Application of the Analytic Hierarchy Process Optimization Algorithm in Best Management Practice Selection

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Abstract

The efficiency of a best management practice (BMP) is defined simply as a measure of how well the practice or series of practices removes targeted pollutants. While this concept is relatively simple, mathematical attempts to quantify BMP efficiency are numerous and complex. Intuitively, the pollutant removal capability of a BMP should be fundamental to the BMP selection process. However, as evidenced by the absence of removal efficiency as an influential criterion in many BMP selection procedures, it is typically not at the forefront of the BMP selection and design process.

Additionally, of particular 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 maintenance costs associated with almost any BMP. Much like pollutant removal efficiency, implementation and maintenance costs seem as though they should be integral considerations in the BMP selection process. However, selection flow charts and matrices employed by many localities neglect these considerations.

Among the categories of criteria to consider in selecting a BMP for a particular site or objective are site-specific characteristics; local, state, and federal ordinances; and implementation and long-term maintenance costs. A consideration such as long-term maintenance cost may manifest itself in a very subjective fashion during the selection process. For example, a BMPs cost may be of very limited interest to the reviewing locality, whereas cost may be the dominant selection criterion in the eyes of a developer. By contrast, the pollutant removal efficiency of a BMP may be necessarily prioritized in the selection process because of the required adherence to governing legislation. These are merely two possible criteria influencing selection. As more and more selection criteria are considered, the task of objectively and optimally selecting a BMP becomes increasingly complex. One mathematical approach for optimization in the face of multiple influential criteria is the Analytic Hierarchy 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, pg. 15).

This paper details the development of two categories of comprehensive BMP selection matrices expressing long-term pollutant removal performance and annual maintenance and operations cost respectively. Additionally, the AHP is applied in multiple scenarios to demonstrate the optimized selection of a single BMP among multiple competing BMP alternatives. Pairwise rankings of competing BMP alternatives are founded on a detailed literature review of the most popular BMPs presently implemented throughout the United States.

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Kevin D. Young
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Chapter 1.0
Introduction

A Best Management Practice (*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 many conventional storm water management practices, such as detention ponds, by not only mitigating the peak rate of runoff from a given site, but also attempting to improve the quality of the runoff. BMPs are broadly categorized as *structural* or *non-structural*. Non-structural BMPs or "source control" systems operate by minimizing the accumulation of pollutants, thus reducing their initial concentrations in stormwater runoff. Street sweeping, fertilizer application controls, and vegetated buffer areas are examples of non-structural BMPs. Structural BMPs are the physically tangible measures that typically come to mind when one thinks of surface runoff treatment. They can range from something as conceptually simple as porous pavement to large engineered wetlands where pollutant removal occurs at the biological and chemical level. The common trait found in all structural BMPs is uncovered by examining 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, pg.181). While the 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 discussed individually, in detail, in Chapter 2.

Structural BMPs can be further categorized as retention, detention, infiltration, wetland, or filtration. Retention BMPs include wet ponds, extended storage ponds, and wet vaults. In contrast to detention facilities, retention BMPs usually exhibit a permanent pool. In most instances, this permanent pool will require that a constant baseflow be present. Detention BMPs exist as extended detention ponds, oversized pipes, oil and grit separators, and dry swales. The mechanism by which detention BMPs operate is to detain a "first flush" volume of runoff to permit pollutants to settle out of the water column. Both retention and detention BMPs have the potential to do an excellent job of mitigating the peak rate of runoff from a developed site to levels equal or less than pre-development conditions. Infiltration BMPs consist of porous pavement, infiltration trenches, and infiltration basins. Typically, infiltration BMPs exhibit very high pollutant removal efficiencies, but do very little to control the peak rate of runoff leaving a site. Wetland BMPs can be naturally occurring or engineered. The unique simultaneous treatment of pollutants by physical, chemical, and biological means define wetland practices. The final category of structural BMPs is filtration measures. Filtration measures include sand filters, underground filters, bioretention devices, and filter strips. Much like infiltration measures, filtration devices exhibit exceptionally high pollutant removal capabilities. However, these measures are associated with inherently high maintenance costs. In addition to the structural BMPs discussed, a number of low impact development *strategies* exist which are also considered viable BMP practices in many settings.

Having such a wide array of BMPs at one's disposal makes selection of the optimal measure for a given site not only daunting, but subject to personal or historical preference. Presently, the engineering community relies heavily on a number of BMP selection matrices to facilitate selection of an adequate BMP for a particular application. However, as discussed later, many significant shortcomings exist in this BMP selection approach, as well as in the selection matrices themselves. 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 state stormwater manual is dedicated solely to the selection and location of BMPs. The Maryland BMP selection process employs six primary criteria, with each of these criteria represented by an individual selection matrix. These matrices assist in the selection of appropriate site-specific BMPs by examining *contributing watershed factors, terrain factors, stormwater treatment suitability, physical feasibility factors, community and environmental factors, and permitting*. Conspicuously absent in the BMP selection approach used by the MDE and other agencies throughout the United States are considerations for long-term BMP pollutant removal performance and maintenance costs.

The efficiency of a BMP is defined simply as a measure of how well the practice or series of practices removes targeted pollutants. While this concept is relatively simple in concept, the mathematical attempts to quantify BMP efficiency are numerous and often complex. Intuitively, the pollutant removal performance of a structural BMP, and the inevitable decline in this performance over the measure's lifetime, should be paramount criteria in the BMP selection process. However, as evidenced by the absence of removal efficiency as a selection criterion in the stormwater management measure selection procedure previously described, it is typically not at the forefront of most BMP selection and design processes.

Of additional interest to any developer or municipal agency is the financial impact of implementing a BMP. Not only does the implementation cost exist, but there exists long-term maintenance costs associated with almost any BMP. Much like pollutant removal efficiency, implementation and maintenance costs logically should be integral considerations in the BMP selection process.   However, the selection flow charts and matrices employed by many agencies neglect these considerations. The Federal Highway Administration 1996 publication titled <u>Evaluation and Management of Highway Runoff Water Quality</u> contains a selection matrix which presents pollutant removal efficiencies and the various costs associated with various BMPs. The selection matrix developed by the FHWA examines the efficiencies and 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, pg.184) reveals that many of the removal efficiencies are not shown, 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.

As previously described, among the categories of criteria to consider in selecting a BMP for a particular site or objective are site-specific characteristics; local, state, and federal ordinances; and implementation and long-term maintenance costs. A selection consideration such as long-term maintenance cost may manifest itself in a very subjective fashion during the BMP selection process. For example, a BMPs cost may be of very limited interest to the reviewing locality, whereas cost may be the dominant selection criterion in the eyes of a developer. By contrast, the pollutant removal efficiency of a BMP may be necessarily prioritized in the selection process because of the required adherence to governing legislation. These are merely two possible criteria influencing selection. As more and more selection criteria are considered, the task of *objectively and optimally* selecting a BMP becomes increasingly complex. One mathematical approach for optimization in the face of multiple influential criteria is the Analytic Hierarchy 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, pg. 15). "Fundamentally, the AHP works by developing priorities for alternatives and the criteria used to judge the alternatives" (Schmoldt, 2001, pg. 16). This prioritization procedure places weights on the influential selection criteria, thus accommodating the varying scales and units exhibited by these criteria. The weighting component of the AHP permits mathematical optimization when the influential criteria exhibit vastly different scales, or even no scale (units) at all.

1.1 Problem Statement

Clearly, while of great value to the practicing engineer or planner, the BMP selection matrices presently in existence exhibit significant shortcomings. In particular, these matrices lack adequate consideration for annual BMP maintenance costs and the inevitable decline in a BMPs pollutant removal performance over time. Furthermore, these matrices are subject to personal, geographic, and historical bias. This research seeks to expand upon the BMP selection matrices used presently in the engineering community. Additionally, this research will apply a mathematical optimization algorithm, namely the Analytic Hierarchy Process, to the BMP selection process in an attempt to minimize human subjectivity in the selection process, thus providing optimal and unbiased selection of BMPs for a given site.

1.2 Research Objectives

In order to successfully address the outlined problem statement, the following tasks must be completed.

1. Construction of stand-alone matrices that facilitate BMP selection based on long-term pollutant removal performance and annual maintenance cost.
2. Construction of hierarchal comparisons between alternative BMPs and also between their relevant selection criteria.
3. Application of the hierarchal comparisons created in step 2 to the Analytic Hierarchy Process in BMP selection case studies.

Chapter 2 of this work provides a literature review of the *Maryland Department of the Environment* and *Minneapolis – St. Paul Metropolitan Council* approaches to BMP selection. Chapter 3 presents a literature review of the AHP and documents the algorithm's theory, equations, and required input data necessary to achieve the aforementioned research objectives. Chapter 4 details the construction of new BMP selection matrices whose selection criteria are long-term pollutant removal performance. Chapter 5 details the construction of new BMP selection matrices whose selection criterion is annual operations and maintenance cost. Chapter 6 subjects existing BMP performance data as well as the BMP selection data developed in Chapters 4 and 5 to the AHP methodology, facilitating hierarchal comparisons of the 14 BMPs described in Chapter 2. Finally, Chapter 7 presents a case study for implementation of the AHP in multiple real-world BMP selection scenarios. Chapter 8 summarizes the successes and shortcomings of this work, and presents areas of future research related to optimal BMP selection.

Chapter 2.0
Literature Review of BMP Selection Approaches And Identification of Individual BMPs

Chapter 2 presents a literature review of two of the BMP selection processes used in the present-day engineering community.

2.1 The Maryland Department of the Environment Approach to BMP Selection

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 state stormwater manual is dedicated solely to the selection and location of BMPs. The MDE has developed a BMP selection process employing six primary criteria, with each of these criteria represented by a selection matrix. These matrices facilitate the selection of appropriate site-specific BMPs by examining contributing watershed factors, terrain factors, stormwater treatment suitability, physical feasibility factors, community and environmental factors, and permitting. Rather than consider each individual BMP in the selection matrices, the MDE approach directs the designer to a particular category of BMPs (ponds, wetlands, infiltration, filters, channels) from which the designer can then chose the specific BMP that he or she considers most appropriate.

The first selection matrix, "Watershed Factors," evaluates BMP suitability by the following six criteria: proximity to intensely developed areas, proximity to designated cold water streams, proximity to sediment-sensitive streams, required aquifer protection, required reservoir protection, and the presence of shellfish harvesting beds. Of fundamental concern when designing urban BMPs are the characteristics of the receiving water body and its entire contributing watershed. This matrix's purpose is to prohibit the selection of BMPs that are not capable of achieving the necessary pollutant removal required for environmentally sensitive watersheds. Additionally, this matrix precludes selection of BMPs that do not satisfy unique watershed design constraints and objectives. Existing as the initial phase of BMP selection, this matrix forces the designer to become aware of any special water quality concerns present in the watershed of interest.

BMP GROUP	CRITICAL AREA	COLD WATER	SENSITIVE STREAM	AQUIFER PROTECTION	RESERVOIR PROTECTION	SHELLFISH BEACH
Ponds	Drainage Area may limit except for P-5, P-1 has lower removal rates	Restricted (see Appendix B.1.2) Offline design recommended Maximize shading of open pool areas	Require additional storage for control of Cp_v	May require liner if A soils are present Pretreat hotspots 2-4 ft SD*	Require control of Cp_v	Moderate bacteria removal, design to prevent geese problems, provide permanent pools
Wetlands	Drainage area may limit, W-4 excepted	May be restricted (see Appendix B.1.2)	Require additional storage for control of Cp_v	May require liner if A soils are present 2-4 ft SD*	Require control of Cp_v	Provide 48 hr ED for max. bacterial dieoff
Infiltration	Often infeasible due to soils or water table in tidal areas.	OK, if site has appropriate soils	OK, if site has appropriate soils	SD* from wells and water table No untreated hotspot runoff OK to infiltrate rooftop runoff	SD* from bedrock and water table	OK, but a min. 2 to 4 ft SD* is required
Filtering Systems	OK	OK, but evaluate for stream warming	May be necessary for pretreatment	OK, if designed w/out exfiltration	May be necessary for pretreatment prior to another BMP	OK, Moderate to high bacterial removal
Open Channels	OK	OK	Should be linked w/basin to provide Cp_v	OK, but hotspot runoff must be adequately pretreated	OK, but hotspot runoff must be adequately pretreated	Poor bacterial removal for O-2

Figure 2.1 MDE Watershed Factors Matrix
Source: Maryland Department of the Environment Stormwater Design Manual, 2000

The first criteria-based column of the Watershed Factors Matrix considers BMPs that are to be located within the Intensely Developed Area (IDA) of the Maryland Critical Area. This critical area is designated as a zone extending 1,000 feet landward from the mean high tide and the landward edge of tidal wetlands. Within this zone, BMPs must demonstrate compliance with Maryland's "10% Rule." This rule requires that post-development stormwater runoff from a site exhibit a minimum 10% reduction in phosphorus loads when compared to the pre-development runoff from the same site. This component of the matrix precludes selection of BMPs not capable of reducing the phosphorus content of stormwater runoff.

The next column in the matrix considers the special requirements governing discharge to designated cold and cool water streams. These designated streams have habitat qualities that are capable of supporting trout and other sensitive aquatic species.

Stormwater discharge from some BMPs can have potentially adverse impacts on cold water streams, and this component of the selection process exists to prevent selection of these measures. When discharge of a site's runoff is planned for a designated cold water stream, certain design objectives arise that otherwise may not be prioritized. These measures include, prevention of stream warming, ensuring naturally occurring recharge, prevention of bank and channel erosion, and preservation of the natural riparian corridor. In addition to prohibiting the use of certain BMPs in the vicinity of designated cold water streams, the matrix also provides special provisions for those measures deemed permissible.

Streams categorized as "sensitive" may be designated by local authorities based on a number of criteria. Typically, these streams are characterized by a contributing watershed whose impervious cover is less than 15%. Additionally, these streams may possess high quality cool or warm water aquatic resources. Much like the previous selection consideration for cold water streams, the sensitive stream criterion attempts to maintain and preserve habitat quality and the stream's natural integrity. Unlike designated cold water streams, stream warming from stormwater runoff is not the paramount concern. However, the inability of a BMP to achieve other sensitive stream requirements may preclude its use.

The next two considerations in the Watershed Factors Matrix, aquifer and reservoir protection, present unique and potentially conflicting elements for the BMP designer. The primary design constraint is to prevent the contamination of drinking water by preventing the entrance of hotspot runoff into the water supply. However, from a water budget standpoint, the recharge of stormwater is needed to maintain flow in streams and wells during periods of dry weather. When stormwater runoff is directed from a BMP to a public supply reservoir, depending on the treatment employed at the water intake, it may be necessary to achieve a greater level of pollutant removal than would otherwise by necessary. Of particular concern is ensuring that hotspot runoff is adequately treated so that it does not contaminate drinking water.

The final element of the Watershed Factors Matrix provides consideration for the unique protection necessary when runoff is directed to a shellfish harvesting area or a public swimming beach. In these areas, a higher level of treatment is required of the

BMP chosen, with the principal concern being bacterial contamination from stormwater runoff. This element of the first MDE BMP selection matrix steers the designer to BMPs that maximize bacteria removal from stormwater runoff.

The second step in the MDE best management practice selection process is executed by employing the “Terrain Factors” matrix. This matrix guides BMP selection by examining the following three factors: site relief, site proximity to karst areas, and special concerns for sites located in mountainous terrain. Sites, such as those found in coastal areas, lacking pronounced relief, may make some BMPs such as ponds infeasible. Conversely, due to the inherently flat slopes found in low relief areas, measures such as swales and infiltration basins may operate exceptionally well. Karst regions with high occurrences of carbonaceous rocks often limit or prohibit the use of the infiltration family of BMPs. These limitations are typically governed by the local review authority. Sites situated in mountainous regions will usually exhibit steep slopes. Slopes in excess of 10 percent require special design provisions for pond embankments, and often prevent the use of infiltration swales, trenches, and basins.

BMP GROUP	LOW RELIEF	KARST	MOUNTAINOUS
Ponds	Maximum normal pool depth of 4 feet (dugout)	• geotechnical tests • max ponding depth • Require poly or clay liner	Embankment heights restricted
Wetlands	OK		Embankment heights restricted
Infiltration	Minimum distance to water table of 2 feet	May be prohibited. Consult with local approval authority.	Max slope 15% trenches must have flat bottom
Filtering Systems	Several designs limited by low head (F-1 and F-2)	Require poly-liner or impermeable membrane to seal bottom	OK
Open Channels	Generally feasible due to low slopes	OK	Often infeasible in steeper slopes

Figure 2.2 MDE Terrain Factors Matrix

Source: Maryland Department of the Environment Stormwater Design Manual, 2000

The next matrix in the MDE selection process is the “Stormwater Treatment” matrix. This matrix evaluates the various BMPs by their ability to provide groundwater recharge, ability to achieve the TSS removal levels required for discharge to impaired streams, ability to provide mitigation of peak *rate* of runoff, potential safety risks, required space, and the ability to accept "hotspot" runoff. This matrix is used in conjunction with Chapter 2 of the MDE stormwater manual to consider the ability of varying BMPs to meet these stormwater treatment criteria. Unlike the two previous MDE selection matrices, the Stormwater Treatment matrix examines individual measures as well as categories of BMPs. It is important to note that the inability of a particular measure to meet one of these criteria may not completely eliminate it from consideration. However, the inability of a BMP to meet one of these criteria, should the BMP be required by governing ordinance, does mean that it must be used as only one of multiple BMPs at the site.

CODE	BMP List	Re_v Ability	Cp_v Control	Qp Control	Additional Safety Concerns	SPACE	ACCEPT HOTSPOT RUNOFF
P-1	Micropool ED	No[1]	Yes	Yes	No	Yes	Yes[3]
P-2	Wet Pond	No[1]	Yes	Yes	Yes	Varies	Yes[3]
P-3	Wet ED Pond	No[1]	Yes	Yes	Yes	Yes	Yes[3]
P-4	Multiple Pond	No[1]	Yes	Yes	Yes	No	Yes[3]
P-5	Pocket Pond	No[1]	Yes	Yes	Varies	Yes	Yes[3]
W-1	Shallow Wetland	Varies[2]	Yes	Yes	No	No	Yes[3]
W-2	ED Wetland	Varies[2]	Yes	Yes	Varies	Varies	Yes[3]
W-3	Pond/Wetland	Varies[2]	Yes	Yes	Yes	No	Yes[3]
W-4	Pocket Wetland	No	Varies	Varies	No	Varies	Yes[3]
I-1	Infiltration Trench	Yes	Varies	Varies	No	Yes	No[3]
I-2	Infiltration Basin	Yes	Varies	Varies	No	Varies	No[3]
F-1	Surface Sand Filter	Varies[2]	Varies	Varies	No	Yes	Yes[4]
F-2	Underground SF	No	No	No	Varies	Yes	Yes
F-3	Perimeter SF	No	No	No	No	Yes	Yes
F-4	Organic Filter	Varies[2]	Varies	Varies	No	Yes	Yes[4]
F-5	Pocket Sand Filter	Varies[2]	Varies	Varies	No	Yes	Yes[4]
F-6	Bioretention	Yes	Varies	Varies	No	Varies	Yes[4]
O-1	Dry Swale	Yes	No	No	No	Varies	Yes[4]
O-2	Wet Swale	No	No	No	No	Varies	No

1 Structures that require impermeable liners or that intercept groundwater may not be used for groundwater recharge.

2 Re_v may be provided by exfiltration (see Chapter 3.4).

3 Not allowed unless pretreatment to remove hydrocarbons, trace metals, and toxicants is provided.

4 Yes, but only if bottom of facility is lined with impermeable filter fabric that prevents leachate infiltration.

Figure 2.3 MDE Stormwater Treatment Matrix

Source: Maryland Department of the Environment Stormwater Design Manual, 2000

The first item considered in Figure 2.3 is groundwater recharge (Re_V). While some BMPs are capable of providing significant recharge of groundwater, others, such as wet ponds equipped with a liner, actually prevent the natural recharge of site runoff that would otherwise occur. It is important to note that other stormwater management measures and approaches such as grass channels, filters, and disconnection of rooftop runoff are capable of meeting Re_v requirements. Therefore, the inability of a BMP to achieve the required recharge may not prohibit its use on a particular site, provided other measures and approaches can be incorporated to provide the required recharge.

The second selection criterion in Figure 2.3 is the ability of the BMP to provide a stream channel protection volume (Cp_V). In addition to the detention volume often required to provide peak runoff rate mitigation, sensitive streams may require stormwater runoff to be detained such that sediment can settle out prior to entering the receiving stream. This selection criterion only examines the individual BMPs ability to meet the Cp_v requirement. However, the inability of a BMP to meet this requirement does not eliminate it from consideration. To the designer, it simply implies that multiple BMPs are necessary to achieve the Cp_v.

The third column in Figure 2.3 presents the peak mitigation performance of the individual BMP practices. Once the lone concern of stormwater management, peak mitigation remains a critical site design consideration. Typically the post-development runoff from a site must be less than or equal to the pre-development runoff. Often, this requirement is enforced for multiple return frequency storms. As with the other selection criteria represented by this matrix, the inability of a single BMP to satisfy a site's peak mitigation requirement does not necessarily preclude its use. However, if a single BMP cannot reduce the peak sufficiently, multiple BMPs may be required.

The matrix's next two columns consider safety issues associated with each BMP and the relative space required of the measure. The "Additional Safety Concerns" column is presented as a comparative index to express the potential need for *additional* safety concerns within a BMP practice. A "no" indicates that no additional measures are needed while a "yes" alerts designers that deep pools inherently associated with the particular practice may present potential safety risks. Liability and safety are primary considerations when BMPs are to be located in the vicinity of residential settings. The

“Adequate Space” column is also a comparative index that examines how much space a BMP typically consumes at a site. A “yes” indicates that, compared to the overall land area of a site, the BMP practice consumes a relatively small area. A “no” indicates that the BMP may consume a relatively high fraction of land on the site.

The final column of the Stormwater Treatment Suitability Matrix considers whether or not the BMP practice can directly receive the highly contaminated runoff from areas classified as “hotspots,” such as industrial parking, loading, and storage areas. The matrix presents not only information on whether or not a particular measure can receive hotspot runoff, but also includes design restrictions and any additional measures that may be required to protect downstream areas from potential spills or leakages.

The next task in the MDE selection process is accomplished by utilizing the “Physical Feasibility” matrix. Existing as the fourth step in the selection process, it is assumed that at this point in the selection process the quantity of feasible BMPs has been reduced to a manageable number from which to choose. The purpose of this matrix is to further evaluate the appropriateness of the remaining measures by the following factors: site soil type, depth to water table, contributing drainage area, slope restrictions, available hydraulic head, and the proximity to “ultra-urban” areas. Infiltration measures as well as filtration measures require a minimum soil permeability. Conversely, soils with excessively high permeability may not support certain BMPs such as ponds. Also of particular interest when considering infiltration measures is the depth to the seasonally high water table, represented by the matrix’s second column. The matrix’s drainage area column allows the designer to identify measures suitable and capable of accepting the runoff volume from the site’s contributing watershed. The site slope column places restrictions on infiltration measures, prohibiting their use if site slopes exceed 15 percent. The hydraulic head criterion provides the designer with an estimate of the elevation *difference* necessary at a site for gravitational processes to operate within a particular BMP practice. Finally, the matrix identifies which measures are suitable for highly urbanized areas. These areas present potential difficulties in that they frequently offer limited space for the BMP, but often produce highly contaminated runoff.

CODE	BMP LIST	SOILS	WATER TABLE	DRAINAGE AREA (Acres)	SLOPE RESTRICT.	HEAD (Ft)	ULTRA URBAN
P-1	Micropool ED	"A" Soils May Require Pond Liner "B" Soils May Require Testing	4 Feet[1] If Hotspot Or Aquifer	10 Min[2]	None	6 to 8 Ft	Not Practical
P-2	Wet Pond			25 Min[2]			
P-3	Wet ED Pond						
P-4	Multiple Pond						
P-5	Pocket Pond	OK	Below WT	5 Max[3]		4 Ft	OK
W-1	Shallow Wetland	"A" Soils May Require Liner	4 Feet[1] If Hotspot Or Aquifer	25 Min	None	3 to 5 Ft	Not Practical
W-2	ED Wetland						
W-3	Pond/Wetland						
W-4	Pocket Wetland	OK	Below WT	5 Max		2 To 3 Ft	Depends
I-1	Infiltration Trench	$f \geq 0.52$ Inch/Hr	4 Feet[1]	5 Max	Installed in No More Than 15% Slopes	1 Ft	Depends
I-2	Infiltration Basin			10 Max		3 Ft	Not Practical
F-1	Surface Sand Filter	OK	2 Feet	10 Max[3]	None	5 Ft	Depends
F-2	Underground SF			2 Max[3]		5 to 7ft	OK
F-3	Perimeter SF			2 Max[3]		2 to 3 Ft	
F-4	Organic Filter			5 Max[3]		2 to 4 Ft	
F-5	Pocket SF			5 Max[3]		2 to 5 Ft	
F-6	Bioretention	Made Soil				5 Ft	
O-1	Dry Swale	Made Soil	2 Feet	5 Max	4% Max Cross-slope	3 to 5 Ft	Not Practical
O-2	Wet Swale	OK	Below WT	5 Max		1 Ft	

Notes: OK= not restricted, WT= water table

1 **Four foot separation distance is maintained to the seasonally high water table (2 feet on Lower Eastern Shore).**

2 **Unless adequate water balance and anti-clogging device installed**

3 **Drainage area can be larger in some instances**

Figure 2.4 MDE Physical Feasibility Matrix

Source: Maryland Department of the Environment Stormwater Design Manual, 2000

Step five in the BMP selection process employed by the MDE examines community and environmental factors. As with previous criteria, selection of BMP practices conforming to various community and environmental factors is facilitated by a selection matrix. This matrix evaluates potentially suitable BMP practices by the following factors: ease of maintenance, community acceptance, construction cost, habitat quality, and "other factors" that may influence selection. The components of this matrix are less quantitative than those previously described. Consequently, practices are evaluated in terms of "benefit" rather than by quantifiable data.

CODE	BMP LIST	EASE OF MAINTENANCE	COMMUNITY ACCEPTANCE	COST (Relative To Drainage Area)	HABITAT QUALITY	OTHER FACTORS
P-1	Micropool ED	Medium	Medium	Low	Medium	Trash/debris
P-2	Wet Pond	Easy	High	Low	High	
P-3	Wet ED Pond	Easy	High	Low	High	
P-4	Multiple Pond	Easy	High	Medium	High	
P-5	Pocket Pond	Difficult	Medium	Low	Low	Drawdowns
W-1	Shallow Wetland	Medium	High	Medium	High	
W-2	ED Wetland	Medium	Medium	Medium	High	Limit ED depth
W-3	Pond/Wetland	Difficult	High	Medium	High	
W-4	Pocket Wetland	Medium	Low	Low	Medium	Drawdowns
I-1	Infiltration Trench	Difficult	High	Medium	Low	Avoid large stone
I-2	Infiltration Basin	Medium	Low	Medium	Low	Frequent pooling
F-1	Surface SF	Medium	Medium	High	Low	
F-2	Underground SF	Difficult	High	High	Low	Underground ∴ Out of sight
F-3	Perimeter SF	Difficult	High	High	Low	Traffic Bearing
F-4	Organic Filter	Medium	High	High	Low	Filter Media Replacement
F-5	Pocket SF	Medium	Medium	Medium	Low	
F-6	Bioretention	Medium	Medium	Medium	Low	Landscaping
O-1	Dry Swale	Easy	High	Medium	Low	
O-2	Wet Swale	Easy	High	Low	Low	Mosquitoes Possible

Figure 2.5 MDE Community / Environmental Factors Matrix
Source: Maryland Department of the Environment Stormwater Design Manual, 2000

The Community / Environmental Factors Matrix's first column provides the user with information on a BMP practice's maintenance requirements. This information assesses the *relative* maintenance effort needed in terms of three criteria: frequency of scheduled maintenance, chronic maintenance problems (such as clogging of infiltration practices), and anticipated failure rates. To maintain expected performance, all BMPs require routine maintenance. However, as evidenced by the matrix, the relative maintenance effort varies considerably among measures.

The Community Acceptance criterion presented in column two of the matrix assesses the community acceptance of BMP practices based on three factors: market and preference surveys, reported nuisance problems, and visual aesthetics. The information presented in this column considers only the BMP practice itself, and does not consider amenities such as landscaping which may potentially improve a practice's ranking.

The Construction Cost column of the matrix evaluates the various BMPs in terms of their relative construction cost per impervious acre treated. The rankings presented in this column are based on cost surveys and data that are geographically specific to the state of Maryland. It should be noted that the cost rankings presented in this matrix represent only initial construction costs, and do not consider long-term maintenance costs, or the costs to repair or overhaul the practice should it fail.

The final two columns of the matrix evaluate the individual BMP practices on their ability to provide wildlife habitat and other factors that may be unique to the practice. The criteria considered in the Habitat Quality column of the matrix include size of the BMP, wetland features and vegetative cover, and the BMP buffer. The quality of wildlife habitat presented in this column is based on the assumption that routine maintenance efforts are made to landscape the measure appropriately.

The final step in the Maryland BMP selection process is the completion of a Location and Permitting Factors checklist. Unlike the previous five steps, this component of the BMP evaluation process does not assist in *selecting* an appropriate or optimal BMP practice for a site. It simply serves as a condensed summary of current BMP restrictions as they relate to site features regulated under local, State, or federal law. The restrictions addressed in the Location and Permitting Factors checklist fall into one of three categories, detailed as follows.

1. Locating a BMP within an area expressly prohibited by law.
2. Locating a BMP within an area that is strongly discouraged and is only allowed on a case-by-case basis.
3. BMPs must be setback a fixed distance from designated site features.

