values of 0 – 4 (there may be less if the site of interest does not have certain HSG types in it). The waterbodies should be represented as a 0 value in the raster. These values should not be included in the averaged values calculations. Therefore they must be reclassified as NoData.

- If there are no waterbodies in the site of interest this step can be skipped.
- In the ArcToolbox select Spatial Analyst Tools → Reclass → Reclassify.
- Select the newly created raster as the input raster.
- The Reclass Field should be VALUE.
- Make sure that the new values are the same as the old values except for 0. The new value for 0 should be NoData.
- Save the new "Output raster" in a known location.
- Click OK

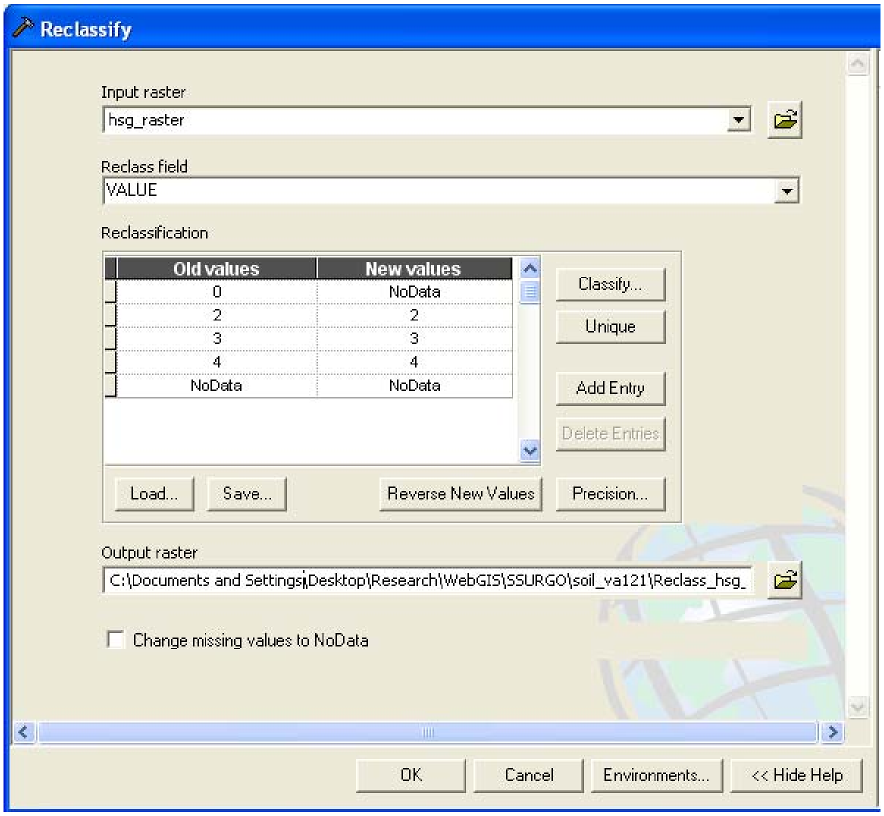


Figure G.2 HSG Reclassification

e) The raster is now ready to be analyzed based on either parcels or subwatersheds. For several parcels or subwatersheds there is more than one type of HSG. The zonal statistics command is able to average the HSG to provide a single value for each individual parcel or subwatershed. Double check that the parcels and subwatershed layers are added in the drawing and that they are in the same coordinate system as the Soil Raster file.

- In the ArcToolbox select Spatial Analyst Tools → Zonal → Zonal Statistics as Table.
- Under Input raster or feature zone data select either the layer for parcels or subwatersheds.