SITE FEATURE	LOCATION AND PERMITTING GUIDANCE
❑ **Jurisdictional Wetland** U.S. Army Corps of Engineers Section 404 Permit and/or MDE Wetlands Permit ✔	• wetlands should be delineated prior to siting stormwater BMPs. • use of wetlands for stormwater treatment strongly discouraged and requires State and federal permit. • BMPs are also restricted in the 25 to 100 foot required wetland buffer. • buffers may be utilized as a non-structural filter strip (e.g., accept sheetflow). • must justify that no practical upland treatment alternatives exist. • stormwater must be treated prior to discharge into a wetland. • where practical, excess stormwater flows should be conveyed away from jurisdictional wetlands.
❑ **Stream Channel** (Waters of the U.S) U.S. Army Corps of Engineers (COE) Section 404 Permit MDE Wetlands and Waterways Permit ✔	• stream channels should be delineated prior to design using MDE criteria. • instream ponds require MDE review and permit. • instream ponds are prohibited in Use III waters. • ponds located within USE III watersheds may require small pond review and approval from the MDE Dam Safety Division. • must justify that no practical upland treatment alternatives exist. • Q_p and Cp_v treatment is preferred over WQ_v treatment. • implement measures that reduce downstream warming.
❑ **100 Year Floodplain** Local Stormwater review Authority MDE Wetlands and Waterways Permit ✔	• grading and fill for BMP construction is strongly discouraged within the ultimate 100 year floodplain, as delineated by FEMA flood insurance rate, FEMA flood boundary and floodway, or local floodplain maps. • floodplain fill cannot raise the floodplain water surface elevation by more than a tenth of a foot.
❑ **Stream Buffer** Check with appropriate review authority whether stream buffers are required	• consult local authority for stormwater policy. • ponds located within 100 feet of a flowing stream in a USE III watershed may require a small pond approval by the MDE Dam Safety Division • BMPs are strongly discouraged in the stream-side zone (within 25 feet of streambank). • consider how outfall channel will cross buffer to reach stream. • BMPs can be located within the outer portion of a buffer.

Figure 2.6 MDE Location and Permitting Checklist

Source: Maryland Department of the Environment Stormwater Design Manual, 2000

2.2 The Minneapolis – St. Paul Metropolitan Council Stormwater Suitability Approach to BMP Selection

In an effort to investigate how other regions of the country address best management practice selection, the Minneapolis – St. Paul Metropolitan Council's stormwater design manual was reviewed. Chapter two of the Minneapolis – St. Paul manual is dedicated exclusively to the selection of BMPs. More abbreviated than the Maryland selection procedure, the Metropolitan Council suggests a three step process to BMP selection. The first step in this process is to evaluate the stormwater treatment suitability of the various practices. This matrix constructed by the Minneapolis – St. Paul Metropolitan Council is analogous to the Stormwater Treatment Suitability Matrix employed by the MDE. This selection step employs three primary criteria. The first component investigated is the ability of various BMPs to meet stormwater runoff rate reduction requirements. Second, the ability to meet stormwater runoff volume reduction requirements is considered. And, finally, the matrix considers the ability of the various BMPs to serve as a primary or secondary treatment practice for pollutant removal.

		RUNOFF HYDROLOGY		WATER QUALITY BENEFIT			
BMP Family	BMP List	Rate Control	Volume Reduction	TSS	P & N	Metals	Fecal Coliform
Retention	Wet Pond	High	Low	Primary	Secondary	Secondary	Secondary
	Extended Storage Pond	High	Low	Primary	Secondary	Secondary	Secondary
	Wet Vaults	Medium	Low	Primary	Secondary	Secondary	Minor
Detention	Dry Pond	High	Low[1]	Secondary	Minor	Minor	Minor
	Oversized Pipes	High	Low	Minor	Minor	Minor	Minor
	Oil Grid/Separator	Low	Low	Secondary	Minor	Minor	Minor
	Dry Swale	Medium	Low[1]	Primary	Secondary	Primary	Minor
Infiltration	On-Lot Infiltration	Medium	High	Primary	Primary	Primary	Secondary
	Infiltration Basin	Medium	High	Primary	Primary	Primary	Secondary
	Infiltration Trench	Medium	High	Primary	Primary	Primary	Secondary
Wetland	Stormwater Wetland	High	Medium	Primary	Secondary	Secondary	Primary
	Wet Swale	Low	Low	Primary	Secondary	Secondary	Minor
Filtration	Surface Sand Filters	Low	Low[1]	Primary	Secondary	Primary	Secondary
	Underground Filters	Low	Low	Primary	Secondary	Primary	Secondary
	Bioretention	Medium	Medium	Primary	Primary	Primary	Secondary
	Filter Strips	Medium	Medium	Secondary	Minor	Minor	Minor

Figure 2.7 Minneapolis-St. Paul Metropolitan Council Stormwater Suitability Matrix

Source: Minnesota Urban Small Sites BMP Manual, 2001

Examination of Figure 2.7 reveals that the Stormwater Suitability Matrix employed by the Minneapolis-St. Paul Metropolitan Council is very qualitative in nature. Evaluation of the individual BMP practices exists in relative terms compared to other BMPs, and not in absolute terms of performance. While the matrix is useful in refining the selection of measures capable of providing volume and/or peak runoff mitigation, it exhibits significant shortcomings in the evaluation of a measure's ability to achieve a *target pollutant removal percentage*. Typically, the installation of BMP practices coincides with a specific performance target for pollutant removal. While the matrix indicates which measures are capable of serving as primary water quality measures, it does not present quantified pollutant removal performance data.

The next step in the BMP selection process described by the Metropolitan Council is to examine physical feasibility factors. The matrix employed in this step is very similar to that developed by the Maryland Department of the Environment, essentially considering any physical restraints at a site that may restrict or preclude the use of a particular BMP practice.

BMP Family	BMP List	Soil Considerations	Water Table[1]	Suitable for Site ≤ 5 acres	Head (feet)	Area Require-ments	Accepts Hotspot Runoff
Retention	Wet Pond	"A" soils may require pond liner	3 feet if hotspot or aquifer	Limited[4]	3 – 8	High	Varies[2]
	Extended Storage Pond	"B" soils may require testing		Limited	4 – 8	High	Varies[2]
	Wet Vaults	NA	NA	Yes	4 – 8	Low	Yes
Detention	Dry Pond	"A" soils may require pond liner "B" soils may require testing	3 feet if hotspot or aquifer	Yes	3 – 8	High	Varies[2]
	Oversized Pipes	NA	NA	Yes	5 – 10	Low	Yes
	Oil Grit/Separator	NA	NA	Yes	4 – 8	Low	Yes
	Dry Swale	Any soil type	3 feet	Yes	3 – 5	Med.	Yes[3]
Infiltration	On-Lot Infiltration	"A" and "B" soils preferred "C" soil difficult "D" soil not recommended	3 feet	Yes	1	Med.	No
	Infiltration Basin		3 feet	Yes	3 – 5	High	No
	Infiltration Trench		3 feet	Yes	2 – 4	Med.	No
Wetland	Stormwater Wetland	Any soil type if below water table	NA	Limited	2 – 6	High	Varies[2]
	Wet Swale	Any soil type if below water table	Below water table	Yes	3 – 5	Med.	No
Filtration	Surface Sand Filters	Any soil type	3 feet or 0 feet with liner	Yes	2 – 4	High	Yes[3]
	Underground Filters	NA	NA	Yes	4 – 8	Low	Yes
	Bioretention	Planting soil	3 feet	Yes	3 – 5	High	Yes[3]
	Filter Strips	Any soil type	3 feet	Yes	1	Med.	Yes

1 Recommended minimum elevation above water table. Check with state and local regulations.
2 Varies depending on type and concentration of contaminants in the runoff and depth to the water table.
3 Yes, but only if bottom of facility includes an impermeable liner that prevents infiltration of highly contaminated water into the groundwater.
4 Suitable only if a consistent source of water (such as groundwater) is available or if the pond is constructed with a liner or in clay soils.

Figure 2.8 Minneapolis-St. Paul Metropolitan Council Physical Feasibility Matrix
Source: Minnesota Urban Small Sites BMP Manual, 2001

The first evaluation column of the matrix shown in Figure 2.8 presents information regarding which hydrologic soil groups (HSG) affect the selection of each individual practice. The presence of hydrologic soil group "A" and, to a lesser degree, "B" often presents obstacles for the implementation of pond BMPs. These soil groups exhibit high and moderate infiltration rates respectively. The water quality benefit of pond BMP practices arises primarily from the gravitational settling of pollutants over some hydraulic residence time in the pond. High infiltration rates exhibited by the soil upon which the pond is constructed result in significant losses of the detained runoff through the pond bottom and embankments. This infiltration loss not only shortens the desired hydraulic residence time, but may also permit the transport of pollutants into ground water supplies. As indicated by Figure 2.8, the presence of high infiltration soils on a site may not preclude the use of pond BMP practices, provided that the measure is constructed with a liner. Contrasting the problems encountered with high infiltration soils, hydrologic soil groups such as “C” and “D” present their own problems. Low infiltration soils often preclude the implementation of infiltration BMP practices. The low infiltration rates observed by these soil groups greatly increase the desired drawdown time for infiltration practices, resulting in undesired ponding and inadequate storage volume for subsequent runoff producing events.

Much like the MDE Physical Feasibility Matrix, the Minneapolis-St. Paul Metropolitan Council matrix considers the depth to the water table on a site, the site’s elevation difference (head), the area requirements for each individual BMP practice relative to overall site area, and the ability of the various measures to accept hotspot runoff. Unlike the MDE BMP selection approach, the Metropolitan Council includes a selection criterion dedicated to small sites (less than five acres in area). BMP practices designed to maintain a permanent pool must possess a source of surface baseflow to maintain the permanent pool during periods of drought and high evaporation rates. As evidenced by Figure 2.8, this minimum area requirement places possible restrictions on which BMP practices can be considered for sites with small contributing watersheds.

The final component of the Metropolitan Council’s selection process is to examine community and environmental factors that influence BMP selection. While the Metropolitan Council’s recommended BMP selection process has only three steps, many selection criteria and considerations overlap with the six step selection process developed by the Maryland Department of the Environment.

BMP Family	BMP List	Maintenance	Community Acceptance	Cost (Relative to Drainage Area)	Wildlife Habitat
Retention	Wet Pond	Low	High	Low	Medium
	Extended Storage Pond	Low	Medium	Low	Medium
	Wet Vaults	High	High	High	None
Detention	Dry Pond	Medium	Medium	Low	Low
	Oversized Pipes	Low	High	High	None
	Oil Grit/Separator	High	High	High	None
	Dry Swale	Medium	High	Medium	Low
Infiltration	On-Lot Infiltration	Medium	Medium	Low	Medium
	Infiltration Basin	Medium	Medium	Medium	Medium
	Infiltration Trench	Medium	Medium	Medium	None
Wetland	Stormwater Wetland	Low	High	Medium	High
	Wet Swale	Medium	High	Low	Medium
Filtration	Surface Sand Filters	Medium	Medium	High	Low
	Underground Filters	High	High	High	None
	Bioretention	Medium	Medium	Medium	Medium
	Filter Strips	Low	High	Low	Medium

Figure 2.9 Minneapolis-St. Paul Metropolitan Council Community / Environmental Factors Matrix
Source: Minnesota Urban Small Sites BMP Manual, 2001

The Metropolitan Council matrix shown in Figure 2.9 is essentially a duplicate of the Community / Environmental Factors matrix used by the MDE and presented as Figure 2.5. The two matrices serve only as relative comparisons between the various BMP practices, or, in the case of the “cost” column, as a relative cost of the practice relative to the area of the practice’s contributing watershed. As with the case of the MDE Community / Environmental Factors matrix, practices are evaluated in terms of “benefit” rather than by absolute, quantifiable units.

Clearly, the Minneapolis-St. Paul Metropolitan Council approach to BMP practice selection is very similar to the Maryland Department of the Environment approach. While useful in refining the selection process, the matrices previously described exhibit significant shortcomings. First, they inherently lend themselves to personal and historical biases. Practicing engineers and review authorities become comfortable with the design and implementation of certain, "favorite" BMP practices. In many cases these same practices are applied in settings where they may be feasible but not optimal. Second, completion of the matrix-based selection processes will present the designer with a collection of practices suited to the site. However, among the *feasible* options, there is no way to determine which measure is *optimal*. Finally, the matrices do not provide quantified data on the pollutant removal performance (initial and long-term), implementation cost, and maintenance cost of the practices.

2.3 Identification of Individual Best Management Practices

Broadly, BMPs are defined as "structural or nonstructural practices, or combination of practices, designed to act as effective, practicable means of minimizing the impacts of development on water quality" (FHWA, 1996). The breadth of this definition leads to an almost limitless number of structural devices and management / development strategies potentially classified as BMPs. However, examining a number of existing state stormwater management manuals, Federal Highway Administration documents, and publications by the Environmental Protection Agency reveals 15 practices/strategies to be the most popular BMP options employed within the United States. These practices are presented, as follows, by BMP class.

Table 2.1 BMPs Grouped by Class

BMP Class	Practice / Strategy
Pond	Dry Extended Detention
	Wet
Infiltration	Porous Pavement
	Trench
	Basin
Wetlands	Constructed Stormwater Wetlands
Filtering	Bioretention
	Vegetated Filter Strips
	Vegetated Water Quality Swales
	Sand Filtering Systems
Proprietary	Water Quality Inlets / Catch Basin Inserts
	Hydrodynamic Separators
Low Impact	Vegetated Roofs
	Minimum Disturbance / Minimum Maintenance
	Rainwater Capture and Reuse

The BMPs identified in Table 2.1 are discussed individually, at length, in Appendix B. The detailed description, review, and technical performance summary of these BMPs found in Appendix B serves as the foundation of the pairwise comparison templates developed in Chapter 6.

Chapter 3.0
Literature Review of the Analytic Hierarchy Process

Chapter 3 introduces and discusses the Analytic Hierarchy Process, including the algorithm, theory, and required inputs to support completion of the research objectives presented in Chapter 1. In summary, these research objectives are:

1. Construction of stand-alone matrices that facilitate BMP selection based on pollutant removal performance long-term maintenance cost.
2. Construction of hierarchal comparisons between alternative BMP measures and also between their relevant selection criteria.
3. Application of the hierarchal comparisons created in step 2 to the Analytic Hierarchy Process in multiple BMP selection and design case studies.

Among the categories of criteria to consider in selecting a BMP for a particular location or objective are site-specific characteristics; local, state, and federal pollution control ordinances; and implementation and long-term maintenance costs. A selection consideration such as long-term maintenance cost may manifest itself in a very subjective fashion during the BMP selection process. For example, in a private development scenario, a BMPs associated costs may be of very limited interest to the reviewing locality, whereas economic considerations may be the dominant selection criterion for the developer. By contrast, the pollutant removal efficiency of a BMP may be *necessaril*y prioritized in the selection process because of the required adherence to governing legislation. These are two possible criteria influencing selection. As more and more selection criteria are considered, the task of *objectively and optimally* selecting a BMP becomes increasingly complex. One mathematical approach for optimization in the face of multiple influential criteria is the Analytic Hierarchy 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, pg. 15).

First introduced by Saaty in 1977 and later revised in 1994, the AHP acts as a decision-support tool capable of solving complex decision 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 & Mann, 1995). Perhaps the greatest strength of the AHP is that, although its foundation lies in complex matrix manipulation, its employment is readily available to those with little knowledge of optimization theory. Furthermore, as illustrated in this document, the computational phases of the AHP are easily executed by employing familiar desktop software such as Microsoft Excel.

During the BMP selection process, in addition to easily quantified engineering and economic criteria, there are often political and financial influences impacting the choice of design options. Popular optimization tools, such as linear and non-linear programming, fall short in resolving these decisions because they inherently lack the ability to address multiple influential criteria with differing units or criteria exhibiting non-quantifiable units. The AHP is a powerful tool 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, pg. 16). Through pairwise comparisons, the AHPs prioritization step compares the various competing alternatives, such as different BMP practices, in terms of each selection criteria. Additionally, the algorithm establishes comparisons and prioritizations of the selection criteria themselves. These pairwise comparisons occur by establishing dimensionless *relative importances* among the competing alternatives and their influential selection criteria. The weighting component of the AHP permits mathematical optimization when the influential criteria exhibit quite different scales, or even no scale (units) at all.

Conceptually, the AHP is a three-step process that enables a decision maker to resolve the daunting task of multiple criteria optimization into an objective algorithmic approach. First, a hierarchy consisting of the possible outcomes and subordinate (intermediate) features influencing these outcomes is constructed. In the application scenario presented later in this paper, the end outcome or *goal* is to choose among competing BMP alternatives the optimal measure capable of addressing all required pollutant removal performance targets while simultaneously proving to be the most economically attractive option. The subordinate features of the hierarchy are the multiple categories of selection criteria influencing the decision. Next, and for each level of the hierarchy, pairwise comparisons between the possible BMP alternatives and between the criteria themselves determine the ordering of decision elements. This step enables priority weighting of the criteria influencing the outcome decision, as well as ranking of the *possible outcomes* in terms of performance for each criterion. Finally, matrix algebra propagates level-specific, local priorities to global priorities. Fundamentally, the AHP algorithm operates by prioritizing competing alternatives as well as the criteria used to judge the alternatives. This prioritization procedure places weights on the influential selection criteria, thus accommodating the varying scales and units exhibited by these criteria.

3.1 Construction of Pairwise Comparison Matrices

The first step in performing the AHP is to identify all possible alternatives from which a single alternative is selected. Next, it is necessary to identify all relevant criteria influencing the selection of a single alternative from the pool of feasible alternatives. Because the numerous selection criteria exhibit varying units (or in some cases no units at all), mathematical evaluation of the criteria requires the operator to determine the *relative* scale, or weight, of the alternatives in terms of each criterion. This task is accomplished by employing Table 3.1. Table 3.1 was first proposed by Saaty 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 *judgment matrices* for *each* selection criterion. This step evaluates the performance of each possible alternative against the other alternatives in terms of the various selection criteria. These judgment matrices are of dimensions *MxM, "M"* being the total number of alternatives considered. The final judgment matrix is termed the *criteria judgment matrix* and evaluates and ranks the importances of each of the influential criterion when compared against the other criteria. The criteria judgment matrix is of dimension *NxN, "N"* being the total number of influential 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 3.1 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 judgment and criteria judgment matrices are expressed in terms of the importance intensities illustrated in Table 3.1. For instance, consider a judgment matrix comparing 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 3.1, consider the following scenario:

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

At this point, the judgment matrix of criterion N appears as follows:

Table 3.2 Preliminary Construction of Judgment Matrix (Criterion "N")

N	A	B	C
A	1	7	1/3
B	1/7		
C	3		

Following the aforementioned convention, notice that the relative importances from Figure 3.1 are found in row one, while their reciprocal values are found in column one. “It is not mandatory to enter a reciprocal value, but it is generally rational to do so.” (Saaty, 1980) Furthermore, observe that, intuitively, alternative A is equally important when compared to itself. Now, consider the following additional constraint in the completion of the criterion N judgment matrix:

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

Table 3.3 Completed Judgment Matrix (Criterion “N”)

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 judgment matrices are constructed for each selection criterion. As presented in Tables 3.1 and 3.2, the competing 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 *judgment matrix* that prioritizes each selection criterion by comparing one against all other selection criteria.

3.2 Extraction of Priority Vectors

Upon creating alternative judgment matrices for each selection criterion as well as the criteria judgment matrix, the analyst then proceeds to the next step in the analytic hierarchy process, which is to extract the relative importances implied by each matrix. This task is accomplished by employing matrix algebra to determine 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 becomes increasingly complex, particularly in the absence of computing software specifically designed for such a task. However, a number of computationally accessible methods exist to facilitate extraction of the priority vectors. These methods are illustrated as follows.

The crudest method of principal eigenvector attainment is to simply sum the elements in each row of the matrix and then normalize them by dividing each sum by the total of all row sums. This will result in a vector whose sum is unity and whose first entry is the priority of the first activity, the second of the second activity, and so on. (Saaty, 1980, pg. 19) This approach is now applied to the matrix presented in Table 3.2.

Table 3.4 Priority Vector Extraction – Method 1

N	A	B	C	***Row Sum***
A	1	7	1/3	***8.333***
B	1/7	1	1/9	***1.254***
C	3	9	1	***13***

Σ Rows = 22.58

$$\begin{Bmatrix} 0.369 \\ 0.056 \\ 0.576 \end{Bmatrix} \qquad \textbf{\textit{(3.1)}}$$

The resulting priority vector, 3.1, indicates that in terms of criterion *"N,"* alternative *C* is prioritized, with alternatives *A* and *B* ranking second and third respectively.

Though still quite crude, a more accurate estimate of the principal eigenvector involves summing the elements of each column and then forming the reciprocals of these sums. Normalization is then accomplished by dividing each reciprocal value by the sum of the reciprocals. The normalized reciprocal values represent the matrix's priority vector. This approach is applied to the previous judgment matrix, with the resulting priority vector shown below.

Table 3.5 Priority Vector Extraction – Method 2

N	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 3.6 Column Reciprocal Values

Column Sum	***4.143***	***17***	***1.444***
Reciprocal Values	***0.241***	***0.059***	***0.693***

Σ Reciprocal Values = 0.993

$$\begin{Bmatrix} 0.243 \\ 0.059 \\ 0.698 \end{Bmatrix} \qquad \textbf{\textit{(3.2)}}$$

As with extraction method 1, the resulting priority vector, in (3.2), indicates that in terms of criterion *"N,"* alternative *C* is prioritized, with alternatives *A* and *B* ranking second and third respectively.

A more accurate estimate of the matrix's principal eigenvector consists of multiplying the *n* elements in each row of the matrix, and taking the n^{th} root of this product. This step is conducted for each row of the matrix, and then the values are normalized to yield the principal eigenvector. (Saaty, 1980, pg. 19)

Table 3.7 Priority Vector Extraction – Method 3

N	A	B	C	***Row Product***
A	1	7	1/3	***2.333***
B	1/7	1	1/9	***0.016***
C	3	9	1	***27***

Table 3.8 Row Root Values

Row Products	***2.333***	***0.016***	***27***
n^{th} Root	***1.326***	***0.252***	***3***

Σ Root Values = 4.578

$$\begin{Bmatrix} 0.290 \\ 0.055 \\ 0.655 \end{Bmatrix} \qquad \textbf{\textit{(3.3)}}$$

Again, as with the previous two extraction methods, the resulting priority vector, 3.3, indicates that in terms of criterion *"N,"* alternative *C* is prioritized, with alternatives *A* and

B ranking second and third respectively. It is interesting to note that methods two and three show a relatively small discrepancy between their respective priority vectors, and in fact appear to be converging on the results found by employing the fourth method detailed below.

The final method of priority vector extraction is an accurate, yet computationally simple method. This approach for obtaining 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. (Saaty, 1980, pg. 19) This method is illustrated as follows.

Table 3.9 Priority Vector Extraction – Method 4

N	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 3.10 Normalized Column Values and Resulting Row Sums

N	A	B	C	***Row Sum***
A	0.241	0.412	0.231	***0.884***
B	0.034	0.059	0.077	***0.170***
C	0.724	0.529	0.693	***1.946***

$$\begin{Bmatrix} 0.295 \\ 0.057 \\ 0.649 \end{Bmatrix} \qquad \textbf{\textit{3.4}}$$

The results of priority vector extraction method 4 reveal that all four methods rank the competing alternatives similarly. Each priority vector extraction method clearly shows alternative *C* as the superior option in terms of criterion *“N.”* The case study application of the AHP found in Chapter 7 employs priority vector extraction method 4 exclusively.

It is important to understand that these methods of priority vector calculation are merely estimates. 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) In the absence of computational software whose function is such priority vector extraction, this step in the AHP algorithm can be exceptionally complex. In practice, however, exact mathematical extraction of the judgment matrices' priority vectors is usually unnecessary. As evidenced, each of the four estimating procedures (as well as the exact solution) will yield slightly different priority vectors. These discrepancies indicate that inconsistencies exist within the judgment matrix weight assignments. The validity of the judgment matrix weighting (in terms of intensity of importance) and priority vector extraction are evaluated by performing a consistency evaluation on the judgment matrix priority vector.

3.3 Consistency Evaluation

The first step in the consistency evaluation is to multiply the original judgment matrix by the estimated, normalized priority vector (termed A_{VE}) obtained by one of the previously described extraction methods. 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}. Upon completing this step, 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 (C.I.) using:

$$C.I. = \frac{(\lambda_{Max} - n)}{(n-1)} \qquad \textbf{\textit{(3.5)}}$$

Where n is the total number of activities in the matrix. The final step in the consistency evaluation is to examine the ratio of the calculated consistency index and the random index (R.I.) derived from the number of matrix activities. Random indices for varying matrix sizes are shown in Table 3.10.

Table 3.11 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 C.I. to R.I. is called the *consistency ratio (C.R.)*. Generally, a consistency ratio of 0.10 or less is acceptable. (Saaty, 1980, pg. 21) In the event that the consistency ratio is greater than 0.10, the operator 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 judgment matrix is multiplied by the computed priority vector. The priority vector obtained by extraction method four is used.

$$\begin{bmatrix} 1 & 7 & 1/3 \\ 1/7 & 1 & 1/9 \\ 3 & 9 & 1 \end{bmatrix} \begin{Bmatrix} 0.295 \\ 0.057 \\ 0.649 \end{Bmatrix} \tag{3.6}$$

The resulting vector, A_W, is:

$$\begin{Bmatrix} 0.910 \\ 0.171 \\ 2.047 \end{Bmatrix} \tag{3.7}$$

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

$$\begin{Bmatrix} 3.085 \\ 3.000 \\ 3.154 \end{Bmatrix} \tag{3.8}$$

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 C.I. is:

$$C.I. = \frac{(3.080 - 3)}{2} = 0.04 \qquad \textbf{\textit{(3.9)}}$$

For a matrix with three activities, the random index, R.I., is 0.58 (see Table 3.10). The consistency ratio is then found to be:

$$\frac{0.04}{0.58} = 0.07 \qquad \textbf{\textit{(3.10)}}$$

This value is less than the allowable value of 0.10. Therefore, the consistency of the judgment matrix is found to be within an acceptable tolerance. The matrix consistency evaluation must be performed for each judgment matrix, the criteria judgment matrix, and the final decision matrix. If the consistency index is found to be greater than 0.10 in any instance, the cell-by-cell intensities of importance must be reevaluated for that matrix and modified accordingly.

3.4 Ranking of Competing Alternatives

The final step in the AHP begins with construction of the decision matrix, whose priority vector determines the optimal alternative among those being considered. Column entries in the decision matrix are simply comprised of the principal eigenvectors (priority vectors) obtained for each selection criteria judgment matrix. The decision matrix is of dimensions *MxN*, *"M"* representing the number of alternatives being considered, and *"N"* indicating the total number of influential criteria for which judgment matrices were constructed. Considering three possible alternatives (*A, B, and C*), three selection criteria (*i, j, and k*), and adopting the following priority vector subscript convention:

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

The decision matrix would appear as follows:

$$\begin{bmatrix} A_i & A_j & A_k \\ B_i & B_j & B_k \\ C_i & C_j & C_k \end{bmatrix} \qquad \textbf{\textit{(3.11)}}$$

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

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

The matrix multiplication operation is then formulated as follows:

$$\begin{bmatrix} A_i & A_j & A_k \\ B_i & B_j & B_k \\ C_i & C_j & C_k \end{bmatrix} \begin{Bmatrix} A_{VE_i} \\ A_{VE_j} \\ A_{VE_k} \end{Bmatrix} \qquad \textbf{\textit{(3.12)}}$$

Executing this operation accomplishes weighting of each of the individual criteria priority vectors by the priority of the corresponding selection criteria. (Saaty, 1980, pg. 26) The overall rank of each alternative is shown as follows:

Rank of alternative A $= A_i A_{VE_i} + A_j A_{VE_j} + A_k A_{VE_k}$

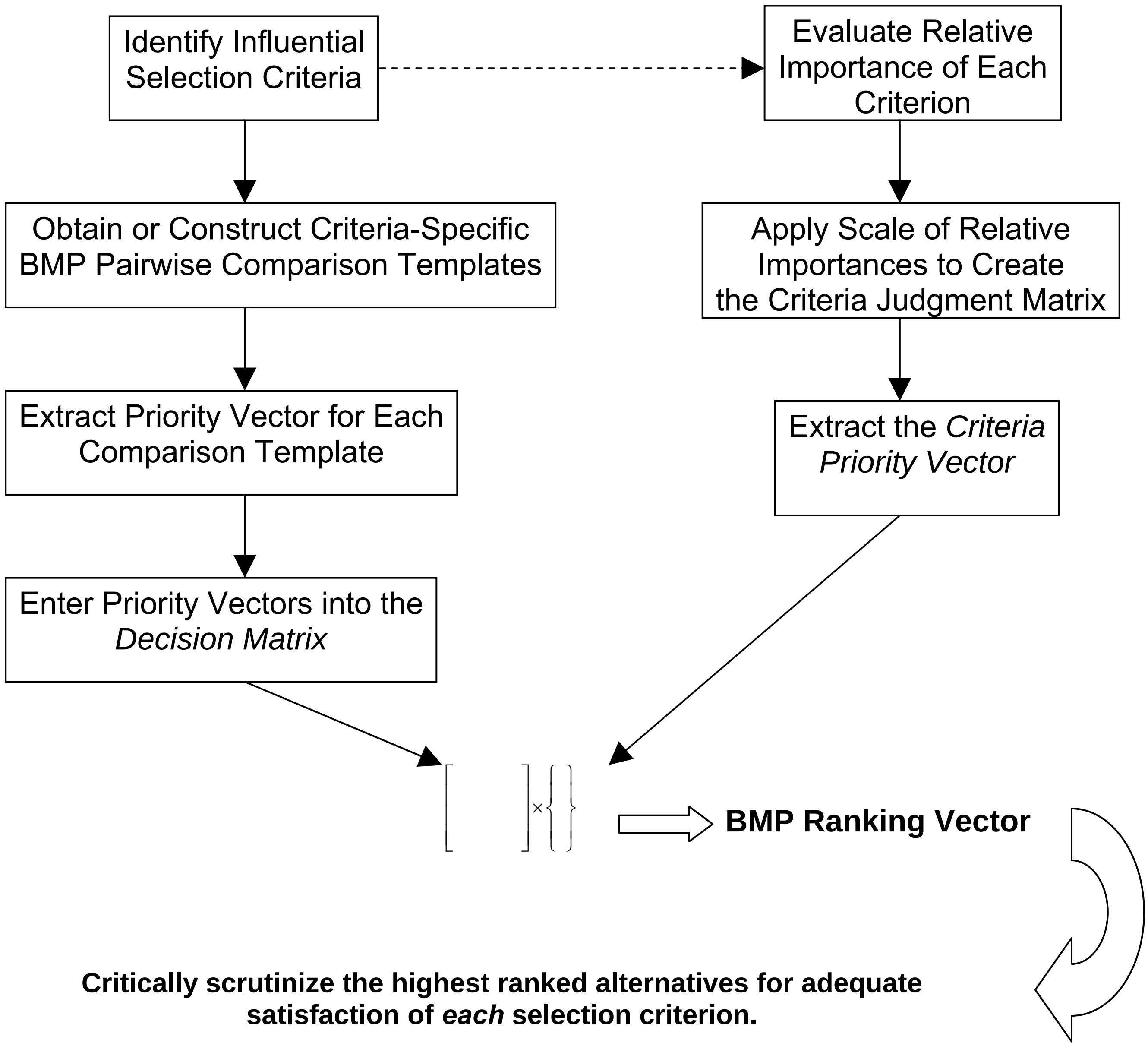
Rank of alternative B $= B_i A_{VE_i} + B_j A_{VE_j} + B_k A_{VE_k}$

Rank of alternative C $= C_i A_{VE_i} + C_j A_{VE_j} + C_k A_{VE_k}$

The alternative with the greatest rank is the most desirable, while successively lower ranks indicate less desirable alternatives. Figure 3.1 illustrates the basic approach in applying the AHP in a BMP selection scenario.

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. Triantaphyllou & Mann (1995) state that, "there is sufficient evidence to suggest that the recommendations made by the AHP should not be taken literally." 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.

Figure 3.1 Flowchart Illustrating AHP Application in the BMP Selection Process



Chapter 4.0
Construction of Long-Term Pollutant Removal Performance Matrices

The BMP selection matrices presently used throughout the engineering community exhibit significant shortcomings. In particular, these matrices lack adequate consideration for long-term BMP maintenance costs and the inevitable decline in a BMPs pollutant removal performance over time. Chapter 4 details the development of a BMP selection matrix specifically dedicated to long-term pollutant removal performance.

4.1 Data Sources – Long-Term Pollutant Removal Performance

To accurately depict the performance of a best management practice's long-term pollutant removal performance, a study must incorporate two key elements. First, the data must be derived from a sufficiently large sample size. Second, the study must be conducted over a period of time adequately illustrating the inevitable decline in performance.

The first of three BMP performance data sources used in this paper, The National Pollutant Removal Database, First Edition (Center for Watershed Protection, 2000), originally published in 1997 spanned a monitoring period of 19 years and included performance data on 129 BMPs. BMPs were sampled for a minimum of four storm events (total, not annually). A second edition of this database was released in 2000, and included the addition of 24 studies. The second edition of the database included the added criteria that each BMP facility be sampled for a minimum of five storm events, and that all flow or time-based samples were collected by automated equipment. These added criteria led to the deletion of 8 studies from the first edition. Additionally, the new database includes detailed influent pollutant concentration data for over half of the samples. Research reveals that when influent concentrations reach a critical "irreducible level," a low or negative removal percentage may be recorded. The inclusion of automated influent monitoring in the revised study sought to stabilize the study results when pollutant levels were at or below this critical level.

Construction of the International Stormwater BMP Database began in 1996 as a cooperative agreement between the *American Society of Civil Engineers* and the *Environmental Protection Agency*. The Database now receives varying levels of support and funding from the *Water Environment Research Foundation* (WERF), the *ASCE Environmental and Water Resources Institute* (EWRI), the *Federal Highway Administration* (FHWA) and the *American Public Works Association* (APWA). The database is presently maintained by Wright Water Engineers, Inc. and GeoSyntec Consultants. The primary goals in constructing the Database were to assemble technical and performance information to improve BMP selection on the local level. Achievement of these goals required the Project Team to develop scientifically-based methods of data collection, management, and analysis. Initially, this required a literature review of over 800 documents which identified not only the most widely used BMPs, but the historical methods used to evaluate BMP performance. The first release of the database to the public occurred in 1999, and represented the analysis of 71 BMPs. Since its initial release, the database has expanded to include over 200 structural BMPs, as well as a number of non-structural practices. In addition to assembling a scientifically-based clearinghouse of BMP performance data, construction of the database also led to the revelation that historical methods of evaluating BMP performance, such as percentage of pollutant removal, were often misleading.

The advent and increasing popularity of proprietary BMPs, such as hydrodynamic separators and water quality inserts, presented a unique problem to the BMP research community. Manufacturers and vendors of these products were, at one time, able to claim pollutant removal efficiencies for their products without any standardized means of performance evaluation and review of those evaluations. To combat these unsubstantiated performance claims, *The Technology Acceptance and Reciprocity Partnership* (TARP) arose from a partnership among the states of California, Illinois, Maryland, Massachusetts, New Jersey, New York, Pennsylvania, and Virginia. The creation of TARP sought to provide a uniform method for demonstrating the effectiveness of proprietary stormwater technologies and to develop test quality assurance plans for certification and verification of performance claims. Arising from the formation of TARP, The University of Massachusetts has developed a searchable database containing performance data and technical information on innovative stormwater treatment technologies. A rigid TARP protocol, discussed later in this paper, is the basis for evaluating treatment efficiencies for various pollutants. The result is a database capable of assisting various stakeholders in interpreting information related to site-specific and environmental considerations, as well as determining which proprietary stormwater technologies meet their performance needs. Construction of the database is ongoing.

The methodology and findings of the National Pollutant Removal Database, the International Stormwater BMP Database, and the TARP/UMass Stormwater Technologies clearinghouse are now discussed and employed to construct a BMP selection matrix reflecting the long-term pollutant removal performance of various BMPs over time.

4.2 National Pollutant Removal Database – Methodology

The National Pollutant Removal Database was published by the Center for Watershed Protection for the U.S. Environmental Protection Agency. This database was prepared for use by engineers, planners, and municipal officials to assist in selection of stormwater treatment practices (STPs) used in watershed restoration and protection efforts. The database includes a total of 139 data sheets, cataloged in Microsoft® Access format. Each of the data sheets is representative of a particular STP (BMP) measure that was monitored for a *minimum* of five storm events. The data sheets are further categorized by STP group and design variation. The various design variations that were studied are shown as follows in Table 4.1. Table 4.2 on the following page provides an itemized listing of the total number of studies and their distribution among various STP measures.

Table 4.1 BMP Design Variations

Source: National Pollutant Removal Database (Center for Watershed Protection, 2000)

Group	Design Variation	
Stormwater Pond		
	Quantity Control Pond	Wet Extended Detention Pond
	Dry Extended Detention Pond	Wet Pond
	Multiple Pond System	
Stormwater Wetland		
	Shallow Marsh	Pond / Wetland System
	Extended Detention Wetlands	Submerged Gravel Wetland
Open Channel Practice		
	Grass Channel	Dry Swale
	Ditch*	Wet Swale
Filtering Practice		
	Perimeter Sand Filter	Bioretention
	Surface Sand Filter	Organic Filter
	Vertical Sand Filter	Multi-Chambered Treatment Train
Infiltration Practice		
	Porous Pavement	Infiltration Trench
Other STPs		
	Stormceptor	Oil-grit separator
*Referes to an open channel practice not explicitly designed for water quality		

Table 4.2 Distribution of Study Data Among Various BMP Types

Source: National Pollutant Removal Database (Center for Watershed Protection, 2000)

STP Type	First Edition # of Studies (1997)	Database # of Studies (2000)	# of Studies with Concentration Data
Pond			
Quantity Control Pond	2	3	0
Dry Extended Detention Pond	6	6	3
Wet Extended Detention Pond	7	14	11
Multiple Pond System	0	1	0
Wet Pond	29	29	15
Total	44	53	29
Wetland			
Shallow Marsh	17	23	9
Extended Detention Wetland	4	4	2
Pond / Wetland System	10	10	7
Pocket Wetland	1	0	0
Submerged Gravel Wetland	0	2	0
Filter / Wetland System	3	0	0
Total	35	39	18
Filtering Practice			
Organic Filter	5	7	5
Perimeter Sand Filter	3	3	3
Surface Sand Filter	6	8	2
Vertical Sand Filter	2	2	2
Vegetated Filter Strip	2	0	0
Bioretention	0	1	1
Total	18	21	13
Infiltration Practice			
Infiltration Trench	3	3	3
Porous Pavement	2	3	1
Total	5	6	4
Open Channel Practice			
Grass Channel	3	3	3
Ditch	11	9	3
Dry Swale	4	4	2
Wet Swale	2	2	2
Total	20	18	10
Other			
Oil-Grit Separator	1	1	1
Stormceptor	0	1	1
Total	1	2	2
Total for All STP Types	123	139	76

The Database developers adopted of a number of conventions to ensure continuity and consistency of results among all of the BMP facilities studied. Only those conventions relevant to the development of a BMP selection matrix expressing pollutant removal performance are mentioned in this paper. It is noted that not every convention adopted by the CWP during development of the Database is discussed. Those relevant conventions are as follows:

- When multiple methods of calculating pollutant removal efficiencies were employed in a single BMP study, those results obtained by mass or loading-based measurements were reported rather than those derived from concentration-based measurements.

- Generally, removal efficiency data corresponds to the median values reported in the studies. When a BMPs removal efficiencies were reported as a range of values, the average of the range was entered into the Database.

- When pollutant removal efficiency evaluations yielded “no significant difference” between influent and effluent levels, the removal percentage was recorded as zero. In the event that the monitoring data revealed pollutant removal as “not detected” the data was not included in the Database.

- When negative removal of pollutants (resuspension) was observed but unspecified in quantity, a value of negative 25% was entered into the Database for that facility. When data analysis revealed negative removal efficiencies in excess of 100%, values were entered as negative 100% to prevent undue weighting in subsequent statistical analysis.

- (NO_x) data represents removal of nitrate as well as nitrate-nitrite.

- Soluble phosphorus employed in the calculation of efficiencies represented lumped data that included ortho-phosphorus and dissolved phosphorus. Effluent phosphorus data only represent ortho-phosphorus.

Unlike the first edition of the Database, the revised study published in 2000 also documented the *Drainage Class* of the BMP. This new data field permitted more specific classification of the BMPs by considering their contributing drainage area. Stormwater ponds and wetland facilities serving drainage areas of less than 10 acres were classified as "Pocket." These facilities whose contributing drainage areas were greater than 10 acres but less than 300 acres were classified as "Regular." BMPs receiving runoff from land areas exceeding 300 acres were termed "Regional." These new classifications provide a more accurate estimate of anticipated BMP performance than would be obtained by grouping very large regional facilities in with those receiving runoff from much smaller areas.

The pollutant removal efficiencies of the various BMP practices expressed in the database are generally derived from one of two methods. The first method is that of event mean concentration (EMC) efficiency. EMC pollutant removal efficiency is computed by averaging the influent and effluent pollutant concentrations for all monitored storm events. These averaged values are then considered the event mean pollutant concentration in ($Conc_{in}$) and event mean pollutant concentration out ($Conc_{out}$). The EMC pollutant removal efficiency is subsequently computed as follows:

$$EMC\ Efficiency(\%) = \frac{Conc_{in} - Conc_{out}}{Conc_{in}} \times 100 \qquad \textbf{(4.1)}$$

This method of expressing a particular BMPs performance gives equal weight to both large and small runoff producing events. Furthermore the water quality volume of a particular practice is not considered in the EMC-based efficiency calculation. As discussed later, this approach to evaluating a BMPs pollutant removal performance has been the subject of much criticism and scrutiny in the BMP research community. Pollutant removal percentages are inherently influenced by the concentration levels of the incoming runoff. Often, when these incoming concentrations are at an "irreducible level," low and negative pollutant removal percentages may be determined from an EMC- based approach.   However, in reality, the effluent concentrations from these facilities may be quite low. (Shueler, 1996) Conforming to aforementioned convention, when mass-based methods of determining pollutant removal efficiency were available, they were reported instead of those derived from EMC-based calculations.

The next method employed by the Database developers for reporting BMP performance is that of Mass Efficiency. Unlike concentration-based methods, the mass efficiency approach is influenced by natural processes resulting in water losses, such as evapotranspiration and infiltration, within the BMP. Mass efficiency is typically computed as follows:

$$Mass\ Efficiency(\%) = \frac{SOL_{in} - SOL_{out}}{SOL_{in}} \times 100 \qquad \textbf{(4.2)}$$

With parameters defined as: SOL_{in} is the sum of all incoming loads (mass units). This value may include sources not related to surface water inflow, such as direct rainfall and atmospheric deposition. SOL_{out} is the sum of all outgoing loads at the BMPs outfall(s). This value is the product of the concentration of the pollutant of interest and the outgoing volume of water from the BMP.

In some instances, a BMP facility's reported pollutant removal efficiencies were computed by a method other than the two previously described. These other methods included mass balance and flux analysis. The 139 data sheets serving as the foundation of the study describe the method employed in computing the pollutant removal efficiency for each BMP analyzed. It is beyond the scope of this paper to critically scrutinize each of the varying methods used in determining pollutant removal efficiencies. Therefore, all methods of reporting a BMPs pollutant removal efficiency are given equal consideration within the context of the NPRD evaluation and pollutant removal performance summary.

4.3 National Pollutant Removal Database – Results

Tables C.1 – C.9 (Appendix C) present the critical information taken from the Database for the structural BMP practices described in Chapter 2 of this paper (for which data was available). The following information is included when it was present:

- Facility location
- Drainage area (acres) contributing to the facility

- Number of runoff producing events represented by the data
- Reported pollutant removal efficiencies for TSS, TP, and TN
- Calculation method employed to determine reported pollutant removal efficiencies (**C**oncentration-based, **M**ass-based, or **O**ther)

Conforming to the aforementioned Database construction conventions and methodology, the results of statistical analysis on the data presented in Tables C.1-C.9 is shown below in Table 4.3. These reported median pollutant removal percentages reflect the most recent CWP Database, and include a statistical re-analysis of the First Edition values. Additionally, the removal efficiencies reported in Table 4.3 include data from the 24 studies not present in the First Edition of the Database, as well as the deletion of data derived from the eight original studies not in compliance with the new sample size and monitoring requirements. STP pollutant removal efficiency can vary significantly between the different classes of STPs as well as among STPs with essentially the same design configuration. It is important to note that the pollutant removal efficiencies expressed in Table 4.3 are not fixed, but rather intended to serve only as a general estimate of a STP's long-term performance.

Table 4.3 Median Pollutant Removal (%) of Various BMPs

Source: CWP National Pollutant Removal Database, 2000

Practice	Pollutant		
	TSS	TP	TN
Extended Dry Detention Pond	61	20	31*
Wet Pond	80	55	35
Infiltration Trench	+	100	42
Infiltration Basin	+	+	+
Porous Pavement	95	65	83
Stormwater Wetlands	76	49	30
Filter Strips	+	+	+
Vegetated Swales	68	29	+
Stormwater Filters (Including Bioretention)	86	59	38
Hydrodynamic Separators	+	+	+
Water Quality Inlets	+	+	+

Notes: * Indicates that the results are based on fewer than five data points

+ Indicates that insufficient data is presently available

Table 4.4 expresses the variability in reported removal efficiency by *Drainage Class*. As previously described, a STP is classified as "Pocket" if its contributing drainage area is less than 10 acres, "Regular" if its contributing drainage area lies between 10 and 300 acres, and "Regional" if its contributing drainage area is greater than 300 acres.

Table 4.4 Median Pollutant Removal (%) of Stormwater Treatment Practices by Drainage Class

Source: CWP National Pollutant Removal Database, 2000

	Drainage Class	Pollutant		
		TSS	TP	TN
Wet Ponds	**Pocket**	87	78	28*
	Regular	80	49	32
	Regional	70	48	37
Wetlands	**Pocket**	57*	57*	44*
	Regular	61	36	15
	Regional	80	43	35

Notes: * Indicates that the results are based on fewer than five data points

As previously discussed, recent research suggests that an analysis of effluent pollutant concentration may be a better measure of a BMP's performance than an evaluation of its pollutant removal efficiency. The rationale behind these claims is discussed in detail in section 4.4 of this paper. Table 4.5 presents the results of the National Pollutant Removal Database STP effluent concentration analysis. It is readily apparent when compared to Table 4.3 that, generally, STPs with high removal efficiencies also exhibit low effluent pollutant concentrations. However, it must be noted that, like removal efficiencies, the data shown in Table 4.5 represents only a *trend* in long-term BMP performance. Careful consideration and scrutiny must be given when attempting to use this data to predict the performance of a newly installed measure.

Table 4.5 Median Effluent Concentration (mg/L) of Various BMPs

Source: CWP National Pollutant Removal Database, 2000

Practice	Pollutant		
	TSS	TP	TN
Extended Dry Detention Pond	28	0.18*	0.86*
Wet Pond	17	0.11	1.30
Infiltration Trench	+	0.63	3.80
Infiltration Basin	+	+	+
Porous Pavement	17	0.10	+
Extended Detention Constructed Wetlands	29	0.27	1.60
Filter Strips	+	+	+
Vegetated Swales	15	0.14	+
Stormwater Filters (Including Bioretention)	11	0.10	1.10*
Hydrodynamic Separators	48	0.41	1.90
Water Quality Inlets	+	+	+

Notes: * Indicates that the results are based on fewer than five data points
+ Indicates that insufficient data is presently available

4.4 International Stormwater BMP Database – Methodology

Developers of the International Stormwater BMP Database (ISBD) employed a considerably different approach to database construction than did the developers of the National Pollutant Removal Database (NPRD). While narrative information in the NPRD makes note that pollutant removal efficiencies alone may not be an accurate depiction of BMP performance, event mean concentration and mass-loading efficiency calculations *are* employed as foundational components of the database. While event mean concentration (EMC) data is included in the ISBD, EMC and mass-loading pollutant removal efficiencies *are not* reported directly. Instead, the ISBD reports effluent pollutant concentrations as the primary measure of BMP performance.

Historical evaluation of BMPs by pollutant removal efficiency analysis alone has falsely labeled a number of BMPs as providing little water quality benefit. In reality, these “poor performers” are often simply BMPs which typically receive inflow exhibiting relatively low pollutant concentrations. Where influent pollutant concentrations are observed to be either exceptionally high or low, pollutant removal efficiencies paint a skewed picture of BMP performance. When high influent concentrations are observed, statistical analyses of EMC data often reveal exceedingly low removal percentages. However, these analyses do not consider the natural processes occurring in many BMPs such as infiltration and evapotranspiration. Such processes often produce a reduction in the volume of water exiting the BMP. In these instances, the effluent pollutant *concentration* may be quite similar to the influent concentration (or even higher). Yet when compared to site runoff in the absence of the BMP, the water quality benefit, in terms of reduced pollutant load, may be tremendous. Conversely, when influent pollutant concentrations are very low, approaching a qualitatively-defined “irreducible level,” EMC analyses may reveal low or negative pollutant removal. However, the effluent concentration, while near that of the influent concentration, may be well within an acceptable level.

Retention / wet ponds and wetlands systems are particularly vulnerable to misrepresentation when their evaluation is based exclusively on pollutant removal efficiency analyses. Arising from the presence of a permanent pool, paired inflow and outflow are often not from the same runoff producing event. This phenomenon is particularly common when the permanent pool volume is very close to the volume of runoff entering the practice from an average runoff producing event. In such cases, the observed effluent is composed primarily of older, stored water from previous runoff producing events. The resulting statistical analysis of data from mixed storm events provides a poor measure of BMP performance.

Due to these shortcomings associated with the EMC-based efficiency approach, the developers of the ISBD elected to report effluent pollutant concentrations as the primary measure of BMP effectiveness. Statistical analyses were then performed in an attempt to determine the relative water quality benefit among various types of BMPs. The conventions and methods of analysis are now itemized and described.

- The data reported in the ISBD summarize two separate data analyses. The first of these analyses is derived from each individual BMPs *average* EMC over its entire monitoring period. The second analysis is derived from all collected effluent EMCs. In both instances, data was grouped by BMP category.

- The first data analysis reflects a “weighting” of the water quality data among individual BMP studies. This approach ultimately results in equal influence for each BMP (one average EMC value per BMP). The influence of individual runoff producing events is rendered essentially negligible, and the results do not favor BMPs for which there exists large numbers of recorded EMCs.

- The second analysis represents the distribution of effluent water quality data from individual storm events. Therefore, greater influence is given to BMP study sites for which there exists a large number of event EMCs.

- For each pollutant examined, only BMP studies with a *minimum* of three influent and effluent EMCs were included. This minimum threshold does permit statistical calculations such as mean, median, and percentile(s). However, caution is issued that the validity of the analyses for these smaller sample sizes is questionable.

- The project team employed notched box-and-whisker plots to graphically display the distributions of both sets of data. The notches encompass the 95% confidence interval of the median (for each data set).

- A logarithmic scale was employed for plotting of the datasets.

- Upper and lower confidence levels for both datasets were computed by the following approach:
    - The natural logs of the effluent values (averaged EMCs *or* individual EMCs) for a given BMP category were sorted in ascending order.
    - The upper and lower quantiles were calculated.
    - The confidence interval of the median was calculated.
    - The median and confidence intervals were translated back to arithmetic space, and then used to delineate the upper and lower bounds of the notch on the box-and-whisker plots.

- For both data sets, an assessment was made of the difference between the median effluent values and their corresponding influent values. This assessment provides a measure of whether or not a particular BMP category exhibits a significant difference in influent and effluent pollutant levels.

- In many instances, no significant difference was observed between influent and effluent medians. In these cases, it is not possible to determine whether the BMP group exhibited a significant impact on the pollutant of interest.

4.5 International Stormwater BMP Database – Results

Tables 4.6 – 4.8 on the following pages detail the ISBD effluent concentration analysis for suspended sediment, total phosphorus, and total nitrogen.

Table 4.6 – Median Total Suspended Sediment Effluent Concentration of Various Categories of BMPs

Source: Analysis of Treatment System Performance, International Stormwater BMP Database, 2006)

BMP Category	Sample Size (Facilities)	Total Suspended Sediment Effluent Concentrations 95% C.I.		Significant Difference From Influent EMC?+
		Study 1 - Median of Avg. Effluent EMCs (mg/L)	Study 1 - Median of all Effluent EMCs (mg/L)	
Detention Basin	11	40.72	32.98	Yes
Biofilter*	40	37.99	24	No
Hydrodynamic Device	14	41.38	36	Yes
Media Filter	19	15.05	14.97	Yes
Retention Pond	24	19.77	12	Yes
Wetlands Basin	9	22.29	7.55	Yes
Wetland Channel	3	24.18	17	Yes

* Biofilters include vegetated water quality swales and vegetated filter strips

+ Comparison based only on Study 2

Table 4.7 – Median Total Phosphorus Effluent Concentration of Various Categories of BMPs

Source: <u>Analysis of Treatment System Performance</u>, International Stormwater BMP Database, 2006)

BMP Category	Sample Size (Facilities)	Total Phosphorus Effluent Concentrations 95% C.I.		Significant Difference From Influent EMC?+
		Study 1 - Median of Avg. Effluent EMCs (mg/L)	Study 2 - Median of all Effluent EMCs (mg/L)	
Detention Basin	9	0.23	0.22	No
Biofilter*	45	0.37	0.26	No
Hydrodynamic Device	12	0.21	0.16	Yes
Media Filter	18	0.18	0.13	Yes
Retention Pond	24	0.18	0.13	Yes
Wetlands Basin	7	0.15	0.06	Yes
Wetland Channel	3	0.23	0.17	Yes

* Biofilters include vegetated water quality swales and vegetated filter strips

+ Comparison based only on Study 2

Table 4.8 – Median Total Nitrogen Effluent Concentration of Various Categories of BMPs

Source: <u>Analysis of Treatment System Performance</u>, International Stormwater BMP Database, 2006)

BMP Category	Sample Size (Facilities)	Total Nitrogen Effluent Concentrations 95% C.I.		Significant Difference From Influent EMC?+
		Study 1 - Median of Avg. Effluent EMCs (mg/L)	Study 2 - Median of all Effluent EMCs (mg/L)	
Detention Basin	1	Insufficient sample size	.86	No
Biofilter*	5	.71	.64	No
Hydrodynamic Device	2	2.88	2.16	No
Retention Pond	8	1.38	1.16	No
Wetlands Basin	4	2.42	1.22	No
Wetland Channel	3	1.58	1.35	Yes

* Biofilters include vegetated water quality swales and vegetated filter strips

+ Comparison based only on Study 2

As previously discussed, the developers of the International Stormwater BMP Database do not view percentage of pollutant removal as a valid method for evaluating a BMP's performance. However, for purposes of comparison with the CWP National Pollutant Removal Database, Tables D.1 – D.6 in Appendix D of this paper present the EMC-based pollutant removal efficiency performance of the structural BMP practices detailed in Chapter 2 (for which ISBD data was available). Presented are only those BMPs for which influent and effluent EMC data was reported. It is noted that the EMC-based pollutant removal efficiency data presented within the scope of this paper is not endorsed by the ISBD, and is intended to serve only as a comparison with comparable NPRD data.

The reported EMC-based pollutant removal percentages, by individual BMP site, shown in Tables D.1 – D.6 reflect the most current ISBD studies. Table 4.9, below, presents a summary of the EMC-based median pollutant efficiencies by BMP category. These median pollutant removal efficiencies are derived directly from the data presented in Tables D.1 – D.6. BMP pollutant removal efficiency can vary significantly between the different classes of STPs as well as among STPs with essentially the same design configuration. It is important to note that the pollutant removal efficiencies expressed in Table 4.9 are not fixed, but rather intended to serve only as a general estimate of a STP's long-term performance.

Table 4.9 Median EMC-Based Pollutant Removal (%) of Various BMP Categories

(Reflects Only Data in the International Stormwater BMP Database)

Practice	Pollutant		
	TSS	TP	TN
Extended Dry Detention Pond	12.0	30.5	17.5
Wet Pond	59.0	40.0	27.0
Extended Detention Wetlands	70.5	29.5	(-17.5)
Vegetated Swale	34.5	(-14.0)	(-3.8)
Vegetated Filter Strips	54	(-42.5)	9
Surface Sand Filters	86	52.5	53.5

4.6 The Technology Acceptance and Reciprocity Partnership (TARP) – Methodology

With the development of proprietary BMP products such as hydrodynamic separators, catch basin media inserts, and water quality inlets, engineers were presented with a wide array of new alternatives for treating surface runoff. However, this new technology also gave rise to questionable manufacturer and vendor-based performance claims for these treatment practices. With the issuance or denial of many federal, state, and local permits fundamentally founded upon technology-based performance data, a means by which to validate and standardize these performance claims became essential. Recognizing this need, the states of California, Illinois, Maryland, Massachusetts, New Jersey, New York, Pennsylvania, and Virginia formed the *Technology Acceptance and Reciprocity Partnership* (TARP). TARP sought to provide its member states with validated performance claims for these proprietary BMPs, thus easing the often unnecessary and financially burdensome performance validation required for environmental permit issuance. TARP now exists as a three-tiered program, described as follows.

The primary goal of Tier I of the TARP is to provide broad vendor guidance for generating scientifically justifiable data pertaining to the performance of environmental technology practices. This guidance exists as a uniform and consistent protocol for performing and evaluating *full-scale* field demonstrations of various proprietary BMPs. The satisfaction of the Tier I protocol by a vendor or manufacturer does not alone validate the performance claims by the vendor. It simply indicates that the claimed performance data was generated by credible scientific methods endorsed by the TARP. Tier II of the TARP expands upon the scope of Tier I, providing more rigid guidance for the comprehensive performance testing of specific technology classes of BMPs. Tier II of the program further focuses on increased coordination and standardization of the methods of data collection, evaluation, and sharing employed by vendors and manufacturers in conducting their BMP performance analyses. The final Tier of the TARP seeks to provide vendors, manufacturers, and review agencies with the necessary regulatory and technical guidance for the issuance of environmental permits. The ultimate goal of Tier III is to create a permit template, accepted by all TARP member states, which can be used in conjunction with a shared database of proprietary BMP information. Each protocol of the TARP requires that the stormwater treatment technologies be *field-tested*. Due to the database's relative infancy, many of the practices contained in the MASTEP clearinghouse are presently not in compliance with the TARP Tier II protocol. The majority of these practices are not in compliance because their data was collected by laboratory analysis rather than field studies.

Arising from the formation of TARP, and funded by an EPA 319 water quality improvement grant, The University of Massachusetts now maintains a searchable database for innovative stormwater management practices. This database is termed the *Massachusetts Stormwater Evaluation Project,* or MASTEP. The MASTEP database presents a catalogue of numerous proprietary BMPs. Proprietary practices currently in the database exhibit a score of 0 – 3. These scores as described as follows:

- 0 – A score of "unrated" generally indicates that the practice has been recently submitted to MASTEP and that a data review has not yet been conducted.
- 1 – A score of 1 indicates that the submitted BMP performance data is sufficiently compliant with the TARP Tier II protocol. Furthermore, a score of 1 indicates that a product exhibits sufficient data to evaluate pollution removal efficiency claims.
- 2 – A score of 2 indicates that the BMP is presently undergoing evaluation, with validated performance data anticipated in the near future.
- 3 – A score of 3 indicates that the present vendor / manufacturer data is insufficient to evaluate performance claims. This score does not necessarily suggest that the data is invalid, but only that some portion of the data was not obtained in compliance with the TARP Tier II protocol.

4.7 TARP / MASTEP Stormwater Technologies Database – Results

The following tables present the pollutant removal efficiency data for the proprietary BMPs presently in the MASTEP database. Many proprietary BMPs are targeted exclusively at removing suspended sediment from runoff. The number of studies including removal data for phosphorus and nitrogen were too few to provide a meaningful performance analysis. Consequently, data for the removal of phosphorus and nitrogen are omitted in this paper.