- The Zone field must be an identifier that is exclusive for each parcel or subwatershed. An ID field is the best option. If there is not an ID field one can be created:
    - Open the attribute table of the shapefile.
    - In the bottom right corner click “Options” and then “Add Field…”
    - Name the field ID and make the type a long integer and then click OK.
    - Right click on the header of the ID field and select “Field Calculator…”
    - Double click the field labeled FID and hit OK.
- Under Input value raster select the soil raster that has NoData values for the water bodies.
- Select a location and name the new table HSG_Parcel (or HSG_Watershed).
- Make sure the box for Ignore NoData in calculations is checked.
- Click OK.

f) The table with HSG statistics for each parcel (or subwatershed) has been added to the drawing. It can be seen by selecting the Source tab in the bottom left corner of the screen. The table will be at the bottom of the list of files in the drawing. This table now needs to be modified and joined to the parcel (or subwatershed) attribute table.
- In the bottom left corner of the screen click on the “Source” tab. It is located between “Display” and “Selection.”
- On the left side of the screen find the newly created HSG table.
- Right click the table and select Open.
- There are several columns. The only ones needed are Rowid, VALUE, and MEAN. Delete the others by right clicking the field header and select “Delete Field”
- In the bottom left corner of the window click “Options” and then “Add Field…”
- Name the field HSG and make the type Text.
- Now right-click the HSG field header and select “Field Calculator…”
- Click the Advanced box to allow VBA code scripting and enter the code as follows:

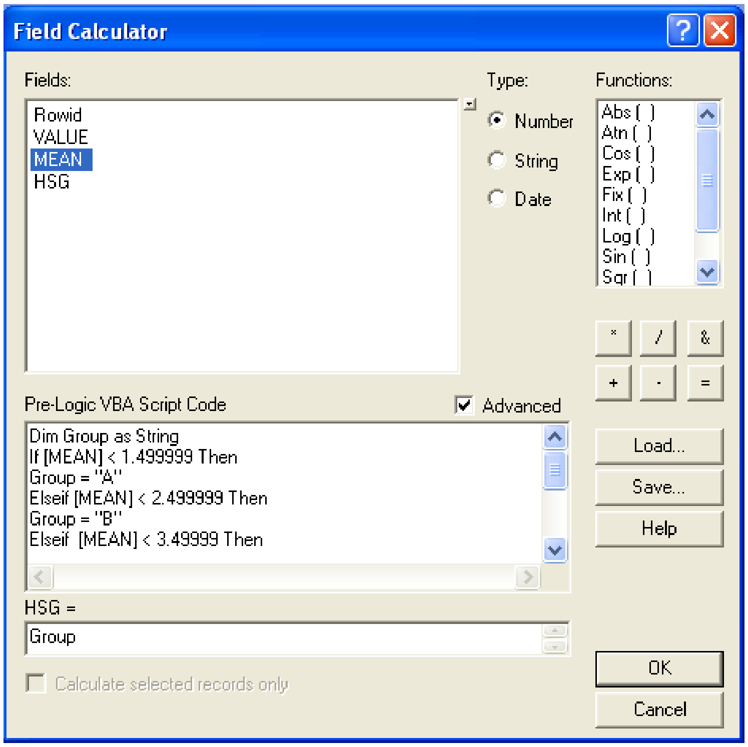


Figure G.3: HSG Field Calculator

```
Dim Group as String
If [MEAN] < 1.499999 Then
Group = "A"
Elseif [MEAN] < 2.499999 Then
Group = "B"
Elseif  [MEAN] < 3.49999 Then
Group = "C"
Elseif [MEAN]  <4.5 then
Group = "D"
Else
Group = "ERROR"
End if
```

Figure G.4: HSG Label VBA Code

- In the bottom bar of the window enter Group as it's shown above. If there are problems with the code double check the spaces between commands are single spaces. Another option is to double click the field MEAN instead of typing it in.
- Click OK. Then delete the field MEAN. Now that HSG has been calculated it is no longer needed.
- Close the table when finished and right click the parcels (or subwatershed) layer and select "Joins and Relates" and then "Joins."
- Under No. 1 "Choose the field in this layer that the join will be based on" choose the ID field that was used to identify each row in the HSG table.
- Under No. 2 "Choose the table to join to this layer, or load the table from disk" choose the HSG table.
- Under No. 3 "Choose the field in the table to base the join on:" choose the field named VALUE. Then click OK.
- Now the two tables have been joined. The attribute table in the parcel (or subwatershed) layer will contain the data in the newly created table.