Table 4.10 Performance Data – Hydrodynamic / Swirl Separator BMPs

(Reflects Only Data in the MASTEP Stormwater Technologies Clearinghouse)

Product Name	Manufacturer	TSS Removal Efficiency(%)		TARP Test Data Status
		Manufacturer Claim	Tested Results	
VortSentry	Vortechnics, Inc.	35-85	-	3
In-Line Stormceptor	Stormceptor	50-80	75	2
Downstream Defender	Hydro International	90	70	2
CDS Inline Unit	CDS Technologies	80	73.7	3
AquaFilter	Aquashield	84	-	0
Table 4.10 Cont'd.				
StormTreat System	StormTreat Systems	99	80	3
CrystalStream Water Quality Vault	CrystalStream Tech.	-	21	3
Storm Water Quality Unit	Hancor, Inc.	95	-	3
BaySaver Separation System	Baysaver	51	51	2
V2B1	Environment 21 LLC	80	75-85	3
Hydroworks HG	Hydroworks LLC	80	-	3
Vortechs System	Vortechnics, Inc.	35-85	35	2
Terre Kleen	Terre Hill Concrete Products	80	80	3

Table 4.11 Median Removal Efficiencies for all Hydrodynamic / Swirl Separator BMPs

Median TSS Removal Efficiency(%)*	
Manufacturer Claim	Tested Results
80.0	73.7

* When an individual study reported a range of values, its lowest removal efficiency was employed in determining the median.

Table 4.12 Performance Data – Catch Basin Inserts and Filters

(Reflects Only Data in the MASTEP Stormwater Technologies Clearinghouse)

Product Name	Manufacturer	TSS Removal Efficiency(%)		TARP Test Data Status
		Manufacturer Claim	Tested Results	
Vort Filter	Vortechnics, Inc.	50-95	-	2
Arkal Stormwater Filt. Sys.	Arkal Filtration Systems	80	82	3
FloGard Plus	Kristar Enterprises, Inc.	80	-	0
SM StormFilter	Stormwater Mgmt., Inc.	50-85	79	2
Cultec Stormfilter	Cultec	70	-	3
Grate Inlet Skimmer Box	Suntree Technologies, Inc.	73.3	-	3
StormScreen	Stormwater Mgmt., Inc.	100*	100*	3

Table 4.12 Cont'd.				
Hydrocartridge	Advanced Aquatic Products	-	40	3
Netting Trash Trap	Fresh Creek Technologies, Inc.	95	-	3
Clearwater Solutions BMP01	Clearwater Solutions	97	-	3
DrainPac	United Stormwater, Inc.	-	22	3
Hydro-Kleen Filtration System	Hydro Compliance Mgmt., Inc.	-	51	3
Enviropod	Contech Construction Products, Inc.	78	-	3

* Indicates Total Solids, Suspended and Dissolved

Table 4.13 Median Removal Efficiencies for all Catch Basin Inserts and Filters

Median TSS Removal Efficiency(%)*	
Manufacturer Claim	**Tested Results**
79.0	65.0

* When an individual study reported a range of values, its lowest removal efficiency was employed in determining the median.

4.8 Performance Review of Individual Practices

The section that follows presents a review of the anticipated long-term pollutant removal performance of each Best Management Practice described in Chapter 2. When available, performance evaluations from the National Pollutant Removal Database, the International Stormwater BMP Database, and the MASTEP proprietary BMP clearinghouse are compared for each BMP. With current research suggesting that pollutant removal efficiency *alone* may not be a good indicator of a BMP's ability to improve the quality of surface runoff, both this criterion and the median effluent pollutant concentration criterion will be examined and compared. Rather than reporting anticipated pollutant removal efficiencies, the comparison and evaluation of these two performance assessment methods will yield a qualitative BMP performance ranking defined as follows:

- High – Research suggests that the BMP is consistently capable of providing both very high removal efficiencies (compared to all other BMPs) as well as low effluent pollutant concentrations. A ranking of "high" further indicates a strong correlation between the computed pollutant removal efficiency and the median effluent pollutant concentration for the particular category of BMP.

- Moderately High – Research suggests that the BMP is consistently capable of providing effluent pollutant concentrations below the median for all BMPs. Ranking priority is given to a practice's median effluent pollutant concentration, and this ranking is not dependent upon a correlation between median effluent concentration and computed pollutant removal efficiency.

- Moderate – Research suggests that the BMP is consistently capable of providing effluent pollutant concentrations similar to the median for all BMPs. Ranking priority is given to a practice's median effluent pollutant concentration, and this ranking is not dependent upon a correlation between the median effluent pollutant concentration and computed pollutant removal efficiency.

- Low – Research suggests that the BMP generally exhibits an effluent pollutant concentration higher than the mean concentration for all BMPs. Additionally, a ranking of "low" *may* imply a correlation between the computed pollutant removal efficiency and the reported median effluent pollutant concentration.

In order to facilitate an evaluation of an individual BMP's performance in terms of effluent pollutant concentration, the median of all reported effluent pollutant concentrations across all BMPs was computed for both the NPRD and ISBD studies. This computation yields the median effluent pollutant concentration of *all studies* for *all BMP classes*. In subjecting each individual practice to this comparison, the measure is evaluated, in terms of effluent pollutant concentration, against all other BMPs. The results are shown as follows:

Table 4.14 Median Effluent Pollutant Concentration (mg/L) Among All Classes of BMP

	NPRD			ISBD		
Average Effluent Concentration (mg/L)	TSS	TP	TN	TSS	TP	TN
	17.00	0.16	1.45	17.00	0.16	1.19

It is noted that although the median suspended sediment and phosphorus effluent concentrations shown are the same for both databases, they are *not derived from the same data*. This observation reveals a striking correlation between the two studies. The correlation also extends well to nitrogen with the two studies exhibiting a discrepancy of less than 18%.

4.8.1 Extended Dry Detention Ponds

Evaluating the NPRD and ISBD data, one obtains the following observed performance for Extended Dry Detention Facilities:

Table 4.15 Performance Summary – Extended Dry Detention Ponds

	NPRD			ISBD		
	TSS	TP	TN	TSS	TP	TN
Removal Efficiency(%)	61	20	31	12	30.5	17.5
Median Effluent Conc.(mg/L)	28.00	0.18	0.86	32.98	0.22	0.86

An examination of the pollutant removal efficiencies reported by both studies reveals that the ability of an extended dry detention facility to remove suspended sediment, phosphorus, and nitrogen from runoff appears to be moderate at best. The removal efficiencies reported for suspended sediment by each study are quite dissimilar. However, neither reported value indicates that the practice is capable of attaining very high (greater than 80%) removal efficiency. The two studies report consistently low removal efficiencies for both phosphorus and nitrogen, *implying* that the practice is not capable of providing exceptionally high removal levels for these pollutants.

The median effluent concentrations of suspended sediment from the extended dry detention facilities studied supports the findings of the removal efficiency analysis. Both databases reveal suspended sediment effluent concentrations significantly higher than the median value (17.00 mg/L) computed for all BMPs. The BMP's effluent concentration of phosphorus from both the NPRD and ISBD studies is similar to the median (0.16 mg/L) for all practices reported in the two respective databases. Both studies indicate that the average effluent nitrogen concentration from this type of BMP is considerably lower than the median effluent nitrogen concentrations computed for all BMPs. Adhering to the evaluation conventions described in section 4.8 of this paper, the long-term pollutant removal performance of an extended dry detention pond is described as follows:

Table 4.16 Long-term Pollutant Removal Performance – Extended Dry Detention Pond

TSS	TP	TN
Low	Moderate	Moderately High

4.8.2 Wet / Retention Ponds

Evaluating the NPRD and ISBD data reveals the following observed performance for Wet Ponds:

Table 4.17 Performance Summary – Wet / Retention Ponds

	NPRD			ISBD		
	TSS	TP	TN	TSS	TP	TN
Removal Efficiency(%)	80	55	35	59	40	27
Median Effluent Conc.(mg/L)	17.00	0.11	1.30	12.00	0.13	1.16

An examination of the pollutant removal efficiencies reported by both studies reveals relatively close agreement between the two database studies. However, as previously discussed, BMPs exhibiting a permanent pool are highly vulnerable to misrepresentation by removal efficiency analyses. Arising from this vulnerability, the evaluation of wet ponds in this paper is based primarily on the median effluent pollutant concentration analysis.

Reviewing the median effluent concentrations of suspended sediment from the wet ponds studied indicates exceptionally strong performance for the practice. The median wet pond effluent concentration of suspended sediment from the NPRD study is equal to the median reported for all practices. The ISBD study reveals that the average effluent suspended sediment concentration from wet ponds is 29% lower than the median concentration for all practices. This strong performance is also observed in an evaluation of effluent phosphorus concentrations, with both studies reporting wet pond effluent concentrations noticeably lower than the median derived from all practices. The strong performance trend continues when nitrogen is considered, with both studies indicating median wet pond effluent concentrations lower than those observed for all other BMPs. Adhering to the evaluation conventions described in section 4.8 of this paper, the long-term pollutant removal performance of an extended dry detention pond is described as follows:

Table 4.18 Long-term Pollutant Removal Performance – Wet Ponds

TSS	TP	TN
High	High	High

4.8.3 Infiltration Trenches, Basins, and Porous Pavement

Scientifically validated performance data for infiltration trenches and basins is presently very limited. However, it is widely accepted that these practices are capable of attaining some of the highest pollutant removal levels possible for a single BMP. The Pennsylvania DEP Draft Stormwater Best Management Practices Manual – January 2005 features recent research on infiltration practices compiled by Cahill Associates, Inc. The pollutant removal efficiencies reported from these studies are shown as follows:

Table 4.19 Pollutant Removal Efficiency – Infiltration Practices (Basins and Trenches)

Source: Pennsylvania DEP Draft Stormwater Best Management Practices

Pollutant	Removal Efficiency(%)
TSS	85
TP	85
TN	30

Presently, the International Stormwater BMP Database contains no entries for infiltration trenches or basins. Similarly, the National Pollutant Removal Database contains only three infiltration studies, and of those three studies, none report the number of storm events monitored. Subsequently, any conclusion on infiltration BMP performance derived from this study must be viewed with great skepticism, and is therefore omitted from this paper.

The physical means by which an infiltration trench and/or basin operates very closely resembles that of a porous pavement system. For each of the three practices, surface runoff is intentionally infiltrated into the subsurface after first passing through an engineered filter media. Significantly more data exists for porous pavement systems than exists for infiltration basins and trenches. Therefore, in an attempt to corroborate the infiltration BMP performance claims reported in the Pennsylvania DEP Draft Stormwater Best Management Practices Manual, they will be compared against the porous pavement data reported in the National Pollutant Removal Database. Porous pavement systems are presently not included in the International Stormwater BMP Database.

Table 4.20 Performance Summary – Porous Pavement

	National Pollutant Removal Database		
	TSS	**TP**	**TN**
Removal Efficiency(%)	95	65	83
Median Effluent Conc.(mg/L)	17.00	0.10	-

With the exception of nitrogen, the performance data for porous pavement systems appears to be in relatively close agreement with the infiltration practice data reported in Table 4.19. The removal of suspended sediment is reported as 80% and 95% for infiltration practices and porous pavement systems respectively. These performance claims are not entirely validated by examining the average effluent concentration of suspended sediment from these practices. The reported porous pavement value of 17.00 mg/L equals the median effluent concentration of all practices reported in both the NPRD and ISBD studies. The high phosphorus removal efficiencies reported are well validated by examining the median effluent phosphorus concentration observed from porous pavement systems. This value of 0.10 mg/L is 31% lower than the median reported for both the NPRD and ISBD studies. Unfortunately, effluent concentration does not exist for nitrogen. However, both the NPRD and Pennsylvania DEP data claim significant removal of nitrogen in surface runoff from the implementation of these practices. Recognizing the physical similarities between infiltration practices and porous pavement, and adhering to the evaluation conventions described in section 4.8 of this paper, the long-term pollutant removal performances of these practices is shown as follows:

Table 4.21 Long-term Pollutant Removal Performance – Infiltration Practices and Porous Pavement

TSS	TP	TN
Moderately High	High	Moderate

4.8.4 Constructed Wetlands

Evaluating the NPRD and ISBD data reveals the following observed performance for Extended Detention Wetlands:

Table 4.22 Performance Summary – Constructed Wetlands

	NPRD			ISBD		
	TSS	TP	TN	TSS	TP	TN
Removal Efficiency(%)	69	39	56	70.5	29.5	-17.5
Median Effluent Conc.(mg/L)	29.00	0.27	1.60	7.55	0.06	1.35

Much in the same manner as wet ponds, wetland systems are easily subject to misrepresentation when evaluated exclusively in terms of pollutant removal efficiency. Additionally, with regards to nitrogen, the pollutant removal efficiencies reported by the two database studies exhibit significant variability. Consequently, like wet ponds, the evaluation of extended detention wetlands in this paper is based primarily on the average effluent pollutant concentration analysis.

Examining the average effluent concentration data reported for suspended sediment reveals a striking discrepancy between the two studies. The NPRD reports a value that is higher than the median effluent concentrations for all practices reported by both respective databases. Conversely, the ISBD reports a value significantly lower than the median effluent concentrations for all practices reported by the studies. The ISBD extends beyond the scope of the NPRD in that it also compares this mean effluent pollutant concentration against the mean influent pollutant concentration. As shown in Table 4.6, the ISBD reports a significant difference between these values, indicating that the studied wetlands BMPs *are* successfully achieving their goal of overall sediment load reduction. This discrepancy between the two studies suggests that perhaps the wetlands data reported in the NPRD were derived from sites producing exceptionally high sediment loads.

The NPRD shows wetland phosphorus release to be considerably higher than the median of all BMPs, while the ISBD-derived median effluent concentrations are significantly lower. Again, a discrepancy exists between the two studies, with the ISBD reporting stronger pollutant removal capabilities for the practice. When compared to average influent phosphorus concentrations, as shown in Table 4.7, the ISBD reports a significant difference between influent and effluent concentrations, indicating that wetland practices can indeed provide an overall reduction in phosphorus. Both studies report average wetland effluent nitrogen concentrations to be higher than the median concentration computed from all BMPs. Table 4.8, as reported in the ISBD, reveals that wetland practices exhibit little reduction between influent and effluent nitrogen levels. Adhering to the evaluation conventions described in section 4.8 of this paper, the long-term pollutant removal performance of stormwater wetlands is described as follows:

Table 4.23 Long-term Pollutant Removal Performance – Constructed Wetlands

TSS	TP	TN
Moderately High	Moderately High	Low

4.8.5 Bioretention

Bioretention facilities are not addressed in the ISBD. Evaluating the NPRD data reveals the following observed performance for Bioretention Facilities:

Table 4.24 Performance Summary – Bioretention

	National Pollutant Removal Database		
	TSS	**TP**	**TN**
Removal Efficiency(%)	86	59	38
Median Effluent Conc.(mg/L)	11.00	0.10	1.10

Examining the reported removal efficiencies implies very strong performance in the removal of each of the three pollutants of interest. Additionally, the average effluent pollutant concentrations reported support the high removal efficiency claims. The median effluent concentration of 11.00 mg/L for suspended sediment is 35% lower than the median reported for all other practices in the NPRD. The median effluent concentration of 0.10 mg/L for phosphorus is 38% lower than the median reported for all other practices in the NPRD. Finally, the average effluent concentration of 1.10 mg/L for nitrogen is 24% lower than the median reported for all other practices in the NPRD. Overall, bioretention facilities, along with wet ponds and infiltration practices, appear to be in the upper echelon of BMPs in terms of removing pollutants from surface runoff. Adhering to the evaluation conventions described in section 4.8 of this paper, the long-term pollutant removal performance of bioretention facilities is described as follows:

Table 4.25 Performance Summary – Bioretention

TSS	TP	TN
High	High	High

4.8.6 Vegetated Filter Strips

Presently, limited data exists on the performance of vegetated filter strips in treating surface runoff. The Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005, reports the following expected removal efficiencies for this type of practice:

Table 4.26 Pollutant Removal Efficiency – Vegetated Filter Strips

Source: Pennsylvania DEP Draft Stormwater Best Management Practices, 2005

Pollutant	Removal Efficiency(%)
TSS	30
TP	20
TN	10

Insufficient data on vegetated filter strips presently exists in the National Pollutant Removal Database, and no performance data is reported for this BMP. The International Stormwater BMP Database groups vegetated filter strips and vegetated swales into one category termed *"Biofilter*" in its median effluent pollutant concentration analysis. However, within the database, there is EMC data identified for 24 vegetated swales. The ISBD median effluent concentration and EMC-based pollutant removal efficiency data are presented as follows:

Table 4.27 Median Pollutant Removal Efficiency – Vegetated Filter Strips

Source: International Stormwater BMP Database

	National Pollutant Removal Database		
	TSS	TP	TN
Removal Efficiency(%)	54	-42.5	9
Median Effluent Conc.(mg/L)*	24	0.26	0.64

*Includes data on vegetated swales

Both suspended sediment and total phosphorus exhibit median effluent concentrations significantly higher than the median for all BMPs. The average nitrogen effluent concentration is reported lower than the median for all practices, but the computed removal efficiency does not support this. As evidenced by the data that currently exist on vegetated filter strips, the practice does not seem to provide a significant water quality benefit. At the present time, any water quality benefit arising from the implementation of vegetated filter strips appears to be limited to only that benefit achieved by the decrease in overall site imperviousness arising from their installation.

Table 4.28 Long-term Pollutant Removal Performance – Vegetated Filter Strips

TSS	TP	TN
Low	Low	Low

4.8.7 Vegetated Water Quality Swales

Evaluating the NPRD and ISBD data reveals the following observed pollutant removal performance for Vegetated Water Quality Swales:

Table 4.29 Performance Summary – Vegetated Water Quality Swales

	NPRD			ISBD		
	TSS	TP	TN	TSS	TP	TN
Removal Efficiency(%)	68	29	-	34.5	(-14)	(-3.8)
Median Effluent Conc.(mg/L)	15.00	0.14	-	24*	0.26*	0.64*

* Includes data on vegetated filter strips

Examining the reported pollutant removal efficiencies in the NPRD and ISBD reveals significant discrepancies between the two databases. The removal efficiencies presented for the ISBD were computed as a part of this paper, and are not endorsed by the database developers for reasons discussed previously. However, with the exception of nitrogen, a comparison reveals that the ISBD-derived pollutant removal efficiencies do appear to be reasonable when compared to the median effluent pollutant concentration values shown. Given the large discrepancy in reported pollutant removal efficiency between the two studies, the author concludes that the performance of vegetated water quality swales is best represented by the average effluent pollutant concentration analysis.

The median effluent pollutant concentrations shown for the two studies also illustrate mixed performance claims for the practice. In attempting to determine the merit of each set of data, it must be noted that the NPRD median effluent concentration is derived from only three studies and therefore must be viewed with skepticism. The ISBD data was obtained from 16 different practices, thus providing a more valid statistical analysis of the practice's performance. Both studies reveal suspended sediment concentrations relatively close to the median computed for all measures in each database (17.0 mg/L), with the ISBD reporting a value slightly higher. The ISBD data reveals average effluent phosphorus concentrations to be 63% higher than the median observed for all practices (0.16 mg/L). Similarly, the median effluent nitrogen concentration presented for the ISBD study is slightly higher than the median concentration observed for all studies. Adhering to the evaluation conventions described in section 4.8 of this paper, the long-term pollutant removal performance of vegetated swales is described as follows:

Table 4.30 Performance Summary – Vegetated Water Quality Swales Swales

TSS	TP	TN
Moderate	Low	Low

4.8.8 Stormwater Filtering Systems

Evaluating the NPRD and ISBD data reveals the following observed pollutant removal performance for Stormwater Filters:

Table 4.31 Performance Summary – Stormwater Filtering Systems

	NPRD			ISBD		
	TSS	TP	TN	TSS	TP	TN
Removal Efficiency(%)	86	59	38	86	52.5	53.5
Median Effluent Conc.(mg/L)	11.00	0.10	1.10	14.97	0.13	-

Comparing the pollutant removal efficiencies expressed by both databases indicates extremely comparable values for each pollutant of interest. This correlation extends to a comparison of the median effluent pollutant concentration values. Both databases report median suspended sediment concentrations that are lower than the median observed for all studies (35% lower for the NPRD data, 12% lower for the ISBD data). The NPRD-derived median effluent phosphorus concentration is 38% lower than the median reported for all values, while the ISBD-derived median effluent phosphorus concentration is 19% lower than that observed for all studies. The NPRD data indicates that the median effluent nitrogen concentration from stormwater filtering practices is 24% lower than the median concentration observed for all practices. Adhering to the evaluation conventions described in section 4.8 of this paper, the long-term pollutant removal performance of stormwater filters is described as follows:

Table 4.32 Long-term Pollutant Removal Performance – Stormwater Filtering Systems

TSS	TP	TN
High	High	High

4.8.9 Proprietary Stormwater Technologies

Evaluating the performance data in the MASTEP stormwater technologies clearinghouse reveals the following anticipated pollutant-removal performance for proprietary practices:

Table 4.33 Performance Summary – Proprietary Stormwater Technologies
(Reflects only an analysis of data in the MASTEP clearinghouse)

Median Removal Efficiency(%)			
Hydrodynamic / Swirl Separators		Catch Basin Inserts / Filters	
Manufacturer Claim	Tested Results	Manufacturer Claim	Tested Results
80	74	79	65

Presently, average effluent pollutant concentration data does not exist for proprietary stormwater technologies. Therefore, the performance analysis of these BMPs must be based, exclusively, on pollutant removal efficiency analysis. Examining the data in Table 4.33 reveals that both manufacture claims and third party tests reveal significant sediment removal performance for these types of practices. The MASTEP database exhibits an insignificant number of studies with performance data on phosphorus and nitrogen removal. Furthermore, many of these technologies are designed *exclusively* for the removal of runoff sediment. Consequently, this paper only considers the suspended sediment removal ability of proprietary BMPs. Adhering to the evaluation conventions described in section 4.8 of this paper, the long-term pollutant removal performance of proprietary stormwater technologies is described as follows:

Table 4.34 Long-term Pollutant Removal Performance – Proprietary Stormwater Technologies

TSS	TP	TN
High	Low	Low

4.8.10 Low Impact Development Strategies

The low impact development strategies addressed in Chapter 2 of this paper include vegetated roof systems, rainwater capture and reuse, and minimum disturbance or site "footprinting."

While various claims for the 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 for this category of BMP to intercept overland flow with its associated load of suspended sediment, phosphorous and nitrogen 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. Consequently, the water quality benefit of rooftop gardens can only be evaluated in terms of an overall reduction in a site's runoff volume and its associated pollutant load. Vegetated roof systems are typically designed to accommodate up to the 10-year return frequency rainfall before their bypass structures are activated. When compared to a conventional impervious roof, the elimination of this runoff can be viewed as providing significant water quality benefit, if only for the runoff which would occur from rooftop itself.

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. The removal of pollutants from runoff 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. Intuitively, any runoff intercepted and stored for later use provides a 100% reduction in the pollutant load observed for that runoff producing event.

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. Additional research found that the concentration of phosphorus in urban lawns was higher than any other non-point source. In addition to fertilizers, the application of pesticides to developed landscape areas presents a significant problem for aquatic biota. Storm events occurring shortly after the application of these types 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)

4.9 Long-term BMP Pollutant Removal Matrices

Table 4.35 provides the relative long-term removal performance, categorized by pollutant, for the BMPs described in Chapter 2 of this document. All rankings are in accordance with the methodology described in section 4.8 of this paper. This matrix serves as the foundation for the pollutant removal pairwise comparison matrices generated in Chapter 6 of this paper.

While the use of EMC-derived pollutant removal efficiency has fallen under considerable recent scrutiny in the BMP research community, it has historically been the primary means by which to evaluate a practice's pollutant removal performance. Table 4.36 presents a matrix illustrating the range of median pollutant removal efficiencies computed from the databases reviewed in this paper. Median removal efficiencies computed to be negative are reported as zero in the matrix.

Table 4.35 – Matrix of Long-Term Expected Pollutant Reduction Performance by BMP

	Long-Term Pollutant Removal Performance		
	Total Suspended Sediment	**Total Phosphorus**	**Total Nitrogen**
Extended Dry Detention Pond	Low	Moderate	Moderately High
Wet / Retention Pond	High	High	High
Infiltration Trench	Moderately High	High	Moderate
Infiltration Basin	Moderately High	High	Moderate
Porous Pavement	Moderately High	High	Moderate
Extended Detention Wetlands	Moderately High	Moderately High	Low
Bioretention	High	High	High
Vegetated Filter Strips	Low	Low	Low
Vegetated Swales	Moderate	Low	Low
Stormwater Filters	High	High	High
Proprietary Stormwater Technologies	High	Low	Low
Vegetated Roof	High	High	High
Rainwater Capture & Reuse	High	High	High
Minimum Disturbance	Moderately High	Moderately High	Moderately High

Table 4.36 – Matrix of Long-Term Anticipated Pollutant Removal Efficiency by BMP

Best Management Practice	Median Pollutant Removal Efficiency(%)		
	Total Suspended Sediment	Total Phosphorus	Total Nitrogen
Extended Dry Detention Pond	12-61	20-31	18-31
Wet / Retention Pond	59-80	40-55	27-35
Infiltration Trench	85*	85*	30*
Infiltration Basin	85*	85*	30*
Porous Pavement	85-95	65-85	30-83
Extended Detention Wetlands	69-71	30-39	0-56
Bioretention	86	59	38
Vegetated Filter Strips	54	0	9
Vegetated Swales	35-68	0-29	0
Stormwater Filters	86	53-59	32-54
Proprietary Stormwater Technologies	65-74+	N/A	N/A
Vegetated Roof	N/A	N/A	N/A
Rainwater Capture & Reuse	N/A	N/A	N/A
Minimum Disturbance	N/A	N/A	N/A

* Data taken from the Pennsylvania DEP <u>Draft Stormwater Best Management Practices Manual</u>, 2005

\+ Reflects test data rather than manufacturer claims

Chapter 5.0
Construction of Annual BMP Operations and Maintenance Cost Matrices

The BMP selection matrices presently used throughout the engineering community exhibit significant shortcomings. In particular, these matrices lack adequate consideration for long-term BMP maintenance costs and the inevitable decline in a BMPs pollutant removal performance over time. Chapter 5 details the development of a BMP selection matrix specifically dedicated to annual BMP operations and maintenance cost.

5.1 Background

Perhaps *the* paramount influence on a BMPs longevity and pollutant removal performance is the degree to which adequate, routine maintenance is performed on the practice. Generally, BMP maintenance operations are categorized as *aesthetic maintenance* or *functional maintenance.* Functional maintenance directly influences the performance of the BMP, and also entails important safety issues. The importance of aesthetic maintenance varies among practices, and is generally a function of the practice's visibility. Despite the obvious importance of proper BMP upkeep, these maintenance operations and expenditures are often neglected. Typical BMP maintenance activities and anticipated frequencies are shown below in Table 5.1.

Table 5.1 Typical Maintenance Activities for BMPs
Source: Urban Stormwater Best Management Practices Study (EPA, 1999)

BMP Category	Activity	Schedule
Retention Ponds / Wetlands	Cleaning and removal of debris Harvest excess vegetation Repair of embankment and side slopes Repair of control structure	Annual or as needed
	Removal of accumulated sediment from forebays or sediment storage areas	5 yr. cycle or as needed
	Removal of accumulated sediment from main cells of pond once the original volume has been significantly reduced	20 yr. cycle
Detention Basins	Removal of accumulated sediment from forebays or Repair of control structure Repair of embankment and side slopes	Annual or as needed

Table 5.1 Cont'd.		
Infiltration Trenches	Cleaning and removal of debris Mowing and maintenance of upland vegetated areas Maintenance of inlets and outlets	Annual or as needed
Infiltration Basins	Cleaning and removal of debris Mowing and maintenance of upland vegetated areas Removal of accumulated sediment from forebays or sediment storage areas	Annual or as needed 3-5 yr. life cycle
Sand Filters	Removal of trash and debris from control openings Repair of leaks from the sedimentation chamber or deterioration of structural components Removal of the top few inches of sand and cultivation of the surface when filter bed is clogged Clean out of accumulated sediment from filter bed chamber Clean out of accumulated sediment from sedimentation chamber	Annual or as needed
Bioretention	Repair of eroded areas Mulching of void areas Removal and replacement of all dead and diseased vegetation Watering of plant material Removal of mulch and application of new layer	Bi-annual or as needed Annual
Grass Swale	Mowing and litter and debris removal Stabilization of eroded side slopes and bottom Nutrient and pesticide use management De-thatching swale bottom and removal of thatching Discing or aeration of swale bottom Scraping swale bottom and removal of sediment to restore original cross section and infiltration rate Seeding or sodding to restore ground cover	Annual or as needed 5 yr. cycle
Filter Strip	Mowing and litter and debris removal Nutrient and pesticide use management Aeration of soil in the filter strip Repair of eroded or sparse grass areas	Annual or as needed

Presently, there is very little data available to analyze, quantify, and subsequently validate the anticipated annual maintenance costs of individual BMPs. There are a number of reasons for the absence of such data. Frequently, the maintenance operations for a privately owned BMP falls under the responsibility of a homeowners association or neighborhood volunteer group. Often, these groups lack the financial resources, manpower, and knowledge to properly carry out BMP maintenance operations. When homeowners associations do attempt to carry out BMP maintenance operations, the intensity of these operations can vary immensely. Furthermore, many of these maintenance operations are funded by "door-to-door" solicitation of donations.

Such funding endeavors do not lend themselves well to the documentation of maintenance expenditures. Often, state highway departments or municipalities do maintain records of the BMPs for which they take ownership responsibility. However, in addition to these maintenance records exhibiting great variability, they are almost always limited in scope to large structural practices such as extended detention dry and wet ponds.

This chapter seeks to compile available data to create a matrix facilitating side-by-side comparisons of the 14 BMPs described in Chapter 2 in terms of annual operation and maintenance cost.