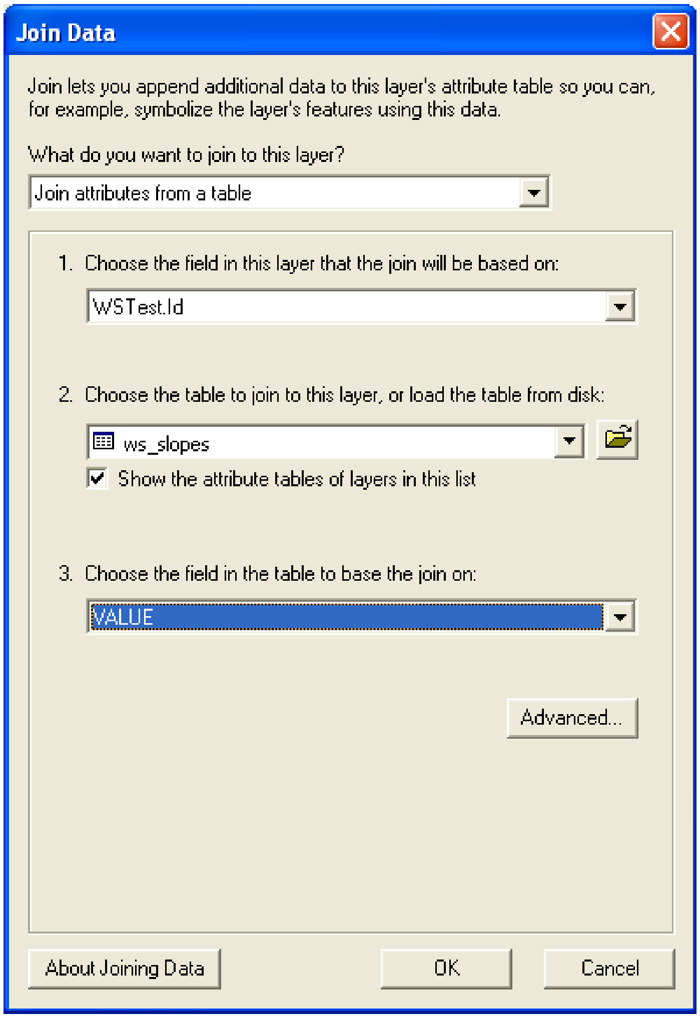


Figure G.5 Join Fields

g) The data has been combined into one table that is related to the shapes in the shapefile; however, the attribute table is only referencing data from the HSG table. They need to be combined into one file.
   - To make one complete file with all the data right-click the parcel (or subwatershed) layer and select "Data" and then "Export Data."
   - A window will appear providing export options. Export all the layer's attributes and select a location for the new file.
   - Name it Parcel_HSG (or WS_HSG)

h) The HSG data has been averaged for each parcel (or subwatershed). The process can be repeated for a different layer other than parcel by starting over at step 2e.

3. Average Slope Calculations:
   a) The user will need an elevation layer file that is a floating point raster. The raster's outer limits should be large enough to encompass the parcel

(or subwatershed) layer. The elevation raster will be converted into a slope raster using spatial analyst.

- If not done so already, add the elevation raster and check to make sure that is in the same coordinate system as the other files.
- In the ArcToolbox  select Spatial Analyst Tools → Surface → Slope.
- Under Input Raster click the drop down arrow and select the elevation raster.
- Under Output measurement click the drop down arrow and select Percent_Rise.
- Click OK.

b) The zonal statistics will be used to calculate an average slope for each parcel (or subwatershed).

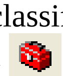
- In the ArcToolbox  select Spatial Analyst Tools → Zonal → Zonal Statistics as Table.
- Under Input raster or feature zone data select either of the new layers for parcels or subwatersheds that were created during the steps in part 2.
- The Zone field must be an identifier that is exclusive for each parcel or subwatershed. It should be the same id field as before.
- Choose a location for the output table and name it Parcel_Slope (or WS_Slope).

c) The newly created table must now be combined with the attribute table for the new parcels (or subwatershed) layer. First they must be joined and then the data must be exported as a single file like before.

- In the bottom left corner of the screen click on the “Source” tab. It is located between “Display” and “Selection.”
- On the left side of the screen find the newly created Parcel_Slope (or WS_Slope) table.
- Right click the table and select Open.
- There are several columns. The only ones needed are Rowid, VALUE, and MEAN. Delete the others by right clicking the field header and select “Delete Field”
- Rename the MEAN field by Right-clicking on it and select options. Name it Mean_Slope.
- Close the table.
- Right-click the Parcel_HSG and select “Joins and Relates” and then “Joins.”
- Under No. 1 “Choose the field in this layer that the join will be based on” choose the ID field that was used to identify the Slope table.
- Under No. 2 “Choose the table to join to this layer, or load the table from disk” choose the Parcel_Slope (or WS_Slope) table.

- Under No. 3 "Choose the field in the table to base the join on:" choose the field named VALUE. Then click OK.
- To make one complete file with all the data right-click the Parcel_HSG (or WS_HSG) layer and select "Data" and then "Export Data."
- A window will appear providing export options. Export all the layer's attributes and select a location for the new file.
- Name it Parcel_Slope_HSG (or WS_Slope_HSG).
- Click OK.

4. Impervious Cover Calculations
   a) The Land cover layer (impervious cover) should be in raster form. If it is not then refer to step 2c. Most Land cover layers are in discrete form and have a field that will indicate the imperviousness as either a value of 0 or 1. The impervious cover calculations are very similar to the slopes calculations except for areas that are waterbodies will have to be classified as NoData.
      - If not already done so add the Land cover layer into the drawing and make sure that it is in the same coordinate system as the other files.
      - If there are no waterbodies in the site of interest this step can be skipped.
      - In the ArcToolbox select Spatial Analyst Tools → Reclass → Reclassify.
      - Select the Land cover raster as the input raster.
      - The Reclass Field should be VALUE.
      - Make sure that the new values are the same as the old values except for those classified as water. The new value for water should be NoData.

   b) After the raster has been reclassified the zonal statistics can be calculated.
      - In the ArcToolbox  select Spatial Analyst Tools → Zonal → Zonal Statistics as Table.
      - Under Input raster or feature zone data select either of the new layers for parcels or subwatersheds that were created during the steps in part 3.
      - The Zone field must be an identifier that is exclusive for each parcel or subwatershed. It should be the same field as before.
      - Choose a location for the output table and name it Parcel_LC (or WS_LC).

   c) Like before the zonal statistic table and the attribute table must be combined into one.
      - In the bottom left corner of the screen click on the "Source" tab. It is located between "Display" and "Selection."

- On the left side of the screen find the newly created Parcel_LC (or WS_LC) table.
- Right click the table and select Open.
- There are several columns. The only ones needed are Rowid, VALUE, and MEAN. Delete the others by right clicking the field header and select “Delete Field”
- Rename the MEAN field by Right-clicking on it and select options. Name it Percent_Imperv.
- Close the table.
- Right-click the Parcel_Slope_HSG (or WS_Slope_HSG) layer and select “Joins and Relates” and then “Joins.”
- Under No. 1 “Choose the field in this layer that the join will be based on” choose the ID field that was used to identify the Land cover table.
- Under No. 2 “Choose the table to join to this layer, or load the table from disk” choose the Parcel_LC (or WS_LC) table.
- Under No. 3 “Choose the field in the table to base the join on:” choose the field named VALUE. Then click OK.
- To make one complete file with all the data right-click the Parcel_Slope_HSG (or WS_Slope_HSG) layer and select “Data” and then “Export Data.”
- A window will appear providing export options. Export all the layer’s attributes and select a location for the new file.
- Name it Parcel_Total (or WS_Total)
- Click OK