5.2 Consideration for the Time Value of Money

This paper employs multiple resources in the development of BMP maintenance and operation cost estimates. Many of these studies were published at various times over the past two decades. In an effort to accurately reflect the present-day costs associated with BMP maintenance and operation, it is necessary to adjust these studies to account for the change in monetary value as a function of time. This adjustment is accomplished by employing the following equation:

$$Present\ Day\ Cost = P \times (1+i)^n \qquad \textbf{\textit{(5.1)}}$$

P = the BMP maintenance cost ($) originally reported in the publication of interest

i = discount interest rate for each period

n = time period of record (difference between present year and year that the publication of interest was constructed)

The Board of Governors of the Federal Reserve System released a document in 2003 itemizing the average monthly federal discount rate from January 1950 to December 2002. The reported discount rates for this document's most recent 10-year period of record are shown in Table 5.2.

Table 5.2 Historical Federal Discount Rates

Source: Discount Rate (Board of Governors of the Federal Reserve System, 2003)

Year	Average Federal Discount Rate(%)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	0.83	0.75
2001	5.52	5.00	4.81	4.28	3.73	3.47	3.25	3.16	2.77	2.02	1.58	1.33
2000	5.24	5.34	5.50	5.71	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
1999	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.56	4.75	4.75	4.86	5.00
1998	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	4.86	4.63	4.50
1997	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
1996	5.24	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
1995	4.75	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
1994	3.00	3.00	3.00	3.00	3.24	3.50	3.50	3.76	4.00	4.00	4.40	4.75
1993	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
1992	3.50	3.50	3.50	3.50	3.50	3.50	3.02	3.00	3.00	3.00	3.00	3.00

Averaging all discount rates reported in Table 5.2 yields a rate of *4.09%*. This discount rate is employed throughout the remainder of this chapter to convert previously published BMP operation and maintenance cost estimates to present day dollar amounts.

5.3 Annual Operations and Maintenance Cost by Individual BMP

5.3.1 Extended Detention Dry and Wet Ponds

In most applications, when properly constructed and maintained, extended detention dry and wet ponds exhibit a lifespan of between 20 and 50 years. (Northern Virginia PDC Division of Environmental Services, 2000) For a basin to fall into the higher end of this range, it is critical that regular maintenance be conducted on the facility. The operations associated with maintaining such a facility are classified as *routine* and *non-routine*. Routine maintenance costs include activities such as mowing, weed control, fertilization, and debris (trash) removal. The non-routine costs associated with an extended detention facility include the dredging and disposal of accumulated sediment and its associated pollutant load.

The cost of dredging a stormwater control pond is primarily a function of the volume of sediment that must be removed. However, mobilization and disposal fees must also be considered. The Northern Virginia PDC Division of Environmental Services identifies the following costs for removing sediment from a pond with a one acre surface area:

Table 5.3 Dry and Wet Pond Sediment Removal Cost (1 Acre Surface Area)

Source: Northern Virginia PDC Division of Environmental Services, 2000

Activity	Cost (2000$)	Cost (2006$)
Mobilization	3,000-5,000	3,997-6,662
Dredging	12,090-16,120	16,109-21,479
Disposal (Onsite / Offsite)	4,030 / 37,882	5,370-50,476
Total Cost	***19,120-59,002***	***25,476-78,617***

The required sediment removal frequency is highly dependant upon the characteristics of the watershed contributing runoff to the facility. However, it is generally recommended that these types of facilities be dredged a minimum of once every 10 years. The total costs presented in Table 5.3 are annualized over a ten year period by applying the following formula:

$$A = P \times \left(\frac{e^{i} - 1}{1 - e^{-in}} \right) \qquad \textbf{(5.2)}$$

A = uniform amount per interest period (annual cost in dollars)

P = present day cost of dredging operations ($)

i = discount rate for each period (4.09% annually)

n = time period of interest (10 years)

Annualizing the cost of dredging a one-acre stormwater control pond over a 10 year period, using 2006 dollar amounts, reveals an annual non-routine maintenance cost ranging between $3,302 and $10,188.

The Northern Virginia PDC Division of Environmental Services cites annual routine maintenance costs ranging between $100 and $500 per acre (2000 dollars). These figures are converted to 2006 dollar amounts and included in Table 5.4 to present a summary of the estimated routine and non-routine maintenance costs associated with an extended detention facility of surface area one acre.

Table 5.4 Estimated Annual Maintenance Costs – Extended Detention Ponds (Surface Area of One Acre)

Cost Category	Annual Cost (2006 $)
Routine	133 - 666
Non Routine	3,302 - 10,188
Total	***3,435 - 10,854***

In an attempt to validate the estimated costs presented in Table 5.4, a comparison is now made with the BMP maintenance cost estimating methodologies reported in the *Urban Stormwater Best Management Practices Study* *(EPA, 1999).* Citing work by Brown and Schueler (1997), the EPA document reports the following equation for estimating the base construction cost of a dry detention basin:

$$Base\ Construction\ Cost = 7.47V^{0.78} \qquad \textbf{(5.3)}$$

V = Total basin volume in cubic feet

Updating this equation to reflect 2006 dollars yields the new equation:

$$Base\ Construction\ Cost = 10.72V^{0.78} \qquad \textbf{(5.4)}$$

The EPA study further reports that the anticipated annual maintenance expenditures for this type of facility typically amount to one percent of the base construction cost. The EPA study estimates basin costs based on a storage *volume*, whereas the estimates presented previously in this paper relate maintenance costs to the basin's surface *area*. Table 5.5 presents the estimated construction and annual maintenance costs for a dry detention pond at various depths and one acre surface area.

Table 5.5 Estimated Construction and Annual Maintenance Costs – Dry Extended Detention Basin (Surface Area of One Acre)

Basin Volume (cf)	Depth (ft)	Cost (2006 $)	Annual Maintenance Cost (2006 $)
130,680	3	104,915	1,049
217,800	5	156,272	1,563
304,920	7	203,170	2,032
435,600	10	268,339	2,683

The EPA document reports the following equation for estimating the base construction cost of a wet detention pond:

$$Base\ Construction\ Cost = 18.5V^{0.70} \qquad \textbf{(5.5)}$$

Updating this equation to reflect 2006 dollars results in:

$$Base\ Construction\ Cost = 26.54V^{0.70} \qquad \textbf{(5.6)}$$

Annual maintenance costs for a wet detention facility are reported to range from three to six percent of the base construction cost of the facility. Table 5.6 presents the estimated construction and maintenance costs for a wet detention pond at various depths and one acre surface area.

Table 5.6 Estimated Construction and Annual Maintenance Costs – Wet Extended Detention Basin (Surface Area of One Acre)

Basin Volume (cf)	Depth (ft)	Cost (2006 $)	Annual Maintenance Cost (2006 $)
130,680	3	101,177	3,035 - 6,070 ($0.02-.05 / cf)
217,800	5	144,670	4,340 - 8,680 ($0.02-.04 / cf)
304,920	7	183,091	5,493 - 10,985 ($0.02-.04 / cf)
435,600	10	235,017	7,050 - 14,101 ($0.02-0.03 / cf)

The analysis reveals that the EPA cost estimating guidelines, when compared to a more detailed cost analysis, seem to underestimate the annual maintenance costs associated with dry extended detention basins. However, the cost estimating guidelines appear to be well corroborated for wet detention facilities whose average depth lies between three and seven feet. Based on this observation, and conforming to the cost estimating approach endorsed by the Northern Virginia PDC Division of Environmental Services, within the context of this paper annual maintenance costs will be considered the same for both dry and wet extended detention facilities. To facilitate comparisons among different BMP practices, it is desirable to relate annual maintenance costs to the volume of storage provided by a BMP. Therefore, derived from Table 5.6, the annual anticipated maintenance cost for both dry and wet extended detention facilities is estimated to range between *$0.02 and $0.04 per cubic foot of storage*. This estimate reflects only anticipated maintenance operations, and does not consider unforeseen repair needs.

5.3.2 Infiltration Trenches

Reported construction and maintenance costs for infiltration trenches are highly variable. Unpredictability in soil type and other geotechnical variance among different sites make quantification of infiltration trench construction costs very difficult. The *Urban Stormwater Best Management Practices Study* cites four separate analyses, each yielding significantly different regression equations for estimating the construction cost of infiltration trenches. Figure 5.1 presents the graphical results of these analyses.

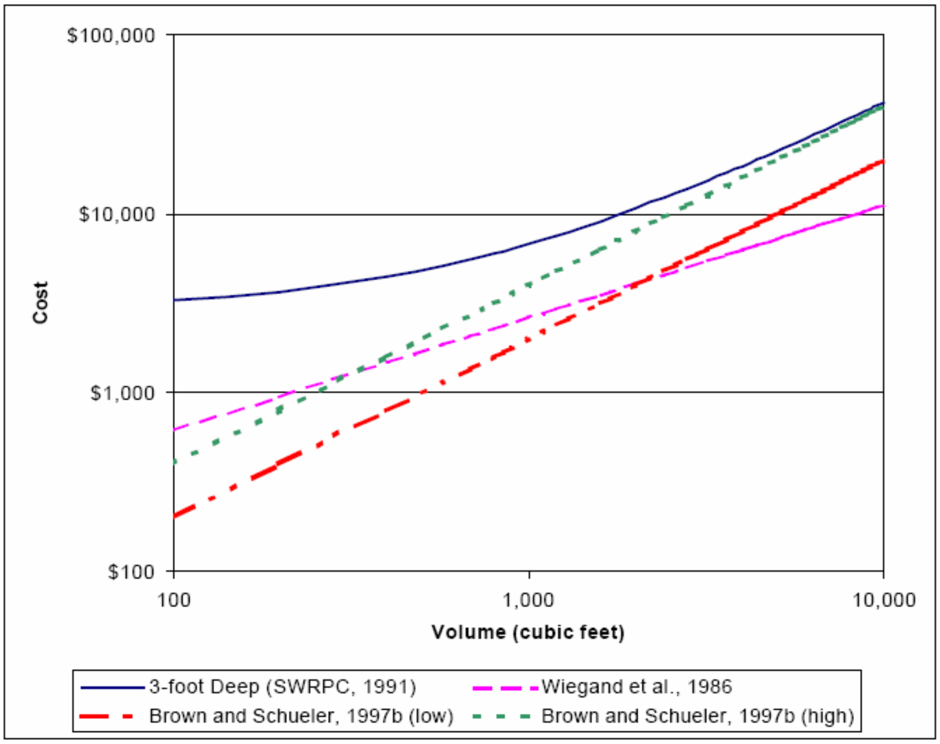


Figure 5.1 Infiltration Trench Construction Costs
Source: Urban Stormwater Best Management Practices Study, EPA, 1999

The most recent of these analyses, Brown and Schueler (1997), provide the following regression-based equation for estimating the construction cost of an infiltration trench:

$$Construction\ Cost = 2.5V \qquad \textbf{\textit{(5.7)}}$$

Updating this equation to 2006 dollars results in:

$$Construction\ Cost = 3.6V \qquad \textbf{\textit{(5.8)}}$$

The most common maintenance operation associated with infiltration trenches is the removal, disposal, and replacement of the top 6 – 12 inches of gravel comprising the infiltration bed. This operation also necessarily includes the disposal of accumulated sediment and its associated pollutant load, replacement of the geotextile filtering fabric, and the installation of a new sediment barrier. The Northern Virginia PDC Division of Environmental Services reports that these operations can cost between $1,500 and $2,000 for "average" size infiltration trenches, though no specific storage volume is associated with these cost figures. Citing Brown and Schueler (1987), the EPA reports that annual maintenance costs can range from 5% to as high as 20% of the trench's construction cost. Based on this information, the anticipated annual maintenance cost of an infiltration trench is estimated to range between *$.18 and $.72 per cubic foot of storage.*

Compared to other BMP options, the anticipated lifespan of 10 years for an infiltration trench is quite short. (NOVA PDC, 2000) High maintenance costs paired with this short lifespan often make infiltration trenches an undesirable BMP option when groundwater recharge and/or high levels of pollutant removal are not required.

5.3.3 Infiltration Basins

Like infiltration trenches, variability in geotechnical conditions from site to site make estimating construction costs extremely difficult. Generally, they are regarded in the engineering community as a moderate cost BMP; however little current data exists to confirm this claim. Citing a 1991 study by the Southeastern Wisconsin Regional Planning Commission (SWRPC), the *Urban Stormwater Best Management Practices Study* reports the following cost equation for a one acre infiltration basin providing at total 76,300 cubic feet of storage:

$$Construction\,Cost = 0.8V \qquad \textbf{(5.9)}$$

Updating this equation to 2006 dollars results in:

$$Construction\,Cost = 1.46V \qquad \textbf{(5.10)}$$

Maintenance costs derived from the same SWRPC study claim anticipated annual expenditures to range from five to ten percent of basin construction costs. However, a more recent study by Livingston, et al (1997) suggests that this figure overestimates annual maintenance needs. The Livingston study reports annual maintenance costs to range from one to three percent of construction costs. While current, validated cost information is sparse regarding infiltration basins, at the present time the annual maintenance cost associated with these practices appears to comparable to that exhibited by the non-infiltrating basins addressed in section 5.3.1 of this paper ($0.02 - $0.04 per cubic foot of storage).

5.3.4 Porous Pavement

The increasing popularity of porous pavement systems and the subsequent availability of cost data are revealing them to be a very economically attractive BMP option. The application of porous pavement systems necessitates an intensive maintenance program. However, unlike many maintenance-intensive BMPs, those activities associated with porous pavement applications are generally of a preventative nature. The Watershed Management Institute identifies the following maintenance activities for porous pavement systems. Clearly, these maintenance operations are targeted at preventing the porous surface from becoming clogged.

Table 5.7 Porous Pavement Maintenance Schedule
Source: Operation, Maintenance, and Management of Stormwater Management Systems (Watershed Management Institute, 1997)

Activity	Schedule
Avoid sealing or repaving with non-porous materials	N/A
Ensure that paving area is clean of debris Ensure that paving dewaters between storms Ensure that the area is clean of sediments	Monthly
Mow upland and adjacent areas, and seed bare areas Vacuum sweep frequently to keep the surface free of sediment (typically 3 – 4 times per year)	As needed
Inspect the surface for deterioration or spalling	Annual

The Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005 reports porous pavement systems to generally be 10 – 20% more expensive than conventional asphalt paving. The majority of this expense is attributed to the infiltration bed that underlies the porous surface. However, the additional costs that are incurred when implementing a porous pavement system in lieu of a conventional system are often more than offset by a reduction in the required number of stormwater conveyance pipes and detention facilities. Recent installations in Pennsylvania averaged between $2,000 and $2,500 per parking space, quite comparable to conventional pavement installations in the same proximity.

The 1999 EPA *Technology Fact Sheet* on porous pavement systems identifies their annual maintenance cost as $200 per acre. This cost includes four inspections each year with jet hosing and vacuum sweeping as determined necessary. Discounting this figure to 2006 dollars indicates an anticipated maintenance cost of *$264 per year per acre*, making porous pavement an extremely attractive BMP option.

5.3.5 Constructed Wetlands

The maintenance expenses associated with constructed stormwater wetlands closely parallel those associated with a wet extended detention facility. Brown and Schueler (1997) claim a reasonable assumption to be that constructed wetlands are generally 25% more expensive to construct than comparably sized retention basins. This added cost is attributed to the specific plant species and sediment forebay requirements associated with constructed stormwater wetlands. The harvesting and care of specific species of plants extends well past the construction phase, and must be accounted for as an annual expense. However, this added expense is usually more than offset by eliminating the need for mowing operations associated with dry and wet detention basins. Brown and Schuler estimate annual maintenance costs to be approximately two percent of wetlands construction cost. This estimate is also endorsed by the EPA in their *Technology Fact Sheet* on stormwater wetlands. Table 5.8 presents the expected annual maintenance cost of stormwater wetland of various depths encompassing a surface area of one acre. These estimates are based on a 25% increase of the construction cost for a comparably sized retention basin and an annual maintenance cost equal to two percent of the computed construction cost.

Table 5.8 Estimated Costs – Constructed Stormwater Wetlands (Surface Area of One Acre)

Basin Volume (cf)	Depth (ft)	Cost (2006 $)	Annual Maintenance Cost (2006 $)
130,680	3	126,471	2,529
217,800	5	180,838	3,617
304,920	7	228,864	4,577
435,600	10	293,771	5,875

Table 5.8 reveals annual wetlands operation and maintenance costs to be *less than $0.02 per cubic foot of storage.*

5.3.6 Bioretention

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. Consequently, the net cost is frequently viewed as considerably less than the actual construction cost would indicate. Furthermore, inclusion of bioretention areas on a site often reduces the number of surface inlets and conveyance piping that is required to accommodate runoff. Brown and Schuler (1997) report that construction costs for bioretention facilities consistently converge to $5.30 per cubic foot of water quality storage. Converting this estimate to 2006 dollars yields an estimated bioretention construction cost of approximately $7.60 per cubic foot of water quality volume.

When properly installed and located, bioretention facilities exhibit an indefinite lifespan. However, a number of annual maintenance activities must be conducted to ensure that a bioretention facility maintains its intended water quality benefit. Initially, while vegetation is being established, pruning and weeding is required. Mulch must be replaced when erosion is evident and/or following extreme runoff producing events. Bioretention areas should be inspected thoroughly a minimum of twice per year to evaluate sediment buildup, erosion, and the condition of trees and shrub vegetation. During drought conditions, bioretention areas may require watering to ensure plant survival. It may appear that bioretention BMPs exhibit an intensive maintenance schedule. However, it must be considered that these facilities are often situated in locations that would necessitate these basic landscaping operations anyway. The EPA *Technology Fact Sheet* on bioretention suggests that operation and maintenance costs be viewed comparably with typical site landscaping expenses, with the exception of specific planting soil requirements in some locations. Viewed separately from typical landscaping costs, Brown and Schuler recommend that the annual maintenance cost of bioretention areas be computed as five to seven percent of implementation costs. This figure yields an estimated annual maintenance cost ranging between *$0.38 and $0.53 per cubic foot of water quality storage volume.*

5.3.7 Vegetated Filter Strips

Like bioretention facilities, the maintenance of vegetated filter strips largely overlaps with site landscaping that would occur in the absence of the strip's implementation. The Pennsylvania DEP <u>Draft Stormwater Best Management Practices Manual</u>, 2005 claims maintenance costs to be highly variable and largely dependent upon local labor rates. However, the manual does quantify annual maintenance expenditures to range between $100 and $1,400 per acre. Citing the SWRPC study (1991), the EPA estimates the annual maintenance cost of vegetated filter strips to be $320 per acre. Discounting this figure to 2006 dollars yields an estimated annual maintenance cost of *$584 per acre*, corroborating the estimated cost range reported in the Pennsylvania DEP publication.

5.3.8 Vegetated Water Quality Swales

Generally, vegetated swales are one of the lowest cost BMPs 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 conventional stormwater conveyance structures. However, when the runoff treatment benefits are considered, along with the long expected lifespan exhibited by vegetated swales, they remain a very financially attractive runoff management option. Table 5.9 reports the findings of a 1991 SWPRC study targeted at identifying the anticipated annual maintenance costs associated with vegetated water quality swales.

Table 5.9 Anticipated Annual Maintenance Costs – Vegetated Swales

Source: <u>Stormwater Technology Fact Sheet – Vegetated Swales</u> (EPA, 1999)

	Swale Size	
	1.5 Foot Depth, One Foot Bottom Width, 10 Foot Top Width	**3 Foot Depth, 3 Foot Bottom Width, 21 Foot Top Width**
Cost ($/linear foot)*	0.58	0.75

* Reflects 1991 Dollars

Discounting the costs reported in Table 5.9 to 2006 dollars and converting the units to dollars per cubic foot indicates that the annual maintenance cost of a vegetated swale ranges between *$0.04 and $0.12 per cubic foot of storage volume.*

5.3.9 Stormwater Filtering Systems

The costs associated with constructed stormwater filters vary significantly both by filter type and geographic region. Studies by Brown and Schueler (1997) were unable to derive a statistically valid correlation between filter cost and water quality volume, with costs ranging between two and six dollars per cubic foot of water quality volume. EPA studies also confirm significant variability in stormwater filter implementation, reporting cost data ranging from $6,600 to $18,500 per treated acre (1997 dollars). Table 5.10 illustrates the geographic variability of stormwater filter costs.

Table 5.10 Construction Costs – Stormwater Filtering Systems

Source: Urban Stormwater Best Management Practices Study (EPA, 1999)

Region (Design Variation)	Cost / Impervious Acre (1994 Dollars)
Delaware (Delaware)	10,000
Alexandria, VA (Delaware)	23,500
Austin, TX (<2 ac.)	16,000
Austin, TX (>5 ac.)	3,400
Washington, D.C. (underground)	14,000
Denver, CO (unspecified)	30,000 - 50,000

The Northern Virginia PDC Division of Environmental Services does attempt to identify typical maintenance operations associated with stormwater filtering systems. The most common maintenance operation associated with these types of BMPs is the removal of the top filter cloth and the removal, disposal, and replacement of filter gravel. Relating this operation to filter size (which is a function contributing impervious area), a range of $1,500 – $2,000 per impervious acre served is reported (2000 dollars). This maintenance operation is required a minimum of once every five years. Discounting these costs to 2006 dollar amounts and then annualizing over a five year period reveals an anticipated *minimum* annual maintenance cost of *$430 – $574 per impervious acre served.*

5.3.10 Proprietary Stormwater Technologies

Both the capital and annual maintenance costs associated with hydrodynamic separators, water quality inlets, and catch basin inserts are highly dependant on site-specific conditions. Often, particularly in the case of hydrodynamic separators, the unit is designed for a very specific flow rate dependant exclusively upon site conditions. Other factors influencing the capital cost of proprietary stormwater technology practices are available land area, required pollutant removal efficiency, and the total number of BMPs addressing the site's runoff. Very little cost data is provided in the MASTEP stormwater technologies clearinghouse. However, the cost data that is reported exhibits great variability with costs for pre-cast units ranging from $1,600 to $60,000.

Basic maintenance operations include regularly checking the level of sediment in the device, and removing it as needed. Inadequate removal of accumulated sediment may result in pollutant resuspension. At a *minimum*, proprietary BMP practices should be inspected and cleaned quarterly. Stormwater technology products are often implemented in areas producing highly contaminated "hotspot" runoff. These hotspot areas often produce runoff laden with hydrocarbon by-products. The accumulated sediment in a proprietary BMP device must be disposed of lawfully, and when hydrocarbons or other toxins are present, maintenance operations may require the owner to coordinate with licensed hazard waste handlers. The EPA *Stormwater Technology Fact Sheet – Hydrodynamic Separators* reports that annual maintenance expenditures are low, generally less that $1,000 for each device. However, caution is issued that this figure is very general, and may climb considerably when hazardous waste disposal is required.

5.3.11 Low Impact Development Strategies

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. The Pennsylvania DEP <u>Draft Stormwater Best Management Practices</u>

Manual, 2005 reports that (in 2004 dollars) the installation cost of extensive vegetated roof assemblies ranges between $8 and $15 per square foot of coverage. Vegetated roofs are an extremely low maintenance BMP, and the document reports that about three man hours of labor are required annually for every 1,000 square feet of coverage.

Capture and Reuse BMPs 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 simple cisterns, rain barrels, and underground storage vaults as well as more elaborate designs such as vertical storage units often termed “fat downspouts.” It is impossible to estimate the implementation or annual maintenance cost of such a wide array of strategies and devices. Similarly, Minimum Disturbance or “site footprinting” is best viewed as a water quality improvement *strategy* rather than *practice*. However, it is important to note that in development scenarios where an MD 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.

5.4 Construction of Operation and Maintenance Cost BMP Selection Matrices

Tables 5.11 and 5.12 serve as respective quantitative and qualitative BMP selection matrices reflecting anticipated annual operation and maintenance costs.

Table 5.11 Expected Annual BMP Operation and Maintenance Costs (Quantitative Comparison)

Best Management Practice	Annual Maintenance and Operation Cost ($ / c.f. Water Quality Volume
Dry Extended Detention Pond	0.02 - 0.04
Wet / Retention Pond	0.02 - 0.04
Infiltration Trench	0.18 - 0.72
Infiltration Basin	0.02 - 0.04
Porous Pavement	$265 per acre
Constructed Stormwater Wetlands	0.02
Bioretention	0.38 - 0.53
Filter Strip	$584 per acre
Vegetated Swale	0.04 - 0.12
Stormwater Filters	$430 - $575 per impervious acre
Proprietary Stormwater Technologies	$1,000*
Vegetated Roof Assembly	3 man hours per 1,000 square feet
Rainwater Capture and Reuse	N/A
Minimum Disturbance "Site Footprinting"	N/A
* Indicates that measure is subject to high variability in reported operation and maintenance costs	

Derived from Table 5.12, the average annual maintenance cost among all practices is *$0.10 – 0.22 per cubic foot of storage volume*.

Table 5.12 Expected Annual BMP Operation and Maintenance Costs (Qualitative Comparison)

Best Management Practice	Annual Maintenance and Operation Cost ($ / c.f. Water Quality Volume
Dry Extended Detention Pond	Moderate
Wet / Retention Pond	Moderate
Infiltration Trench	High
Infiltration Basin	Moderate
Porous Pavement	Low
Constructed Stormwater Wetlands	Moderate
Bioretention	High
Filter Strip	Low
Vegetated Swale	Moderate
Stormwater Filters	Low
Proprietary Stormwater Technologies	*
Vegetated Roof Assembly	Low
Rainwater Capture and Reuse	Low
Minimum Disturbance "Site Footprinting"	Low
* Indicates that measure is subject to high variability in reported operation and maintenance costs	

Chapter 6.0
Construction of BMP Pairwise Comparison Templates

Chapter 6 details the construction of pairwise comparison matrices for use in the Analytic Hierarchy Process optimization algorithm. These pairwise comparison matrices evaluate the performance of each individual BMP against every other BMP in terms of *each* influential selection criterion. By developing fixed “templates” for these comparisons, the user is able to quickly and efficiently apply the AHP algorithm in multiple selection scenarios without having to construct pairwise BMP rankings for each new scenario. The methodology applied in the creation of these templates is discussed, at length, in Chapter 3 of this paper. The hierarchal rankings of the competing BMP alternatives is founded upon the BMP performance and cost data presented in Chapters 2, 4, and 5 of this paper.

6.1 Identification of Relevant Selection Criteria

A seemingly unlimited number of factors can influence the selection of a single BMP for a particular site. Certainly there are criteria, such as the ability of the chosen BMP to accommodate the anticipated runoff flow rates from the site, which are *necessarily* included in the selection process. But other factors, such as the BMPs ability to provide groundwater recharge, are often omitted from the selection process. Furthermore, the criteria deemed “essential” to the selection process almost certainly varies among a project’s stakeholders. While the owner or developer may view annual BMP maintenance cost as the paramount selection consideration, the engineer likely views any number of technical performance criteria more important. In an effort to span both technical and more subjective selection considerations the following selection criteria are addressed in this paper.

Table 6.1 Relevant BMP Selection Criteria

Contributing Drainage Area to the BMP Depth to Seasonally High Groundwater Depth to Bedrock Site Hydrologic Soil Group(s) Ability of the BMP to Provide Groundwater Recharge Capital Cost of Implementing the BMP Annual Operations and Maintenance Cost of the BMP	Ability of the BMP to Receive "Hotspot" Runoff Ability of the BMP to Mitigate Peak Runoff Rates Aesthetic Benefit of the BMP Safety Issues Associated With the BMP Ability of the BMP to Reduce Suspended Sediment Levels Ability of the BMP to Reduce Phosphorus Levels Ability of the BMP to Reduce Nitrogen Levels

For each of these identified BMP selection criteria, a pairwise comparison matrix was constructed. The cell-by-cell ranking of competing BMP alternatives expressed in these matrices is founded on Saaty's scale of relative importances (see Chapter 3, Figure 3.1). While it is not inherently required that pairwise comparison matrices are constructed symmetrically, in most applications it is rational to do so. All of the pairwise comparison templates constructed in this paper are symmetrical about their diagonal.

6.2 Pairwise Comparison Template Construction

6.2.1 Contributing Drainage Area Criterion

Table 6.2 illustrates the contributing drainage area, in acres, recommended for each BMP considered. This information is taken from Chapter 2.

Table 6.2 Recommended Contributing Drainage Area (Acres) By BMP

BMP	Recommended Contributing Drainage Area (acres)
Extended Dry Detention Pond	>10
Wet / Retention Pond	>10
Infiltration Trench	<10
Infiltration Basin	<50, No Minimum
Porous Pavement	<10
Constructed Wetlands	>10
Bioretention	<10
Filter Strip	<5
Vegetated Swale	Flow Rate Dependant*
Stormwater Filtering Systems	Flow Rate Dependant*
Proprietary BMP Technologies	Generally<1
Vegetated Roof	N/A
Minimum Disturbance / Minimum Maintenance	N/A
Rainwater Capture and Reuse	N/A

* Practice generally performs best for smaller contributing drainage areas

The pairwise comparison templates reflecting contributing drainage area are broken into three classifications as follows:

1. Contributing drainage area less than ten acres
2. Contributing drainage area between 10 and 25 acres
3. Contributing drainage area greater than 25 acres

This grouping permits the user to choose a BMP comparison template which reflects the site-specific characteristics. Based on the information shown in Table 6.2, and employing the scale of relative importances (Figure 3.1), these templates are presented on the following pages.

Table 6.3 Pairwise Comparison Template – Drainage Area Less Than Ten Acres

	EDDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	1.00	1.00	0.14	0.14	0.14	1.00	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Wet Pond	1.00	1.00	0.14	0.14	0.14	1.00	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Infil. Trench	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Infil. Basin	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Por. Pvmt.	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wetlands	1.00	1.00	0.14	0.14	0.14	1.00	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Bioretention	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Filter Strip	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Veg. Swale	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Filters	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Proprietary	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Veg. Roof	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
MD/MM	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C&R	7.00	7.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

BMP	Matrix Priority Vector
Extended Dry Detention Pond	0.0125
Wet / Retention Pond	0.0125
Infiltration Trench	0.0875
Infiltration Basin	0.0875
Porous Pavement	0.0875
Constructed Wetlands	0.0125
Bioretention	0.0875
Filler Strip	0.0875
Vegetated Swale	0.0875
Stormwater Filtering Systems	0.0875
Proprietary BMP Technologies	0.0875
Vegetated Roof	0.0875
Minimum Disturbance / Minimum Maintenance	0.0875
Rainwater Capture and Reuse	0.0875

Consistency Ratio = 0.00

Table 6.4 Pairwise Comparison Template – Drainage Area 10 Acres - 25 Acres

	EDDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	1.00	1.00	7.00	1.00	5.00	1.00	7.00	7.00	7.00	7.00	5.00	5.00	1.00	5.00
Wet Pond	1.00	1.00	7.00	1.00	5.00	1.00	7.00	7.00	7.00	7.00	5.00	5.00	1.00	5.00
Infil. Trench	0.14	0.14	1.00	0.14	1.00	0.14	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Infil. Basin	1.00	1.00	7.00	1.00	5.00	1.00	7.00	7.00	7.00	7.00	5.00	5.00	1.00	5.00
Por. Pvmt.	0.20	0.20	1.00	0.20	1.00	0.20	3.00	3.00	3.00	3.00	1.00	1.00	1.00	1.00
Wetlands	1.00	1.00	7.00	1.00	5.00	1.00	7.00	7.00	7.00	7.00	5.00	5.00	1.00	5.00
Bioretention	0.14	0.14	1.00	0.14	0.33	0.14	1.00	1.00	1.00	1.00	0.33	1.00	1.00	1.00
Filter Strip	0.14	0.14	1.00	0.14	0.33	0.14	1.00	1.00	1.00	1.00	0.33	1.00	1.00	1.00
Veg. Swale	0.14	0.14	1.00	0.14	0.33	0.14	1.00	1.00	1.00	1.00	0.33	1.00	1.00	1.00
Filters	0.14	0.14	1.00	0.14	0.33	0.14	1.00	1.00	1.00	1.00	0.33	1.00	1.00	1.00
Proprietary	0.20	0.20	1.00	0.20	1.00	0.20	3.00	3.00	3.00	3.00	1.00	1.00	1.00	1.00
Veg. Roof	0.20	0.20	1.00	0.20	1.00	0.20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
MD/MM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C&R	0.20	0.20	1.00	0.20	1.00	0.20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

BMP	Matrix Priority Vector
Extended Dry Detention Pond	0.1597
Wet / Retention Pond	0.1597
Infiltration Trench	0.0300
Infiltration Basin	0.1597
Porous Pavement	0.0462
Constructed Wetlands	0.1597
Bioretention	0.0266
Filter Strip	0.0266
Vegetated Swale	0.0266
Stormwater Filtering Systems	0.0266
Proprietary BMP Technologies	0.0462
Vegetated Roof	0.0325
Minimum Disturbance / Minimum Maintenance	0.0676
Rainwater Capture and Reuse	0.0325

Consistency Ratio = 0.05

Table 6.5 Pairwise Comparison Template – Drainage Area Greater Than 25 Acres

	EDDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*
Wet Pond	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*
Infil. Trench	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Infil. Basin	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*
Por. Pvmt.	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Wetlands	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*	*9.00*
Bioretention	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Filter Strip	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Swale	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Filters	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Proprietary	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Roof	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
MD/MM	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
C&R	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.1957*
Wet / Retention Pond	*0.1957*
Infiltration Trench	*0.0217*
Infiltration Basin	*0.1957*
Porous Pavement	*0.0217*
Constructed Wetlands	*0.1957*
Bioretention	*0.0217*
Filter Strip	*0.0217*
Vegetated Swale	*0.0217*
Stormwater Filtering Systems	*0.0217*
Proprietary BMP Technologies	*0.0217*
Vegetated Roof	*0.0217*
Minimum Disturbance / Minimum Maintenance	*0.0217*
Rainwater Capture and Reuse	*0.0217*

Consistency Ratio = 0.00

6.2.2 Shallow Groundwater Table Area Criterion

The presence of a shallow groundwater table (less than three feet below a site's finished grade) typically precludes the use of infiltration practices. These practices include bioretention, porous pavement, and stormwater filtering systems. By contrast, 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 biofilters (grass swales and filter strips), proprietary stormwater technologies, and rainwater capturing systems. When dry detention facilities are being considered in the presence of a shallow groundwater table, they often must be equipped with a synthetic or clay liner to prevent unwanted infiltration. Wet ponds and constructed wetlands are capable of utilizing readily available groundwater as a source of baseflow, and thus such site characteristics are considered beneficial. Table 6.6 serves as the pairwise comparison template for the shallow groundwater criterion.

Table 6.6 Pairwise Comparison Template – Shallow Groundwater Depth

	EDDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*0.20*	*5.00*	*5.00*	*5.00*	*0.20*	*5.00*	*0.33*	*0.33*	*5.00*	*0.14*	*0.14*	*0.14*	*0.14*
Wet Pond	*5.00*	*1.00*	*7.00*	*7.00*	*7.00*	*1.00*	*7.00*	*0.20*	*0.20*	*5.00*	*0.13*	*0.13*	*0.13*	*0.13*
Infil. Trench	*0.20*	*0.14*	*1.00*	*1.00*	*1.00*	*0.14*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Infil. Basin	*0.20*	*0.14*	*1.00*	*1.00*	*1.00*	*0.14*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Por. Pvmt.	*0.20*	*0.14*	*1.00*	*1.00*	*1.00*	*0.14*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Wetlands	*5.00*	*1.00*	*7.00*	*7.00*	*7.00*	*1.00*	*7.00*	*0.20*	*0.20*	*5.00*	*0.13*	*0.13*	*0.13*	*0.13*
Bioretention	*0.20*	*0.14*	*1.00*	*1.00*	*1.00*	*0.14*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Filter Strip	*3.00*	*5.00*	*7.00*	*7.00*	*7.00*	*5.00*	*7.00*	*1.00*	*1.00*	*7.00*	*0.50*	*0.50*	*0.50*	*0.50*
Veg. Swale	*3.00*	*5.00*	*7.00*	*7.00*	*7.00*	*5.00*	*7.00*	*1.00*	*1.00*	*7.00*	*0.50*	*0.50*	*0.50*	*0.50*
Filters	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Proprietary	*7.00*	*8.00*	*9.00*	*9.00*	*9.00*	*8.00*	*9.00*	*2.00*	*2.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Roof	*7.00*	*8.00*	*9.00*	*9.00*	*9.00*	*8.00*	*9.00*	*2.00*	*2.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
MD/MM	*7.00*	*8.00*	*9.00*	*9.00*	*9.00*	*8.00*	*9.00*	*2.00*	*2.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
C&R	*7.00*	*8.00*	*9.00*	*9.00*	*9.00*	*8.00*	*9.00*	*2.00*	*2.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0376*
Wet / Retention Pond	*0.0516*
Infiltration Trench	*0.0128*
Infiltration Basin	*0.0128*
Porous Pavement	*0.0128*
Constructed Wetlands	*0.0516*
Bioretention	*0.0128*
Fitler Strip	*0.0912*
Vegetated Swale	*0.0912*
Stormwater Filtering Systems	*0.0129*
Proprietary BMP Technologies	*0.1532*
Vegetated Roof	*0.1532*
Minimum Disturbance / Minimum Maintenance	*0.1532*
Rainwater Capture and Reuse	*0.1532*

Consistency Ratio = 0.08

6.2.3 Shallow Bedrock Depth Criterion

Much like the presence of a shallow groundwater table, the presence of exceptionally 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. Practices which infiltrate little or no runoff into the subsurface are favored as treatment options in the presence of shallow bedrock depths. These practices include biofilters (grass swales and filter strips), proprietary stormwater technologies, and rainwater capturing systems. When dry and wet detention facilities are considered, site soil conditions must be evaluated to determine whether clay or synthetic liners are required to prevent undesirable infiltration. Unlike the presence of a shallow groundwater table, the presence of shallow bedrock depths provides no benefit for the implementation of constructed wetlands, and in fact may necessitate that a liner be installed. Table 6.7 serves as the pairwise comparison template for the shallow bedrock depth criterion.

Table 6.7 Pairwise Comparison Template – Shallow Bedrock Depth

	EDDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*1.00*	*5.00*	*5.00*	*5.00*	*1.00*	*5.00*	*0.33*	*0.33*	*5.00*	*0.14*	*0.14*	*0.14*	*0.14*
Wet Pond	*1.00*	*1.00*	*5.00*	*5.00*	*5.00*	*1.00*	*5.00*	*0.33*	*0.33*	*5.00*	*0.14*	*0.14*	*0.14*	*0.14*
Infil. Trench	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Infil. Basin	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Por. Pvmt.	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Wetlands	*1.00*	*1.00*	*5.00*	*5.00*	*5.00*	*1.00*	*5.00*	*0.33*	*0.33*	*5.00*	*0.14*	*0.14*	*0.14*	*0.14*
Bioretention	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Filter Strip	*3.00*	*3.00*	*7.00*	*7.00*	*7.00*	*3.00*	*7.00*	*1.00*	*1.00*	*7.00*	*0.50*	*0.50*	*0.50*	*0.50*
Veg. Swale	*3.00*	*3.00*	*7.00*	*7.00*	*7.00*	*3.00*	*7.00*	*1.00*	*1.00*	*7.00*	*0.50*	*0.50*	*0.50*	*0.50*
Filters	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.14*	*0.14*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Proprietary	*7.00*	*7.00*	*9.00*	*9.00*	*9.00*	*7.00*	*9.00*	*2.00*	*2.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Roof	*7.00*	*7.00*	*9.00*	*9.00*	*9.00*	*7.00*	*9.00*	*2.00*	*2.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
MD/MM	*7.00*	*7.00*	*9.00*	*9.00*	*9.00*	*7.00*	*9.00*	*2.00*	*2.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
C&R	*7.00*	*7.00*	*9.00*	*9.00*	*9.00*	*7.00*	*9.00*	*2.00*	*2.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0420*
Wet / Retention Pond	*0.0420*
Infiltration Trench	*0.0133*
Infiltration Basin	*0.0133*
Porous Pavement	*0.0133*
Constructed Wetlands	*0.0420*
Bioretention	*0.0133*
Fitler Strip	*0.0887*
Vegetated Swale	*0.0887*
Stormwater Filtering Systems	*0.0133*
Proprietary BMP Technologies	*0.1575*
Vegetated Roof	*0.1575*
Minimum Disturbance / Minimum Maintenance	*0.1575*
Rainwater Capture and Reuse	*0.1575*

Consistency Ratio = 0.04

6.2.4 Hydrologic Soil Group D Criterion

Hydrologic soil group (HSG) D consists primarily of clay loam, silty clay loam, sandy clay, silty clay, or clay. This HSG has the highest runoff potential among the four different 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 much like 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 selection of pond practices in a considerably different manner. The presence of HSG D can be viewed as a benefit when considering the implementation of dry and wet extended detention facilities. The low infiltration rates exhibited by these soils may significantly reduce undesirable exfiltration loss of detained runoff. The comparison matrix dedicated to this selection criterion values all non-infiltration practices equally. Table 6.8 serves as the pairwise comparison template for the hydrologic soil group D criterion.

Table 6.8 Pairwise Comparison Template – Hydrologic Soil Group D

	EDDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*1.00*	*9.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
Wet Pond	*1.00*	*1.00*	*9.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
Infil. Trench	*0.11*	*0.11*	*1.00*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Infil. Basin	*0.11*	*0.11*	*1.00*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Por. Pvmt.	*0.11*	*0.11*	*1.00*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Wetlands	*1.00*	*1.00*	*9.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
Bioretention	*0.11*	*0.11*	*1.00*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Filter Strip	*1.00*	*1.00*	*9.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Swale	*1.00*	*1.00*	*9.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
Filters	*0.11*	*0.11*	*1.00*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Proprietary	*1.00*	*1.00*	*9.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Roof	*1.00*	*1.00*	*9.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
MD/MM	*1.00*	*1.00*	*9.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
C&R	*1.00*	*1.00*	*9.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.1047*
Wet / Retention Pond	*0.1047*
Infiltration Trench	*0.0116*
Infiltration Basin	*0.0116*
Porous Pavement	*0.0116*
Constructed Wetlands	*0.1047*
Bioretention	*0.0116*
Fitler Strip	*0.1047*
Vegetated Swale	*0.1047*
Stormwater Filtering Systems	*0.0116*
Proprietary BMP Technologies	*0.1047*
Vegetated Roof	*0.1047*
Minimum Disturbance / Minimum Maintenance	*0.1047*
Rainwater Capture and Reuse	*0.1047*

Consistency Ratio = 0.00

6.2.5 Hydrologic Soil Group A Criterion

Hydrologic soil group (HSG) A consists of sand, loamy sand, or sandy loam types of soils. It exhibits low runoff potential and high infiltration rates even when thoroughly wetted. These soils consist primarily of deep, well drained sands or gravels and have a high rate of water transmission.

The presence of HSG A on a site greatly reduces the BMP options from which a designer can choose. Generally, the soil group exhibits infiltration rates beyond what is recommended for infiltration practices. Similarly, these excessively high infiltration rates may present difficulties in achieving minimum hydraulic residence times in detention facilities, vegetated swales and filters, and wetlands. In the absence of synthetic liners, the presence of HSG A often precludes the use of these practices. Table 6.9 serves as the pairwise comparison template for the hydrologic soil group A criterion.

Table 6.9 Pairwise Comparison Template – Hydrologic Soil Group A

	EDDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*1.00*	*5.00*	*5.00*	*5.00*	*1.00*	*5.00*	*1.00*	*1.00*	*5.00*	*0.33*	*0.33*	*0.33*	*0.33*
Wet Pond	*1.00*	*1.00*	*5.00*	*5.00*	*5.00*	*1.00*	*5.00*	*1.00*	*1.00*	*5.00*	*0.33*	*0.33*	*0.33*	*0.33*
Infil. Trench	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.20*	*0.20*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Infil. Basin	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.20*	*0.20*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Por. Pvmt.	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.20*	*0.20*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Wetlands	*1.00*	*1.00*	*5.00*	*5.00*	*5.00*	*1.00*	*5.00*	*1.00*	*1.00*	*5.00*	*0.33*	*0.33*	*0.33*	*0.33*
Bioretention	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.20*	*0.20*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Filter Strip	*1.00*	*1.00*	*5.00*	*5.00*	*5.00*	*1.00*	*5.00*	*1.00*	*1.00*	*5.00*	*0.33*	*0.33*	*0.33*	*0.33*
Veg. Swale	*1.00*	*1.00*	*5.00*	*5.00*	*5.00*	*1.00*	*5.00*	*1.00*	*1.00*	*5.00*	*0.33*	*0.33*	*0.33*	*0.33*
Filters	*0.20*	*0.20*	*1.00*	*1.00*	*1.00*	*0.20*	*1.00*	*0.20*	*0.20*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*
Proprietary	*3.00*	*3.00*	*9.00*	*9.00*	*9.00*	*3.00*	*9.00*	*3.00*	*3.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Roof	*3.00*	*3.00*	*9.00*	*9.00*	*9.00*	*3.00*	*9.00*	*3.00*	*3.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
MD/MM	*3.00*	*3.00*	*9.00*	*9.00*	*9.00*	*3.00*	*9.00*	*3.00*	*3.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*
C&R	*3.00*	*3.00*	*9.00*	*9.00*	*9.00*	*3.00*	*9.00*	*3.00*	*3.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0622*
Wet / Retention Pond	*0.0622*
Infiltration Trench	*0.0145*
Infiltration Basin	*0.0145*
Porous Pavement	*0.0145*
Constructed Wetlands	*0.0622*
Bioretention	*0.0145*
Fitler Strip	*0.0622*
Vegetated Swale	*0.0622*
Stormwater Filtering Systems	*0.0145*
Proprietary BMP Technologies	*0.1541*
Vegetated Roof	*0.1541*
Minimum Disturbance / Minimum Maintenance	*0.1541*
Rainwater Capture and Reuse	*0.1541*

Consistency Ratio = 0.01

6.2.6 Groundwater Recharge Criterion

A number of locations in the United States presently require site development projects to a minimum provide some level of post-development groundwater recharge. The Maryland Department of the Environment evaluates the following BMPs in terms of ability to provide groundwater recharge.

Table 6.10 Groundwater Recharge Ability of BMPs
Source: Maryland Department of the Environment, 2000

BMP	Groundwater Recharge Capability
Extended Dry Detention Pond	No
Wet / Retention Pond	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 stormwater filtering systems.

Filter strips, proprietary stormwater technologies, and vegetated roofs do not provide groundwater recharge.

Minimum Disturbance / Minimum Maintenance development strategies do not provide an easily quantified groundwater recharge rate or volume. However, when considering the resulting reduction in site imperviousness arising from their implementation, the groundwater recharge capabilities of this strategy can be considered at least moderate.

Table 6.11 serves as the pairwise comparison template for the groundwater recharge criterion.

Table 6.11 Pairwise Comparison Template – Ability to Provide Groundwater Recharge

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*1.00*	*0.11*	*0.11*	*0.20*	*0.20*	*0.11*	*1.00*	*0.11*	*0.20*	*1.00*	*1.00*	*0.20*	*1.00*
Wet Pond	*1.00*	*1.00*	*0.11*	*0.11*	*0.20*	*0.20*	*0.11*	*1.00*	*0.11*	*0.20*	*1.00*	*1.00*	*0.20*	*1.00*
Infil. Trench	*9.00*	*9.00*	*1.00*	*1.00*	*5.00*	*5.00*	*1.00*	*9.00*	*1.00*	*5.00*	*9.00*	*9.00*	*5.00*	*9.00*
Infil. Basin	*9.00*	*9.00*	*1.00*	*1.00*	*5.00*	*5.00*	*1.00*	*9.00*	*1.00*	*5.00*	*9.00*	*9.00*	*5.00*	*9.00*
Pour. Pvmt.	*5.00*	*5.00*	*0.20*	*0.20*	*1.00*	*1.00*	*0.20*	*5.00*	*0.20*	*1.00*	*5.00*	*5.00*	*1.00*	*5.00*
Wetlands	*5.00*	*5.00*	*0.20*	*0.20*	*1.00*	*1.00*	*0.20*	*5.00*	*0.20*	*1.00*	*5.00*	*5.00*	*1.00*	*5.00*
Bioretention	*9.00*	*9.00*	*1.00*	*1.00*	*5.00*	*5.00*	*1.00*	*9.00*	*1.00*	*5.00*	*9.00*	*9.00*	*5.00*	*9.00*
Filter Strip	*1.00*	*1.00*	*0.11*	*0.11*	*0.20*	*0.20*	*0.11*	*1.00*	*0.11*	*0.20*	*1.00*	*1.00*	*0.20*	*1.00*
Veg. Swale	*9.00*	*9.00*	*1.00*	*1.00*	*5.00*	*5.00*	*1.00*	*9.00*	*1.00*	*5.00*	*9.00*	*9.00*	*5.00*	*9.00*
Filters	*5.00*	*5.00*	*0.20*	*0.20*	*1.00*	*1.00*	*0.20*	*5.00*	*0.20*	*1.00*	*5.00*	*5.00*	*1.00*	*5.00*
Proprietary	*1.00*	*1.00*	*0.11*	*0.11*	*0.20*	*0.20*	*0.11*	*1.00*	*0.11*	*0.20*	*1.00*	*1.00*	*0.20*	*1.00*
Veg. Roof	*1.00*	*1.00*	*0.11*	*0.11*	*0.20*	*0.20*	*0.11*	*1.00*	*0.11*	*0.20*	*1.00*	*1.00*	*0.20*	*1.00*
MD/MM	*5.00*	*5.00*	*0.20*	*0.20*	*1.00*	*1.00*	*0.20*	*5.00*	*0.20*	*1.00*	*5.00*	*5.00*	*1.00*	*5.00*
C&R	*1.00*	*1.00*	*0.11*	*0.11*	*0.20*	*0.20*	*0.11*	*1.00*	*0.11*	*0.20*	*1.00*	*1.00*	*0.20*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0150*
Wet / Retention Pond	*0.0150*
Infiltration Trench	*0.1712*
Infiltration Basin	*0.1712*
Porous Pavement	*0.0564*
Constructed Wetlands	*0.0564*
Bioretention	*0.1712*
Filter Strip	*0.0150*
Vegetated Swale	*0.1712*
Stormwater Filtering Systems	*0.0564*
Proprietary BMP Technologies	*0.0150*
Vegetated Roof	*0.0150*
Minimum Disturbance / Minimum Maintenance	*0.0564*
Rainwater Capture and Reuse	*0.0150*

Consistency Ratio = 0.03

6.2.7 Capital Implementation Cost

Table 6.12 summarizes the initial costs associated with implementing various BMPs. These figures are taken from Chapter 4 of this paper.

Table 6.12 BMP Implementation Costs

BMP	Typical Implementation Cost
Extended Dry Detention Pond	$0.60 - $0.80 per c.f. Storage Volume
Wet / Retention Pond	$0.60 - $0.80 per c.f. Storage Volume
Infiltration Trench	$3.60 per c.f. Storage Volume
Infiltration Basin	$1.46 per c.f. Storage Volume
Constructed Wetlands	$0.75 - $1.00 per c.f. Storage Volume
Bioretention	$7.60 per c.f. Storage Volume
Stormwater Filtering Systems	$10,000 - $50,000 per Impervious Acre Treated
Proprietary BMP Technologies	Highly Variable and Site Specific
Vegetated Roof	$8 - $15 per s.f. Coverage Area

The implementation costs associated with porous pavement systems, vegetated filter strips, and vegetated water quality swales must be viewed differently than the structural BMPs described in Table 6.12. The use of these measures often results in a reduction of required stormwater conveyance piping and surface inlets. As reported in the Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005, the cost of recent porous pavement installations has been very comparable to historical costs for conventional asphalt applications. When this is considered alongside the reduction in surface inlets and stormwater conveyance piping, porous pavement appears to a financially attractive BMP option. Similarly, in the case of vegetated filter strips and buffers, the cost of implementation can often be compared with site landscaping requirements that would be required even in their absence. Because of these factors, it is useful to consider the *relative* cost of BMP implementation rather than the absolute cost of installing these practices. Table 6.12 presents the relative cost of implementing various BMPs. This table serves as the basis for the pairwise comparison matrix presented as Table 6.13

Table 6.13 Relative Comparison of BMP Implementation Costs

BMP	Relative Implementation Cost
Extended Dry Detention Pond	Moderate
Wet / Retention Pond	Moderate
Infiltration Trench	High
Infiltration Basin	Moderately High
Porous Pavement	Moderate
Constructed Wetlands	Moderately High
Bioretention	High
Filter Strip	Low
Vegetated Swale	Moderate
Stormwater Filtering Systems	High
Proprietary BMP Technologies	Moderate
Vegetated Roof	Moderate
Minimum Disturbance / Minimum Maintenance	Low
Rainwater Capture and Reuse	Low

Table 6.14 Pairwise Comparison Template – Capital Implementation Cost

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*1.00*	*5.00*	*2.00*	*1.00*	*2.00*	*5.00*	*0.33*	*1.00*	*5.00*	*1.00*	*1.00*	*0.33*	*0.33*
Wet Pond	*1.00*	*1.00*	*5.00*	*2.00*	*1.00*	*2.00*	*5.00*	*0.33*	*1.00*	*5.00*	*1.00*	*1.00*	*0.33*	*0.33*
Infil. Trench	*0.20*	*0.20*	*1.00*	*0.33*	*0.20*	*0.33*	*1.00*	*0.14*	*0.20*	*1.00*	*0.20*	*0.20*	*0.14*	*0.14*
Infil. Basin	*0.50*	*0.50*	*3.00*	*1.00*	*0.50*	*1.00*	*3.00*	*0.33*	*0.50*	*3.00*	*0.50*	*0.50*	*0.33*	*0.33*
Pour. Pvmt.	*1.00*	*1.00*	*5.00*	*2.00*	*1.00*	*2.00*	*5.00*	*0.33*	*1.00*	*5.00*	*1.00*	*1.00*	*0.33*	*0.33*
Wetlands	*0.50*	*0.50*	*3.00*	*1.00*	*0.50*	*1.00*	*3.00*	*0.33*	*0.50*	*3.00*	*0.50*	*0.50*	*0.33*	*0.33*
Bioretention	*0.20*	*0.20*	*1.00*	*0.33*	*0.20*	*0.33*	*1.00*	*0.14*	*0.20*	*1.00*	*0.20*	*0.20*	*0.14*	*0.14*
Filter Strip	*3.00*	*3.00*	*7.00*	*3.00*	*3.00*	*3.00*	*7.00*	*1.00*	*3.00*	*7.00*	*3.00*	*3.00*	*1.00*	*1.00*
Veg. Swale	*1.00*	*1.00*	*5.00*	*2.00*	*1.00*	*2.00*	*5.00*	*0.33*	*1.00*	*5.00*	*1.00*	*1.00*	*0.33*	*0.33*
Filters	*0.20*	*0.20*	*1.00*	*0.33*	*0.20*	*0.33*	*1.00*	*0.14*	*0.20*	*1.00*	*0.20*	*0.20*	*0.14*	*0.14*
Proprietary	*1.00*	*1.00*	*5.00*	*2.00*	*1.00*	*2.00*	*5.00*	*0.33*	*1.00*	*5.00*	*1.00*	*1.00*	*0.33*	*0.33*
Veg. Roof	*1.00*	*1.00*	*5.00*	*2.00*	*1.00*	*2.00*	*5.00*	*0.33*	*1.00*	*5.00*	*1.00*	*1.00*	*0.33*	*0.33*
MD/MM	*3.00*	*3.00*	*7.00*	*3.00*	*3.00*	*3.00*	*7.00*	*1.00*	*3.00*	*7.00*	*3.00*	*3.00*	*1.00*	*1.00*
C&R	*3.00*	*3.00*	*7.00*	*3.00*	*3.00*	*3.00*	*7.00*	*1.00*	*3.00*	*7.00*	*3.00*	*3.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0673*
Wet / Retention Pond	*0.0673*
Infiltration Trench	*0.0157*
Infiltration Basin	*0.0413*
Porous Pavement	*0.0673*
Constructed Wetlands	*0.0413*
Bioretention	*0.0157*
Filter Strip	*0.1555*
Vegetated Swale	*0.0673*
Stormwater Filtering Systems	*0.0157*
Proprietary BMP Technologies	*0.0673*
Vegetated Roof	*0.0673*
Minimum Disturbance / Minimum Maintenance	*0.1555*
Rainwater Capture and Reuse	*0.1555*

Consistency Ratio = 0.01

6.2.8 Operations and Maintenance Cost

The operations and maintenance cost pairwise comparison template is based exclusively on the two operations and maintenance cost BMP selection matrices constructed in Chapter 5 of this paper (Figures 5.2 and 5.3). Table 6.15 serves as the pairwise comparison template for the operations and maintenance cost criterion.

Table 6.15 Pairwise Comparison Template – Operations and Maintenance Cost

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	1.00	1.00	4.00	1.00	0.25	1.00	4.00	0.25	1.00	0.50	0.50	0.25	0.25	0.25
Wet Pond	1.00	1.00	4.00	1.00	0.25	1.00	4.00	0.25	1.00	0.50	0.50	0.25	0.25	0.25
Infil. Trench	0.25	0.25	1.00	0.25	0.14	0.25	1.00	0.14	0.25	0.14	0.33	0.14	0.14	0.14
Infil. Basin	1.00	1.00	4.00	1.00	0.25	1.00	4.00	0.25	1.00	0.50	0.50	0.25	0.25	0.25
Pour. Pvmt.	4.00	4.00	7.00	4.00	1.00	4.00	7.00	1.00	4.00	2.00	1.00	1.00	1.00	1.00
Wetlands	1.00	1.00	4.00	1.00	0.25	1.00	4.00	0.25	1.00	0.50	0.50	0.25	0.25	0.25
Bioretention	0.25	0.25	1.00	0.25	0.14	0.25	1.00	0.14	0.25	0.14	0.33	0.14	0.14	0.14
Filter Strip	4.00	4.00	7.00	4.00	1.00	4.00	7.00	1.00	4.00	2.00	1.00	1.00	1.00	1.00
Veg. Swale	1.00	1.00	4.00	1.00	0.25	1.00	4.00	0.25	1.00	0.50	0.50	0.25	0.25	0.25
Filters	2.00	2.00	7.00	2.00	0.50	2.00	7.00	0.50	2.00	1.00	1.00	0.20	0.14	0.14
Proprietary	2.00	2.00	3.00	2.00	1.00	2.00	3.00	1.00	2.00	1.00	1.00	1.00	0.33	0.33
Veg. Roof	4.00	4.00	7.00	4.00	1.00	4.00	7.00	1.00	4.00	5.00	1.00	1.00	0.33	0.33
MD/MM	4.00	4.00	7.00	4.00	1.00	4.00	7.00	1.00	4.00	7.00	3.00	3.00	1.00	1.00
C&R	4.00	4.00	7.00	4.00	1.00	4.00	7.00	1.00	4.00	7.00	3.00	3.00	1.00	1.00

BMP	Matrix Priority Vector
Extended Dry Detention Pond	0.0360
Wet / Retention Pond	0.0360
Infiltration Trench	0.0138
Infiltration Basin	0.0360
Porous Pavement	0.1199
Constructed Wetlands	0.0360
Bioretention	0.0138
Filter Strip	0.1199
Vegetated Swale	0.0360
Stormwater Filtering Systems	0.0601
Proprietary BMP Technologies	0.0696
Vegetated Roof	0.1126
Minimum Disturbance / Minimum Maintenance	0.1550
Rainwater Capture and Reuse	0.1550

Consistency Ratio = 0.04

6.2.9 Ability to Accept Hotspot 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 (see Chapter 2, Figure 2.3). The cell-by-cell pairwise comparisons expressed for this criterion function in a “yes or no” capacity. All practices which are capable of receiving hotspot runoff are ranked equal. The three practices toward which hotspot runoff cannot be directed are given the lowest order of preference by the scale of relative importances. Needless to say, runoff cannot be “directed” toward the low impact development strategies included in the pairwise comparison matrix. However, because the presence of hotspot runoff on a site does not preclude their consideration, they are given equal ranking to the structural practices to which hotspot runoff can be directed. Table 6.16 serves as the pairwise comparison template for the hotspot runoff criterion.