5. Attribute Table formatting

   a) Now that the final layers have been created they can be formatted to display only the information necessary. When joining the tables fields are renamed from their previous names to the layer’s title.previous name. Also when the tables are joined many of the zonal statistics fields revert back to the original name of MEAN. ArcMap does not allow for fields to be renamed, only aliases can be applied to them. Instead the user must create a new field with the desired name.
      - Open up the attribute table of the Parcel_Total (or WS_Total) file.
      - In the bottom right corner of the window select “Options” and then “Add Field…”
      - The field name should define its contents (i.e. Mean_Slope, Percent_Imperv, HSG)
      - Select the type based on the data that will be in the field. A short integer is good for discrete values (0, 1, 2…) and Double is good for numbers with several significant figures (3.38403, 0.1839472…)
      - The precision can be increased by adding zeros after the decimal point (0.0, 0.00, 0.000…)

- Choose the desired options and click OK.
- Right-click on the newly created field header and select "Field Calculator…"
- The field with the improper name (such as MEAN) should be listed in the Fields box. Double click on that field and then click OK (see below).
-

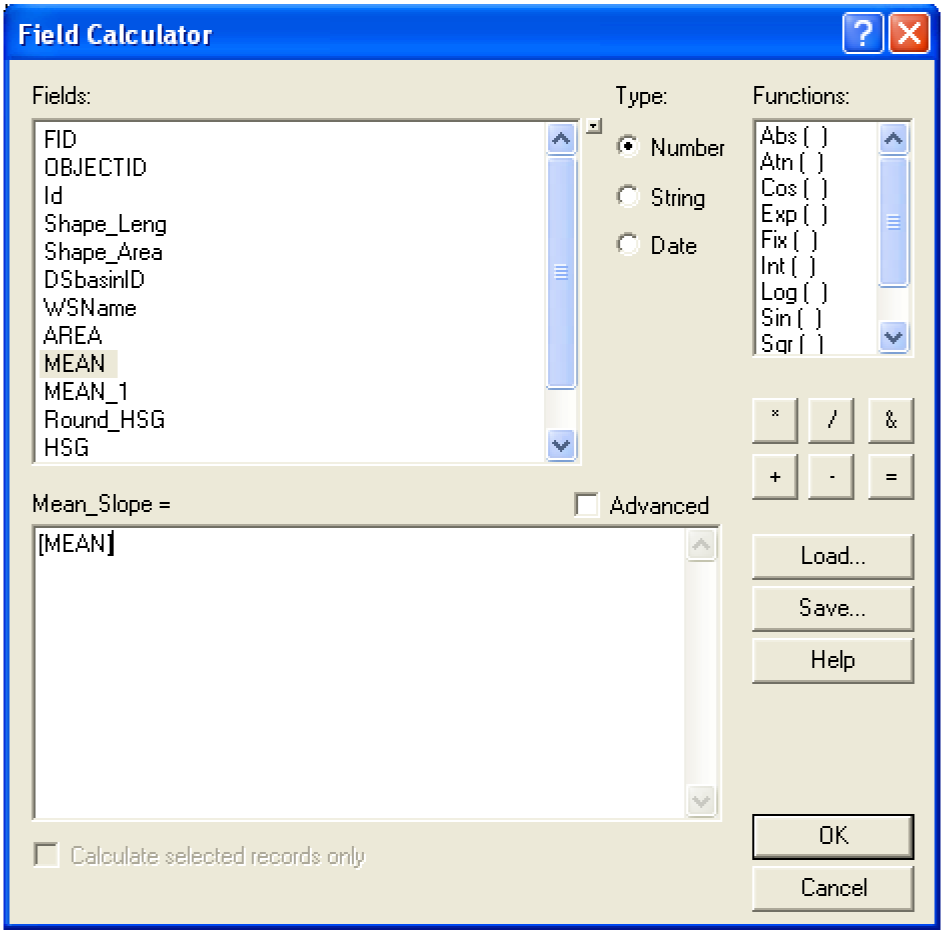


Figure G.6 Formatting Field Calculator

- Now the old field can be deleted. Right-click the old field and select "Delete Field"
- These steps can be repeated for any number of fields.