Table 6.16 Pairwise Comparison Template – Ability to Accept Hotspot Runoff

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Wet Pond	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Infil. Trench	*0.11*	*0.11*	*1.00*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*
Infil. Basin	*0.11*	*0.11*	*1.00*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*
Pour. Pvmt.	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Wetlands	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Bioretention	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Filter Strip	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Swale	*0.11*	*0.11*	*1.00*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*
Filters	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Proprietary	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Roof	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
MD/MM	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
C&R	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0882*
Wet / Retention Pond	*0.0882*
Infiltration Trench	*0.0098*
Infiltration Basin	*0.0098*
Porous Pavement	*0.0882*
Constructed Wetlands	*0.0882*
Bioretention	*0.0882*
Filter Strip	*0.0882*
Vegetated Swale	*0.0098*
Stormwater Filtering Systems	*0.0882*
Proprietary BMP Technologies	*0.0882*
Vegetated Roof	*0.0882*
Minimum Disturbance / Minimum Maintenance	*0.0882*
Rainwater Capture and Reuse	*0.0882*

Consistency Ratio = 0.00

6.2.10 Ability to Mitigate Peak Rate of Runoff

Table 6.17 summarizes the peak mitigation performance of each BMP discussed in Chapter 2 of this paper. These relative performance rankings are employed to construct a pairwise comparison template reflecting peak mitigation performance.

Table 6.17 Peak Mitigation Performance of Various BMPs

BMP	Relative Ability to Mitigate Peak Runoff Rates
Extended Dry Detention Pond	High
Wet / Retention Pond	High
Infiltration Trench	Medium
Infiltration Basin	High
Porous Pavement	High
Constructed Wetlands	High
Bioretention	Low – Medium
Filter Strip	Low
Vegetated Swale	Medium – High
Stormwater Filtering Systems	Low
Proprietary BMP Technologies	Low
Vegetated Roof	High*
Minimum Disturbance / Minimum Maintenance	N/A
Rainwater Capture and Reuse	High*

*Rank based on a 100% rate reduction for the intercepted portion of runoff. The inability of the practice to mitigate runoff from other areas is reflected in the contributing drainage area criterion

Table 6.18 serves as the pairwise comparison template for the peak mitigation criterion.

Table 6.18 Pairwise Comparison Template – Ability to Mitigate Peak Rate of Runoff

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*1.00*	*2.00*	*1.00*	*1.00*	*1.00*	*2.00*	*9.00*	*2.00*	*7.00*	*9.00*	*1.00*	*4.00*	*1.00*
Wet Pond	*1.00*	*1.00*	*2.00*	*1.00*	*1.00*	*1.00*	*2.00*	*9.00*	*2.00*	*7.00*	*9.00*	*1.00*	*4.00*	*1.00*
Infil. Trench	*0.50*	*0.50*	*1.00*	*0.50*	*0.50*	*0.50*	*1.00*	*5.00*	*1.00*	*3.00*	*7.00*	*0.50*	*3.00*	*0.50*
Infil. Basin	*1.00*	*1.00*	*2.00*	*1.00*	*1.00*	*1.00*	*2.00*	*9.00*	*2.00*	*7.00*	*9.00*	*1.00*	*4.00*	*1.00*
Pour. Pvmt.	*1.00*	*1.00*	*2.00*	*1.00*	*1.00*	*1.00*	*2.00*	*9.00*	*2.00*	*7.00*	*9.00*	*1.00*	*4.00*	*1.00*
Wetlands	*1.00*	*1.00*	*2.00*	*1.00*	*1.00*	*1.00*	*2.00*	*9.00*	*2.00*	*7.00*	*9.00*	*1.00*	*4.00*	*1.00*
Bioretention	*0.50*	*0.50*	*1.00*	*0.50*	*0.50*	*0.50*	*1.00*	*5.00*	*1.00*	*1.00*	*7.00*	*0.33*	*3.00*	*0.33*
Filter Strip	*0.11*	*0.11*	*0.20*	*0.11*	*0.11*	*0.11*	*0.20*	*1.00*	*0.20*	*0.50*	*2.00*	*0.14*	*0.33*	*0.14*
Veg. Swale	*0.50*	*0.50*	*1.00*	*0.50*	*0.50*	*0.50*	*1.00*	*5.00*	*1.00*	*1.00*	*7.00*	*0.33*	*3.00*	*0.33*
Filters	*0.14*	*0.14*	*0.33*	*0.14*	*0.14*	*0.14*	*1.00*	*2.00*	*1.00*	*1.00*	*7.00*	*0.33*	*1.00*	*0.33*
Proprietary	*0.11*	*0.11*	*0.14*	*0.11*	*0.11*	*0.11*	*0.14*	*0.50*	*0.14*	*0.14*	*1.00*	*0.11*	*0.14*	*0.11*
Veg. Roof	*1.00*	*1.00*	*2.00*	*1.00*	*1.00*	*1.00*	*3.00*	*7.00*	*3.00*	*3.00*	*9.00*	*1.00*	*5.00*	*1.00*
MD/MM	*0.25*	*0.25*	*0.33*	*0.25*	*0.25*	*0.25*	*0.33*	*3.00*	*0.33*	*1.00*	*7.00*	*0.20*	*1.00*	*0.50*
C&R	*1.00*	*1.00*	*2.00*	*1.00*	*1.00*	*1.00*	*3.00*	*7.00*	*3.00*	*3.00*	*9.00*	*1.00*	*2.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.1087*
Wet / Retention Pond	*0.1087*
Infiltration Trench	*0.0577*
Infiltration Basin	*0.1087*
Porous Pavement	*0.1087*
Constructed Wetlands	*0.1087*
Bioretention	*0.0521*
Filter Strip	*0.0124*
Vegetated Swale	*0.0521*
Stormwater Filtering Systems	*0.0291*
Proprietary BMP Technologies	*0.0093*
Vegetated Roof	*0.1098*
Minimum Disturbance / Minimum Maintenance	*0.0298*
Rainwater Capture and Reuse	*0.1042*

Consistency Ratio = 0.03

6.2.11 Aesthetic Benefit of BMPs

In determining the aesthetic *benefit* of the various BMP options, the following conventions were adopted:

1. A practice was considered beneficial if it provided recreational activities, wildlife habitat, or generally improved site aesthetics.
2. A practice was considered neutral if it was generally unnoticeable to the public, or if it was noticeable but not readily recognized as a stormwater control practice.
3. A practice was considered a liability if it negatively impacted site aesthetics.

The relative aesthetic benefit of the BMPs discussed in Chapter 2 of this paper is presented below in Table 6.19.

Table 6.19 Relative Aesthetic Benefit of Various BMPs

BMP	Relative Aesthetic Benefit
Extended Dry Detention Pond	Low
Wet / Retention Pond	High
Infiltration Trench	Low
Infiltration Basin	Low
Porous Pavement	Moderate
Constructed Wetlands	High
Bioretention	High
Filter Strip	High
Vegetated Swale	Moderate
Stormwater Filtering Systems	Low
Proprietary BMP Technologies	Moderate
Vegetated Roof	High
Minimum Disturbance / Minimum Maintenance	High
Rainwater Capture and Reuse	Moderate

Table 6.20 serves as the pairwise comparison template for the peak mitigation criterion.

Table 6.20 Pairwise Comparison Template – Aesthetic Benefit

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*0.14*	*1.00*	*1.00*	*0.25*	*0.14*	*0.14*	*0.14*	*0.25*	*1.00*	*0.25*	*0.14*	*0.14*	*0.25*
Wet Pond	*7.00*	*1.00*	*7.00*	*7.00*	*4.00*	*1.00*	*1.00*	*1.00*	*4.00*	*7.00*	*4.00*	*1.00*	*1.00*	*4.00*
Infil. Trench	*1.00*	*0.14*	*1.00*	*1.00*	*0.25*	*0.14*	*0.14*	*0.14*	*0.25*	*1.00*	*0.25*	*0.14*	*0.14*	*0.25*
Infil. Basin	*1.00*	*0.14*	*1.00*	*1.00*	*0.25*	*0.14*	*0.14*	*0.14*	*0.25*	*1.00*	*0.25*	*0.14*	*0.14*	*0.25*
Pour. Pvmt.	*4.00*	*0.25*	*4.00*	*4.00*	*1.00*	*0.25*	*0.25*	*0.25*	*1.00*	*4.00*	*1.00*	*0.25*	*0.25*	*1.00*
Wetlands	*7.00*	*1.00*	*7.00*	*7.00*	*4.00*	*1.00*	*1.00*	*1.00*	*4.00*	*7.00*	*4.00*	*1.00*	*1.00*	*4.00*
Bioretention	*7.00*	*1.00*	*7.00*	*7.00*	*4.00*	*1.00*	*1.00*	*1.00*	*4.00*	*7.00*	*4.00*	*1.00*	*1.00*	*4.00*
Filter Strip	*7.00*	*1.00*	*7.00*	*7.00*	*4.00*	*1.00*	*1.00*	*1.00*	*4.00*	*7.00*	*4.00*	*1.00*	*1.00*	*4.00*
Veg. Swale	*4.00*	*0.25*	*4.00*	*4.00*	*1.00*	*0.25*	*0.25*	*0.25*	*1.00*	*0.25*	*1.00*	*0.25*	*0.25*	*1.00*
Filters	*1.00*	*0.14*	*1.00*	*1.00*	*0.25*	*0.14*	*0.14*	*0.14*	*4.00*	*1.00*	*0.25*	*0.14*	*0.14*	*0.25*
Proprietary	*4.00*	*0.25*	*4.00*	*4.00*	*1.00*	*0.25*	*0.25*	*0.25*	*1.00*	*4.00*	*1.00*	*0.25*	*0.25*	*1.00*
Veg. Roof	*7.00*	*1.00*	*7.00*	*7.00*	*4.00*	*1.00*	*1.00*	*1.00*	*4.00*	*7.00*	*4.00*	*1.00*	*1.00*	*4.00*
MD/MM	*7.00*	*1.00*	*7.00*	*7.00*	*4.00*	*1.00*	*1.00*	*1.00*	*4.00*	*7.00*	*4.00*	*1.00*	*1.00*	*4.00*
C&R	*4.00*	*0.25*	*4.00*	*4.00*	*1.00*	*0.25*	*0.25*	*0.25*	*1.00*	*4.00*	*1.00*	*0.25*	*0.25*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0152*
Wet / Retention Pond	*0.1277*
Infiltration Trench	*0.0152*
Infiltration Basin	*0.0152*
Porous Pavement	*0.0425*
Constructed Wetlands	*0.1277*
Bioretention	*0.1277*
Filter Strip	*0.1277*
Vegetated Swale	*0.0379*
Stormwater Filtering Systems	*0.0233*
Proprietary BMP Technologies	*0.0425*
Vegetated Roof	*0.1277*
Minimum Disturbance / Minimum Maintenance	*0.1277*
Rainwater Capture and Reuse	*0.0425*

Consistency
Ratio = 0.04

6.2.12 Safety Issues Associated With the BMP

In determining the safety issues and potential nuisance liability associated with the various BMP options, the following conventions were adopted:

1. Practices exhibiting a permanent pool of water were given the lowest rank with regard to safety and potential liability.

2. Practices, such as vegetative water quality swales, with the potential to become marshy and stagnant were recognized as potential sources of nuisance liability by providing mosquito habitat.

The relative safety / nuisance liability rank of the BMPs discussed in Chapter 2 of this paper is presented below in Table 6.21.

Table 6.21 Safety and Liability of Various BMPs

BMP	Relative Safety / Liability Concern
Extended Dry Detention Pond	Moderate
Wet / Retention Pond	High
Infiltration Trench	Moderate
Infiltration Basin	Moderate
Porous Pavement	Low
Constructed Wetlands	High
Bioretention	Low
Filter Strip	Low
Vegetated Swale	Moderate
Stormwater Filtering Systems	Low
Proprietary BMP Technologies	Low
Vegetated Roof	Low
Minimum Disturbance / Minimum Maintenance	Low
Rainwater Capture and Reuse	Low

Table 6.22 serves as the pairwise comparison template for the peak mitigation criterion.

Table 6.22 Pairwise Comparison Template – Safety / Nuisance Liability

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*4.00*	*1.00*	*1.00*	*0.25*	*4.00*	*0.25*	*0.25*	*1.00*	*0.25*	*0.25*	*0.25*	*0.25*	*0.25*
Wet Pond	*0.25*	*1.00*	*0.25*	*0.25*	*0.14*	*1.00*	*0.14*	*0.14*	*0.25*	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*
Infil. Trench	*1.00*	*4.00*	*1.00*	*1.00*	*0.25*	*4.00*	*0.25*	*0.25*	*1.00*	*0.25*	*0.25*	*0.25*	*0.25*	*0.25*
Infil. Basin	*1.00*	*4.00*	*1.00*	*1.00*	*0.25*	*4.00*	*0.25*	*0.25*	*1.00*	*0.25*	*0.25*	*0.25*	*0.25*	*0.25*
Pour. Pvmt.	*4.00*	*7.00*	*4.00*	*4.00*	*1.00*	*7.00*	*1.00*	*1.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Wetlands	*0.25*	*1.00*	*0.25*	*0.25*	*0.14*	*1.00*	*0.14*	*0.14*	*0.25*	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*
Bioretention	*4.00*	*7.00*	*4.00*	*4.00*	*1.00*	*7.00*	*1.00*	*1.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Filter Strip	*4.00*	*7.00*	*4.00*	*4.00*	*1.00*	*7.00*	*1.00*	*1.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Swale	*1.00*	*4.00*	*1.00*	*1.00*	*0.25*	*4.00*	*0.25*	*0.25*	*1.00*	*0.25*	*0.25*	*0.25*	*0.25*	*0.25*
Filters	*4.00*	*7.00*	*4.00*	*4.00*	*1.00*	*7.00*	*1.00*	*1.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Proprietary	*4.00*	*7.00*	*4.00*	*4.00*	*1.00*	*7.00*	*1.00*	*1.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Veg. Roof	*4.00*	*7.00*	*4.00*	*4.00*	*1.00*	*7.00*	*1.00*	*1.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
MD/MM	*4.00*	*7.00*	*4.00*	*4.00*	*1.00*	*7.00*	*1.00*	*1.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
C&R	*4.00*	*7.00*	*4.00*	*4.00*	*1.00*	*7.00*	*1.00*	*1.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0309*
Wet / Retention Pond	*0.0127*
Infiltration Trench	*0.0309*
Infiltration Basin	*0.0309*
Porous Pavement	*0.1064*
Constructed Wetlands	*0.0127*
Bioretention	*0.1064*
Filter Strip	*0.1064*
Vegetated Swale	*0.0309*
Stormwater Filtering Systems	*0.1064*
Proprietary BMP Technologies	*0.1064*
Vegetated Roof	*0.1064*
Minimum Disturbance / Minimum Maintenance	*0.1064*
Rainwater Capture and Reuse	*0.1064*

Consistency Ratio = 0.01

6.2.13 Pollutant Removal Capability

The long-term pollutant removal performance pairwise comparison templates in this section are based exclusively on the qualitative BMP selection matrix constructed in Chapter 4 of this paper (Figure 4.2). Tables 6.22 – 6.24 serve as the pairwise comparison templates for the pollutant removal criteria.

Table 6.23 Pairwise Comparison Template – Long-Term Suspended Sediment Removal

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*0.13*	*0.17*	*0.17*	*0.17*	*0.17*	*0.13*	*1.00*	*0.25*	*0.13*	*0.13*	*0.13*	*0.13*	*0.17*
Wet Pond	*8.00*	*1.00*	*2.00*	*2.00*	*2.00*	*2.00*	*1.00*	*8.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*
Infil. Trench	*6.00*	*0.50*	*1.00*	*1.00*	*1.00*	*1.00*	*0.50*	*6.00*	*2.00*	*0.50*	*0.50*	*0.50*	*0.50*	*1.00*
Infil. Basin	*6.00*	*0.50*	*1.00*	*1.00*	*1.00*	*1.00*	*0.50*	*6.00*	*2.00*	*0.50*	*0.50*	*0.50*	*0.50*	*1.00*
Pour. Pvmt.	*6.00*	*0.50*	*1.00*	*1.00*	*1.00*	*1.00*	*0.50*	*6.00*	*2.00*	*0.50*	*0.50*	*0.50*	*0.50*	*1.00*
Wetlands	*6.00*	*0.50*	*1.00*	*1.00*	*1.00*	*1.00*	*0.50*	*6.00*	*2.00*	*0.50*	*0.50*	*0.50*	*0.50*	*1.00*
Bioretention	*8.00*	*1.00*	*2.00*	*2.00*	*2.00*	*2.00*	*1.00*	*8.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*
Filter Strip	*1.00*	*0.13*	*0.17*	*0.17*	*0.17*	*0.17*	*0.13*	*1.00*	*0.25*	*0.13*	*0.13*	*0.13*	*0.13*	*0.17*
Veg. Swale	*4.00*	*0.25*	*0.50*	*0.50*	*0.50*	*0.50*	*0.25*	*4.00*	*1.00*	*0.25*	*0.25*	*0.25*	*0.25*	*1.00*
Filters	*8.00*	*1.00*	*2.00*	*2.00*	*2.00*	*2.00*	*1.00*	*8.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*
Proprietary	*8.00*	*1.00*	*2.00*	*2.00*	*2.00*	*2.00*	*1.00*	*8.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*
Veg. Roof	*8.00*	*1.00*	*2.00*	*2.00*	*2.00*	*2.00*	*1.00*	*8.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*
MD/MM	*8.00*	*1.00*	*2.00*	*2.00*	*2.00*	*2.00*	*1.00*	*8.00*	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*
C&R	*6.00*	*0.50*	*1.00*	*1.00*	*1.00*	*1.00*	*0.50*	*6.00*	*1.00*	*0.50*	*0.50*	*0.50*	*0.50*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0115*
Wet / Retention Pond	*0.1093*
Infiltration Trench	*0.0581*
Infiltration Basin	*0.0581*
Porous Pavement	*0.0581*
Constructed Wetlands	*0.0581*
Bioretention	*0.1093*
Filter Strip	*0.0115*
Vegetated Swale	*0.0327*
Stormwater Filtering Systems	*0.1093*
Proprietary BMP Technologies	*0.1093*
Vegetated Roof	*0.1093*
Minimum Disturbance / Minimum Maintenance	*0.1093*
Rainwater Capture and Reuse	*0.0560*

Consistency Ratio = 0.01

Table 6.24 Pairwise Comparison Template – Long-Term Total Phosphorus Removal

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*0.25*	*0.25*	*0.25*	*0.25*	*0.50*	*0.25*	*4.00*	*4.00*	*0.25*	*4.00*	*0.25*	*0.25*	*0.50*
Wet Pond	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
Infil. Trench	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
Infil. Basin	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
Pour. Pvmt.	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
Wetlands	*2.00*	*0.50*	*0.50*	*0.50*	*0.50*	*1.00*	*0.50*	*6.00*	*6.00*	*0.50*	*6.00*	*0.50*	*0.50*	*1.00*
Bioretention	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
Filter Strip	*0.25*	*0.13*	*0.13*	*0.13*	*0.13*	*0.17*	*0.13*	*1.00*	*1.00*	*0.13*	*1.00*	*0.13*	*0.13*	*0.17*
Veg. Swale	*0.25*	*0.13*	*0.13*	*0.13*	*0.13*	*0.17*	*0.13*	*1.00*	*1.00*	*0.13*	*1.00*	*0.13*	*0.13*	*0.17*
Filters	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
Proprietary	*0.25*	*0.13*	*0.13*	*0.13*	*0.13*	*0.17*	*0.13*	*1.00*	*1.00*	*0.13*	*1.00*	*0.13*	*0.13*	*0.17*
Veg. Roof	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
MD/MM	*4.00*	*1.00*	*1.00*	*1.00*	*1.00*	*2.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
C&R	*2.00*	*0.50*	*0.50*	*0.50*	*0.50*	*1.00*	*0.50*	*6.00*	*6.00*	*0.50*	*6.00*	*0.50*	*0.50*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0308*
Wet / Retention Pond	*0.1026*
Infiltration Trench	*0.1026*
Infiltration Basin	*0.1026*
Porous Pavement	*0.1026*
Constructed Wetlands	*0.0565*
Bioretention	*0.1026*
Filter Strip	*0.0117*
Vegetated Swale	*0.0117*
Stormwater Filtering Systems	*0.1026*
Proprietary BMP Technologies	*0.0117*
Vegetated Roof	*0.1026*
Minimum Disturbance / Minimum Maintenance	*0.1026*
Rainwater Capture and Reuse	*0.0565*

Consistency Ratio = 0.01

Table 6.25 Pairwise Comparison Template – Long-Term Total Nitrogen Removal

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*0.50*	*2.00*	*2.00*	*2.00*	*6.00*	*0.50*	*6.00*	*6.00*	*0.50*	*6.00*	*0.50*	*0.50*	*1.00*
Wet Pond	*2.00*	*1.00*	*4.00*	*4.00*	*4.00*	*8.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
Infil. Trench	*0.50*	*0.25*	*1.00*	*1.00*	*1.00*	*4.00*	*0.25*	*4.00*	*4.00*	*0.25*	*4.00*	*0.25*	*0.25*	*0.50*
Infil. Basin	*0.50*	*0.25*	*1.00*	*1.00*	*1.00*	*4.00*	*0.25*	*4.00*	*4.00*	*0.25*	*4.00*	*0.25*	*0.25*	*0.50*
Pour. Pvmt.	*0.50*	*0.25*	*1.00*	*1.00*	*1.00*	*4.00*	*0.25*	*4.00*	*4.00*	*0.25*	*4.00*	*0.25*	*0.25*	*0.50*
Wetlands	*0.17*	*0.13*	*0.25*	*0.25*	*0.25*	*1.00*	*0.13*	*1.00*	*1.00*	*0.13*	*1.00*	*0.13*	*0.13*	*0.17*
Bioretention	*2.00*	*1.00*	*4.00*	*4.00*	*4.00*	*8.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
Filter Strip	*0.17*	*0.13*	*0.25*	*0.25*	*0.25*	*1.00*	*0.13*	*1.00*	*1.00*	*0.13*	*1.00*	*0.13*	*0.13*	*0.17*
Veg. Swale	*0.17*	*0.13*	*0.25*	*0.25*	*0.25*	*1.00*	*0.13*	*1.00*	*1.00*	*0.13*	*1.00*	*0.13*	*0.13*	*0.17*
Filters	*2.00*	*1.00*	*4.00*	*4.00*	*4.00*	*8.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
Proprietary	*0.17*	*0.13*	*0.25*	*0.25*	*0.25*	*1.00*	*0.13*	*1.00*	*1.00*	*0.13*	*1.00*	*0.13*	*0.13*	*0.17*
Veg. Roof	*2.00*	*1.00*	*4.00*	*4.00*	*4.00*	*8.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
MD/MM	*2.00*	*1.00*	*4.00*	*4.00*	*4.00*	*8.00*	*1.00*	*8.00*	*8.00*	*1.00*	*8.00*	*1.00*	*1.00*	*2.00*
C&R	*1.00*	*0.50*	*2.00*	*2.00*	*2.00*	*6.00*	*0.50*	*6.00*	*6.00*	*0.50*	*6.00*	*0.50*	*0.50*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0752*
Wet / Retention Pond	*0.1337*
Infiltration Trench	*0.0418*
Infiltration Basin	*0.0418*
Porous Pavement	*0.0418*
Constructed Wetlands	*0.0140*
Bioretention	*0.1337*
Filter Strip	*0.0140*
Vegetated Swale	*0.0140*
Stormwater Filtering Systems	*0.1337*
Proprietary BMP Technologies	*0.0140*
Vegetated Roof	*0.1337*
Minimum Disturbance / Minimum Maintenance	*0.1337*
Rainwater Capture and Reuse	*0.0752*

Consistency Ratio = 0.01

6.2.14 Supplemental Pollutant Removal Templates

It is reiterated that most current BMP research points to pollutant removal percent or efficiency as being a poor indicator of BMP performance. However, this method remains the most widespread means of BMP performance evaluation in the United States today. The pairwise comparison matrices that follow evaluate the various BMPs by their ability to achieve pollutant removal efficiencies of 80%, 40%, and 30% for total suspended sediment, total phosphorus, and total nitrogen respectively. All practices that are capable of attaining these pollutant removal levels are ranked equally, while practices unable to meet these targets are given the lowest order of preference.

Table 6.26 Pairwise Comparison Template – Ability to Achieve 80% Removal of TSS

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Wet Pond	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Infil. Trench	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Infil. Basin	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Pour. Pvmt.	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Wetlands	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Bioretention	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Filter Strip	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Veg. Swale	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Filters	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Proprietary	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Veg. Roof	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
MD/MM	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
C&R	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0116*
Wet / Retention Pond	*0.1047*
Infiltration Trench	*0.1047*
Infiltration Basin	*0.1047*
Porous Pavement	*0.1047*
Constructed Wetlands	*0.0116*
Bioretention	*0.1047*
Filter Strip	*0.0116*
Vegetated Swale	*0.0116*
Stormwater Filtering Systems	*0.1047*
Proprietary BMP Technologies	*0.0116*
Vegetated Roof	*0.1047*
Minimum Disturbance / Minimum Maintenance	*0.1047*
Rainwater Capture and Reuse	*0.1047*

Consistency Ratio = 0.00

Table 6.27 Pairwise Comparison Template – Ability to Achieve 40% Removal of TP

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Wet Pond	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*8.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Infil. Trench	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*8.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Infil. Basin	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*8.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Pour. Pvmt.	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*8.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Wetlands	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Bioretention	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*8.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Filter Strip	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Veg. Swale	*1.00*	*0.13*	*0.13*	*0.13*	*0.13*	*1.00*	*0.13*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Filters	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Proprietary	*1.00*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Veg. Roof	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
MD/MM	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
C&R	*9.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0117*
Wet / Retention Pond	*0.1042*
Infiltration Trench	*0.1042*
Infiltration Basin	*0.1042*
Porous Pavement	*0.1042*
Constructed Wetlands	*0.0117*
Bioretention	*0.1042*
Filter Strip	*0.0117*
Vegetated Swale	*0.0122*
Stormwater Filtering Systems	*0.1051*
Proprietary BMP Technologies	*0.0117*
Vegetated Roof	*0.1051*
Minimum Disturbance / Minimum Maintenance	*0.1051*
Rainwater Capture and Reuse	*0.1051*

Consistency Ratio = 0.00

Table 6.28 Pairwise Comparison Template – Ability to Achieve 30% Removal of TN

	EDP	WP	IT	IB	PP	WLDS	BIO	FS	VSWL	FILT	PROP	VR	MD/MM	C&R
EDD Pond	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Wet Pond	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Infil. Trench	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Infil. Basin	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Pour. Pvmt.	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Wetlands	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Bioretention	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Filter Strip	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.13*	*0.13*	*0.17*
Veg. Swale	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Filters	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*9.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
Proprietary	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*	*0.11*	*1.00*	*1.00*	*0.11*	*1.00*	*0.11*	*0.11*	*0.11*
Veg. Roof	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*8.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
MD/MM	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*8.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*
C&R	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*6.00*	*9.00*	*1.00*	*9.00*	*1.00*	*1.00*	*1.00*

BMP	Matrix Priority Vector
Extended Dry Detention Pond	*0.0885*
Wet / Retention Pond	*0.0885*
Infiltration Trench	*0.0885*
Infiltration Basin	*0.0885*
Porous Pavement	*0.0885*
Constructed Wetlands	*0.0885*
Bioretention	*0.0885*
Filter Strip	*0.0104*
Vegetated Swale	*0.0098*
Stormwater Filtering Systems	*0.0885*
Proprietary BMP Technologies	*0.0098*
Vegetated Roof	*0.0878*
Minimum Disturbance / Minimum Maintenance	*0.0878*
Rainwater Capture and Reuse	*0.0863*

Consistency Ratio = 0.00

Chapter 7.0
Application of the AHP in Multiple BMP Selection Scenarios

Chapter 7 demonstrates the AHP in multiple BMP selection scenarios. The scenarios described in this chapter are hypothetical, but many real-world elements are incorporated into the demonstrations.

7.1 Application Scenarios

7.1.1 Hospital Development

A hospital is proposed to be constructed on a 10.4 acre site. Prior to development, the site consisted primarily of open lawn in fair condition with essentially no impervious area. The pre-development site is treated as a single sub area for purposes of hydrologic analysis. The developed site is broken into three distinct sub drainage areas. The first area (DA-1) is comprised of the hospital itself, and encompasses an area of approximately 3.1 acres. Rooftop runoff from DA-1 is collected by a gutter system. The second sub area (DA-2) consists primarily of the hospital's parking lot, and makes up 5.22 acres. Islands within the parking lot total 0.5 acres resulting in an overall imperviousness of 90% for DA-2. Stormwater runoff from DA-2 is conveyed by a storm sewer system. The final drainage area, DA-3, encompasses all open pervious area on the site. Totaling 2.08 acres, DA-3 consists of the site's grassed areas, and drains via overland flow rather than a storm sewer. The post-developed site exhibits a generally uniform drainage direction, with all three sub areas eventually draining to a common point. The developers of the site set aside a small area dedicated to stormwater management. Schematic illustrations of the pre and post developed site are presented in Figure 7.1.

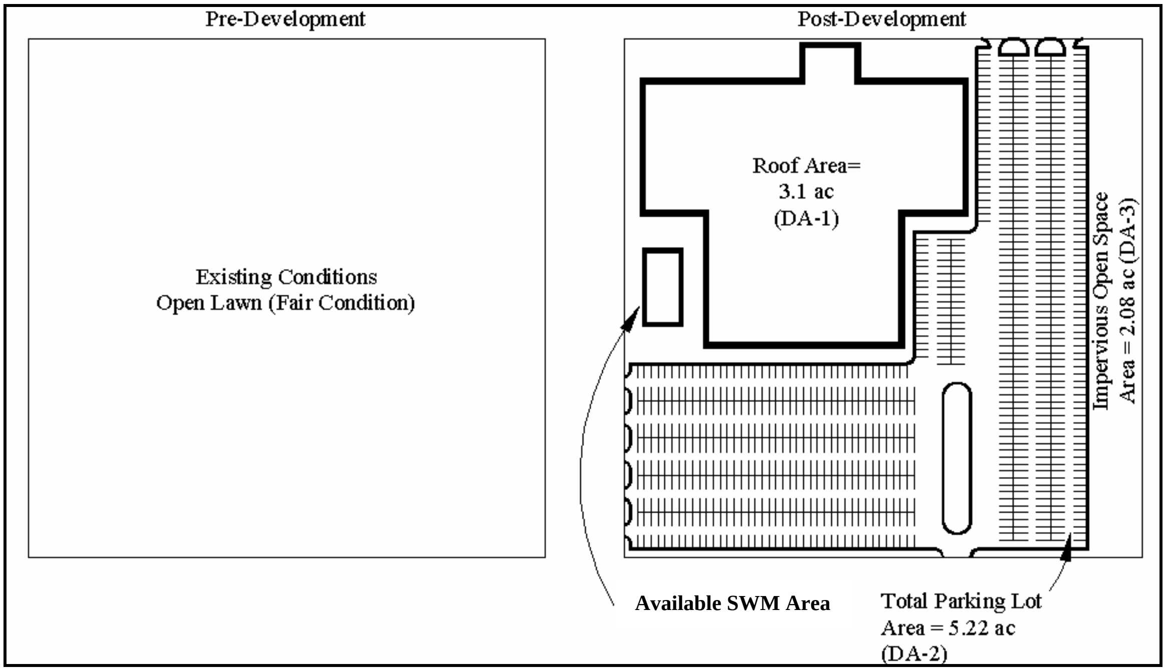


Figure 7.1 Schematic Pre and Post Development Site Conditions

In addition to the aforementioned site characteristics, the following apply:

- During spring snow melt, the water table is observed to be less than three feet below the ground surface.
- Peak mitigation of runoff rate is required.
- The hospital does not maintain a staff capable of addressing annual maintenance on the BMP facility. Therefore, maintenance operations will be contracted. These costs must be considered when selecting the BMP alternative.
- The hospital is situated in a high profile area, and desires to maintain an enhanced aesthetic value.
- The developed site exhibits 80% more impervious cover compared to pre-development conditions. For this intensity of development, local ordinances require that a BMP practice is installed that is capable of providing a minimum of 40% removal of total phosphorus.

These influential criteria will now be subjected to the AHP to facilitate selection of the optimal BMP for this site.

The first step in executing the AHP is to identify the criteria that are to be employed in the BMP selection process. Upon identification of these influential selection criteria, a criteria judgment matrix is constructed. For the aforementioned items, this criteria judgment matrix appears as follows:

Table 7.1 Preliminary Criteria Judgment Matrix

	A	B	C	D	E	F
10.4 Acre Site (A)	1					
Shallow Groundwater Table (B)		1				
Peak Mitigation Requirement (C)			1			
Maintenance Costs (D)				1		
Maintain Aesthetic Value (E)					1	
40% Phosphorus Removal (F)						1

Next, the user must formulate pairwise rankings of the influential criteria. At this point in the process, it is important to solicit the input of all stakeholders. Owner, maintenance personnel, engineer, and the permit issuing authority should all give input, or at least have their interests considered. The rankings reported in this paper reflect only those of the author for this particular design scenario.

In order to obtain the necessary environmental permits, the BMP must exhibit a minimum phosphorus removal efficiency of 40%. Similarly, peak mitigation of post-development runoff to pre-development levels is required. These criteria are necessarily prioritized in the given scenario. The next most influential selection criteria are annual maintenance expenditures, site area, and groundwater depth. It is assumed that excessive loading of a BMP results in increased maintenance costs. Therefore, a BMP targeted for site areas of at least 10.4 acres is preferred. The shallow groundwater depth must be considered because of applicable infiltration concerns, though no specific restrictions exist in this locality. The selection criterion receiving the lowest priority is aesthetic value. Certainly implementing a BMP exhibiting a positive aesthetic value is desirable, but this criterion is not valued as importantly as permit attainment and maintenance costs. Based on these opinions, and adhering to the methodology described in Chapter 3 of this paper, the scale of relative importances is applied to prioritize the selection criteria. These pairwise rankings are presented in Table 7.2.

Table 7.2 Completed Criteria Judgment Matrix

	A	B	C	D	E	F
10.4 Acre Site (A)	1.00	1.00	0.33	1.00	2.00	0.33
Shallow Groundwater Table (B)	1.00	1.00	0.33	1.00	2.00	0.33
Peak Mitigation Requirement (C)	3.00	3.00	1.00	3.00	5.00	1.00
Maintenance Costs (D)	1.00	1.00	0.33	1.00	2.00	0.20
Maintain Aesthetic Value (E)	0.50	0.50	0.20	0.50	1.00	0.20
40% Phosphorus Removal (F)	3.00	3.00	1.00	3.00	5.00	1.00

The computed priority vector for this matrix is:

10.4 Acre Site (A)	*0.11*
Shallow Groundwater Table (B)	*0.11*
Peak Mitigation Requirement (C)	*0.31*
Maintenance Costs (D)	*0.10*
Maintain Aesthetic Value (E)	*0.06*
40% Phosphorus Removal (F)	*0.31*

Consistency Ratio = 0.00

Next, the relevant pairwise comparison templates are selected from Chapter 6, and their corresponding comparison priority vectors entered into a decision matrix. The priority vectors for the site area, shallow groundwater table, peak mitigation, maintenance costs, aesthetic benefit, and phosphorus removal criteria are shown, in matrix form, in Table 7.3

Table 7.3 Hospital Site Decision Matrix

Corresponding Table From Chapter 6	6.4	6.6	6.18	6.15	6.20	6.27
BMP	**Site Area >10 Ac.**	**Shallow GW**	**Peak Mit.**	**Maintenance**	**Aesthetics**	**TP Removal**
Extended Dry Detention Pond	*0.1597*	*0.0376*	*0.1087*	*0.036*	*0.0152*	*0.0117*
Wet / Retention Pond	*0.1597*	*0.0516*	*0.1087*	*0.036*	*0.1277*	*0.1042*
Infiltration Trench	*0.03*	*0.0128*	*0.0577*	*0.0138*	*0.0152*	*0.1042*
Infiltration Basin	*0.1597*	*0.0128*	*0.1087*	*0.036*	*0.0152*	*0.1042*
Porous Pavement	*0.0462*	*0.0128*	*0.1087*	*0.1199*	*0.0425*	*0.1042*
Constructed Wetlands	*0.1597*	*0.0516*	*0.1087*	*0.036*	*0.1277*	*0.0117*
Bioretention	*0.0266*	*0.0128*	*0.0521*	*0.0138*	*0.1277*	*0.1042*
Filter Strip	*0.0266*	*0.0912*	*0.0124*	*0.1199*	*0.1277*	*0.0117*
Vegetated Swale	*0.0266*	*0.0912*	*0.0521*	*0.036*	*0.0379*	*0.0122*
Stormwater Filtering Systems	*0.0266*	*0.0129*	*0.0291*	*0.0601*	*0.0233*	*0.1051*
Proprietary BMP Technologies	*0.0462*	*0.1532*	*0.0093*	*0.0696*	*0.0425*	*0.0117*
Vegetated Roof	*0.0325*	*0.1532*	*0.1098*	*0.1126*	*0.1277*	*0.1051*
Minimum Disturbance / Minimum Maintenance	*0.0676*	*0.1532*	*0.0298*	*0.155*	*0.1277*	*0.1051*
Rainwater Capture and Reuse	*0.0325*	*0.1532*	*0.1042*	*0.155*	*0.0425*	*0.1051*

This decision matrix is then multiplied by the previously extracted criteria priority vector from Table 7.2. The results of this matrix operation are shown in Table 7.4.

Site Area >10 Ac.	Shallow GW	Peak Mit.	Maintenance	Aesthetics	TP Removal
0.1597	*0.0376*	*0.1087*	*0.036*	*0.0152*	*0.0117*
0.1597	*0.0516*	*0.1087*	*0.036*	*0.1277*	*0.1042*
0.03	*0.0128*	*0.0577*	*0.0138*	*0.0152*	*0.1042*
0.1597	*0.0128*	*0.1087*	*0.036*	*0.0152*	*0.1042*
0.0462	*0.0128*	*0.1087*	*0.1199*	*0.0425*	*0.1042*
0.1597	*0.0516*	*0.1087*	*0.036*	*0.1277*	*0.0117*
0.0266	*0.0128*	*0.0521*	*0.0138*	*0.1277*	*0.1042*
0.0266	*0.0912*	*0.0124*	*0.1199*	*0.1277*	*0.0117*
0.0266	*0.0912*	*0.0521*	*0.036*	*0.0379*	*0.0122*
0.0266	*0.0129*	*0.0291*	*0.0601*	*0.0233*	*0.1051*
0.0462	*0.1532*	*0.0093*	*0.0696*	*0.0425*	*0.0117*
0.0325	*0.1532*	*0.1098*	*0.1126*	*0.1277*	*0.1051*
0.0676	*0.1532*	*0.0298*	*0.155*	*0.1277*	*0.1051*
0.0325	*0.1532*	*0.1042*	*0.155*	*0.0425*	*0.1051*

Criteria Priority Vector
0.11
0.11
0.31
0.10
0.06
0.31

Figure 7.2 Decision Matrix and Criteria Priority Vector for Hospital AHP Example Problem

Table 7.4 BMP Ranks for Hospital Development Scenario

Extended Dry Detention Pond	0.0635
Wet / Retention Pond	***0.1004***
Infiltration Trench	0.0576
Infiltration Basin	0.0898
Porous Pavement	0.0876
Constructed Wetlands	0.0714
Bioretention	0.0619
Filter Strip	0.0396
Vegetated Swale	0.0386
Stormwater Filtering Systems	0.0537
Proprietary BMP Technologies	0.0375
Vegetated Roof	***0.1060***
Minimum Disturbance / Minimum Maintenance	0.0890
Rainwater Capture and Reuse	***0.1036***

Multi-criteria decision making algorithms should immediately be viewed by their user as tools in the decision making process and not as the lone means for obtaining a final answer. Therefore, the results are now scrutinized. The highest ranking practice, a vegetated roof assembly, does not address runoff from the 5.22 acre parking lot, and therefore must be discarded as a viable alternative. Similarly, the BMP ranked second highest, rainwater capture and reuse, is not applicable to land areas as large as this hospital site. The BMP ranked third, wet ponds, appears to be an excellent choice for this site. The relative performance of this practice is now expressed in terms of the site-specific selection criteria.

Table 7.5 Performance of Wet Pond in Addressing Identified Selection Criteria

Criteria	Wet Pond Performance
Site Area	Pond suited for site drainage area
Shallow site groundwater table	Readily available baseflow viewed beneficial
Peak Mitigation Requirement	Strong peak mitigation performance
Maintenance	$0.02-$0.04 annually per cubic foot of storage (low)
Aesthetics	Wildlife habitat viewed beneficial
TP Removal	40-55% Anticipated Removal Efficiency

7.1.2 Hospital Development – Alternative Approach

An alternative approach for applying the AHP to the hospital development scenario presented in section 7.1.1 is to execute the algorithm for each individual post-development drainage area. This approach will yield three BMPs, one serving each respective drainage area. The criteria are weighed the same as in the previous example (except where noted), but the new decision matrices for each sub area will employ the priority vector from the pairwise comparison template constructed for drainage areas *less* than 10 acres.

The algorithm's inputs are the same for the 3.1 acre roof area comprising post development drainage area one (DA-1) and the 5.22 acre parking lot area comprising post-development drainage area two (DA-2). The decision matrix is updated to utilize the pairwise comparison template for drainage areas less than 10 acres (Table 6.3). This updated decision matrix and criteria vector are shown as follows:

Site Area <10 Ac.	Shallow GW	Peak Mit.	Maintenance	Aesthetics	TP Removal
0.0125	*0.0376*	*0.1087*	*0.036*	*0.0152*	*0.0117*
0.0125	*0.0516*	*0.1087*	*0.036*	*0.1277*	*0.1042*
0.0875	*0.0128*	*0.0577*	*0.0138*	*0.0152*	*0.1042*
0.0875	*0.0128*	*0.1087*	*0.036*	*0.0152*	*0.1042*
0.0875	*0.0128*	*0.1087*	*0.1199*	*0.0425*	*0.1042*
0.0125	*0.0516*	*0.1087*	*0.036*	*0.1277*	*0.0117*
0.0875	*0.0128*	*0.0521*	*0.0138*	*0.1277*	*0.1042*
0.0875	*0.0912*	*0.0124*	*0.1199*	*0.1277*	*0.0117*
0.0875	*0.0912*	*0.0521*	*0.036*	*0.0379*	*0.0122*
0.0875	*0.0129*	*0.0291*	*0.0601*	*0.0233*	*0.1051*
0.0875	*0.1532*	*0.0093*	*0.0696*	*0.0425*	*0.0117*
0.0875	*0.1532*	*0.1098*	*0.1126*	*0.1277*	*0.1051*
0.0875	*0.1532*	*0.0298*	*0.155*	*0.1277*	*0.1051*
0.0875	*0.1532*	*0.1042*	*0.155*	*0.0425*	*0.1051*

Criteria
0.11
0.11
0.31
0.10
0.06
0.31

Figure 7.3 Alternative Decision Matrix and Criteria Priority Vector

The results of the matrix – vector multiplication operation are shown below in Table 7.6.

Table 7.6 BMP Ranks for DA1 and DA2

Extended Dry Detention Pond	0.0476
Wet / Retention Pond	***0.0846***
Infiltration Trench	0.0638
Infiltration Basin	0.082
Porous Pavement	***0.092***
Constructed Wetlands	0.0556
Bioretention	0.0685
Filter Strip	0.0462
Vegetated Swale	0.0452
Stormwater Filtering Systems	0.0602
Proprietary BMP Technologies	0.0419
Vegetated Roof	***0.1119***
Minimum Disturbance / Minimum Maintenance	***0.0911***
Rainwater Capture and Reuse	***0.1095***

The results suggest that a vegetated roof assembly is clearly the optimal BMP option. Given the low annual maintenance costs paired with the strong peak mitigation and phosphorus removal abilities of this type of BMP, such an assembly appears to be a very strong candidate for implementation on this site. It is likely that the 5.22 acre parking lot drainage area is beyond the scope of a rainwater harvesting approach. Similarly, the impervious area of the parking lot is fixed, and a minimum disturbance approach cannot be considered. Considering both drainage areas, the results indicate that the *combination* of a vegetated roof assembly (DA-1) and porous pavement (DA-2) may ideally serve this site.   Should the porous pavement option not be considered, the results further imply that some sort of detention facility is still required to accommodate runoff from the hospital parking lot. However, with the inclusion of a vegetated roof assembly, the required volume of this facility can be greatly reduced.

The 2.08 acre open area comprising post-development drainage area three exhibits land cover characteristics similar to pre-development conditions. Therefore, the stringent phosphorus removal and peak mitigation requirement do not apply to this sub area (when considered separately from the other two post-development sub areas). The modified criteria judgment matrix and corresponding priority vector are shown as follows.

Table 7.7 Revised Criteria Judgment Matrix (DA-3)

	A	B	C	D	E	F
Site Area Under 10 Acres (A)	1.00	1.00	9.00	1.00	2.00	9.00
Shallow Groundwater Table (B)	1.00	1.00	9.00	1.00	2.00	9.00
Peak Mitigation Requirement (C)	0.11	0.11	1.00	0.20	0.33	1.00
Maintenance Costs (D)	1.00	1.00	5.00	1.00	2.00	3.00
Maintain Aesthetic Value (E)	0.50	0.50	3.00	0.50	1.00	3.00
40% Phosphorus Removal (F)	0.11	0.11	1.00	0.20	0.33	1.00

The computed priority vector for this matrix is:

10.4 Acre Site (A)	*0.29*
Shallow Groundwater Table (B)	*0.29*
Peak Mitigation Requirement (C)	*0.04*
Maintenance Costs (D)	*0.22*
Maintain Aesthetic Value (E)	*0.12*
40% Phosphorus Removal (F)	*0.04*

Consistency Ratio = 0.00

The decision matrix is now multiplied by the revised criteria judgment vector to rank BMP options for the 2.08 acre pervious drainage area.

Site Area <10 Ac.	Shallow GW	Peak Mit.	Maintenance	Aesthetics	TP Removal
0.0125	0.0376	0.1087	0.036	0.0152	0.0117
0.0125	0.0516	0.1087	0.036	0.1277	0.1042
0.0875	0.0128	0.0577	0.0138	0.0152	0.1042
0.0875	0.0128	0.1087	0.036	0.0152	0.1042
0.0875	0.0128	0.1087	0.1199	0.0425	0.1042
0.0125	0.0516	0.1087	0.036	0.1277	0.0117
0.0875	0.0128	0.0521	0.0138	0.1277	0.1042
0.0875	0.0912	0.0124	0.1199	0.1277	0.0117
0.0875	0.0912	0.0521	0.036	0.0379	0.0122
0.0875	0.0129	0.0291	0.0601	0.0233	0.1051
0.0875	0.1532	0.0093	0.0696	0.0425	0.0117
0.0875	0.1532	0.1098	0.1126	0.1277	0.1051
0.0875	0.1532	0.0298	0.155	0.1277	0.1051
0.0875	0.1532	0.1042	0.155	0.0425	0.1051

Criteria
0.29
0.29
0.04
0.22
0.12
0.04

Figure 7.4 Decision Matrix and Criteria Priority Vector (DA-3)

The results of the matrix – vector multiplication operation are shown below in Table 7.8

Table 7.8 BMP Ranks For DA-3

Extended Dry Detention Pond	0.029
Wet / Retention Pond	0.0506
Infiltration Trench	0.04
Infiltration Basin	0.0469
Porous Pavement	0.0692
Constructed Wetlands	0.047
Bioretention	0.0538
Filter Strip	***0.0951***
Vegetated Swale	0.0666
Stormwater Filtering Systems	0.0504
Proprietary BMP Technologies	0.0908
Vegetated Roof	0.1185
Minimum Disturbance / Minimum Maintenance	***0.125***
Rainwater Capture and Reuse	0.1172

The results indicate that preservation of existing land cover through minimum disturbance practices during construction operations, or installation of a vegetated filter strip will serve the runoff treatment needs from this sub area. However, Table 7.8 does not explicitly state that either of these options will satisfy the given site requirements and constraints. To confirm the adequacy of these options, design calculations must be completed and their results compared against site requirements.

7.1.3 Industrial "Hotspot" Application Scenario

A heavy equipment maintenance yard has recently been fined for discharging unacceptable levels of pollutants to downstream waterways. The characteristics of this site are as follows:

- The site is completely impervious.
- Total site area is relatively small, less than 0.75 acres.
- Site runoff has been revealed to contain hydrocarbon by-products, and is subsequently classified as "hotspot" runoff.
- The locality within which the facility is located is requiring the facility owner to implement a BMP capable of achieving an 80%, 40%, and 30% removal efficiency for total suspended sediment, total phosphorus, and total nitrogen respectively.
- Peak mitigation is not required, as no land cover change is proposed. The required BMP shall address only water quality.
- The facility owner wishes to consider annual maintenance costs of the chosen practice.

The chosen BMP selection criteria and their respective consideration are described in Table 7.9.

Table 7.9 Industrial BMP Application – Importance of Selection Criteria

Criteria	Relative Importance
Achieving Pollutant Removal Targets	Facility is presently being fined for unacceptable discharges. Achieving pollutant removal targets given highest priority.
Hotspot Runoff	Chosen BMP must be able to accommodate the site's known hotspot runoff.
Annual Maintenance Costs	The facility owner wishes to consider annual maintenance costs to the extent that the pollutant removal ability of the chosen BMP is not compromised
Site Area	The BMP selected should be targeted toward a contributing drainage area of less than one acre.

Table 7.10 presents the criteria judgment matrix and associated priority vector reflecting these BMP selection criteria and their assigned importances.

Table 7.10 Criteria Judgment Matrix – Industrial BMP Application

	A	B	C	D	E	F
0.75 Acre Site (A)	1.00	0.14	0.20	0.11	0.11	0.11
Hotspot Runoff (B)	7.00	1.00	4.00	0.50	0.50	0.50
Annual Maintenance Costs (C)	5.00	0.25	1.00	0.17	0.17	0.17
80% TSS Removal (D)	9.00	2.00	6.00	1.00	1.00	1.00
40% TP Removal (E)	9.00	2.00	6.00	1.00	1.00	1.00
30% TN Removal (F)	9.00	2.00	6.00	1.00	1.00	1.00

The computed priority vector for this matrix is:

0.75 Acre Site (A)	*0.02*
Hotspot Runoff (B)	*0.15*
Annual Maintenance Costs (C)	*0.06*
80% TSS Removal (D)	*0.26*
40% TP Removal (E)	*0.26*
30% TN Removal (F)	*0.26*

Consistency Ratio = 0.04

Next, the relevant pairwise comparison templates are obtained from Chapter 6 and entered into the decision matrix. This matrix is shown on the following page.

Table 7.11 Industrial Site Decision Matrix

Corresponding Table From Chapter 6	6.3	6.16	6.15	6.26	6.27	6.28
BMP	**Site Area <10 Ac.**	**Hotspot**	**Maintenance**	**80% TSS Removal**	**40% TP Removal**	**30% TN Removal**
Extended Dry Detention Pond	*0.0125*	*0.0882*	*0.036*	*0.0116*	*0.0117*	*0.0885*
Wet / Retention Pond	*0.0125*	*0.0882*	*0.036*	*0.1047*	*0.1042*	*0.0885*
Infiltration Trench	*0.0875*	*0.0098*	*0.0138*	*0.1047*	*0.1042*	*0.0885*
Infiltration Basin	*0.0875*	*0.0098*	*0.036*	*0.1047*	*0.1042*	*0.0885*
Porous Pavement	*0.0875*	*0.0882*	*0.1199*	*0.1047*	*0.1042*	*0.0885*
Constructed Wetlands	*0.0125*	*0.0882*	*0.036*	*0.0116*	*0.0117*	*0.0885*
Bioretention	*0.0875*	*0.0882*	*0.0138*	*0.1047*	*0.1042*	*0.0885*
Filter Strip	*0.0875*	*0.0882*	*0.1199*	*0.0116*	*0.0117*	*0.0104*
Vegetated Swale	*0.0875*	*0.0098*	*0.036*	*0.0116*	*0.0122*	*0.0098*
Stormwater Filtering Systems	*0.0875*	*0.0882*	*0.0601*	*0.1047*	*0.1051*	*0.0885*
Proprietary BMP Technologies	*0.0875*	*0.0882*	*0.0696*	*0.0116*	*0.0117*	*0.0098*
Vegetated Roof	*0.0875*	*0.0882*	*0.1126*	*0.1047*	*0.1051*	*0.0878*
Minimum Disturbance / Minimum Maintenance	*0.0875*	*0.0882*	*0.155*	*0.1047*	*0.1051*	*0.0878*
Rainwater Capture and Reuse	*0.0875*	*0.0882*	*0.155*	*0.1047*	*0.1051*	*0.0863*

This decision matrix is then multiplied by the previously extracted criteria priority vector from Table 7.10.

Site Area <10 Ac.	Hotspot	Maintenance	80% TSS Removal	40% TP Removal	30% TN Removal
0.0125	*0.0882*	*0.036*	*0.0116*	*0.0117*	*0.0885*
0.0125	*0.0882*	*0.036*	*0.1047*	*0.1042*	*0.0885*
0.0875	*0.0098*	*0.0138*	*0.1047*	*0.1042*	*0.0885*
0.0875	*0.0098*	*0.036*	*0.1047*	*0.1042*	*0.0885*
0.0875	*0.0882*	*0.1199*	*0.1047*	*0.1042*	*0.0885*
0.0125	*0.0882*	*0.036*	*0.0116*	*0.0117*	*0.0885*
0.0875	*0.0882*	*0.0138*	*0.1047*	*0.1042*	*0.0885*
0.0875	*0.0882*	*0.1199*	*0.0116*	*0.0117*	*0.0104*
0.0875	*0.0098*	*0.036*	*0.0116*	*0.0122*	*0.0098*
0.0875	*0.0882*	*0.0601*	*0.1047*	*0.1051*	*0.0885*
0.0875	*0.0882*	*0.0696*	*0.0116*	*0.0117*	*0.0098*
0.0875	*0.0882*	*0.1126*	*0.1047*	*0.1051*	*0.0878*
0.0875	*0.0882*	*0.155*	*0.1047*	*0.1051*	*0.0878*
0.0875	*0.0882*	*0.155*	*0.1047*	*0.1051*	*0.0863*

Criteria
0.02
0.15
0.06
0.26
0.26
0.26

Figure 7.5 Decision Matrix and Criteria Priority Vector – Industrial Site

The decision matrix is now multiplied by the criteria judgment vector to rank BMP options for the given selection considerations. The results are presented as follows.

Table 7.12 BMP Ranks for Industrial Site Application

Extended Dry Detention Pond	0.0441
Wet / Retention Pond	0.092
Infiltration Trench	0.081
Infiltration Basin	0.0822
Porous Pavement	***0.0984***
Constructed Wetlands	0.0441
Bioretention	0.0925
Filter Strip	0.0304
Vegetated Swale	0.0142
Stormwater Filtering Systems	***0.0953***
Proprietary BMP Technologies	0.0274
Vegetated Roof	0.0981
Minimum Disturbance / Minimum Maintenance	0.1004
Rainwater Capture and Reuse	0.1000

With the site runoff resulting primarily from impervious ground cover, the vegetated roof option is discarded. Similarly, the site impervious area is fixed and MD/MM design strategies are not applicable. The presence of hydrocarbon by-products in the runoff limits its use even for non-potable applications, thus precluding the use of rainwater capture and reuse strategies. Consequently, among the feasible BMP options for the site, it appears as though implementation of a *stormwater filtering system* is the optimal BMP to address pollutant removal needs of the facility. As evidenced by Table 7.12, porous pavement also ranks high. If the maintenance yard is in need of repaving in the near future, strong consideration should be given to a "retrofit" of the yard with a porous pavement system capable of providing significant pollutant load reduction as well as decreasing the overall volume of site runoff. The performance of a stormwater filtering system, in terms of the identified selection criteria is provided below in Table 7.13.

Table 7.13 Performance of Stormwater Filtering System in Addressing Identified Selection Criteria

Criteria	Stormwater Filter Performance
Site area of 0.75 acres	Well suited to small drainage areas
Presence of hotspot runoff	Fully capable of receiving hotspot runoff
Maintenance	$430-$575 annually per impervious acre treated (low)
80% TSS Removal	86% Removal efficiency anticipated
40% TP Removal	55% Removal efficiency anticipated
30% TN Removal	32% Removal efficiency anticipated

7.1.4 Parking Lot Retrofit Application Scenario

A community civic group that utilizes a local church as a weekly meeting location wishes to express their gratitude to the congregation by improving the church's existing parking lot. However, the group has been informed by the local planning and engineering department that converting the land cover of the existing parking lot from grass and gravel to an impervious paved surface will require the implementation of a BMP. The following criteria apply:

- Mitigation of peak rate of runoff is required
- The civic group has extremely limited funds, both for implementation and annual maintenance expenditures
- The church is located in the Chesapeake Bay watershed, and the chosen BMP must exhibit strong phosphorus removal potential for its anticipated lifespan

- Local ordinance dictates that all development projects provide a minimum level of groundwater recharge.

The relevant BMP selection criteria and their respective consideration are described in Table 7.9.

Table 7.14 Retrofit BMP Application – Importance of Selection Criteria

Criteria	Relative Importance
Mitigation of Peak Runoff Rate	Required for project implementation – necessarily prioritized.
Implementation Costs	The civic group has very limited funds. This criterion is considered of high priority in determining the overall feasibility of the project.
Annual Maintenance Costs	The civic group has very limited funds. This criterion is considered of high priority in determining the overall feasibility of the project.
Phosphorus Removal	The chosen BMP must qualitatively demonstrate long-term phosphorus removal capability
Groundwater Recharge	Chosen BMP must demonstrate the ability to provide some minimum level of groundwater recharge.

Table 7.15 presents the criteria judgment matrix and associated priority vector reflecting these BMP selection criteria and their assigned importances.

Table 7.15 Criteria Judgment Matrix – Parking Lot Retrofit Application

	A	B	C	D	E
Peak Mitigation (A)	1.00	1.00	1.00	2.00	4.00
Implementation Cost (B)	1.00	1.00	1.00	2.00	4.00
Annual Maintenance Costs (C)	1.00	1.00	1.00	2.00	4.00
Long-term Phosphorus Removal (D)	0.50	0.50	0.50	1.00	1.00
Groundwater Recharge (E)	0.25	0.25	0.25	1.00	1.00

The computed priority vector for this matrix is:

Peak Mitigation	*0.27*
Implementation Cost	*0.27*
Annual Maintenance Costs	*0.27*
Long-term Phosphorus Removal	*0.12*
Groundwater Recharge	*0.08*

Consistency Ratio = 0.02

Next, the relevant pairwise comparison templates are obtained from Chapter 6 and entered into the decision matrix. This matrix is shown on the following page.

Table 7.16 Retrofit Scenario Decision Matrix

Corresponding Table From Chapter 6	6.18	6.14	6.15	6.24	6.11
BMP	**Peak Mit.**	**Capital Costs**	**Maintenance**	**Long-term TP Removal**	**GW Recharge**
Extended Dry Detention Pond	*0.1087*	*0.0673*	*0.0360*	*0.0308*	*0.0150*
Wet / Retention Pond	*0.1087*	*0.0673*	*0.0360*	*0.1026*	*0.0150*
Infiltration Trench	*0.0577*	*0.0157*	*0.0138*	*0.1026*	*0.1712*
Infiltration Basin	*0.1087*	*0.0413*	*0.0360*	*0.1026*	*0.1712*
Porous Pavement	*0.1087*	*0.0673*	*0.1199*	*0.1026*	*0.0564*
Constructed Wetlands	*0.1087*	*0.0413*	*0.0360*	*0.0565*	*0.0564*
Bioretention	*0.0521*	*0.0157*	*0.0138*	*0.1026*	*0.1712*
Filter Strip	*0.0124*	*0.1555*	*0.1199*	*0.0117*	*0.0150*
Vegetated Swale	*0.0521*	*0.0673*	*0.0360*	*0.0117*	*0.1712*
Stormwater Filtering Systems	*0.0291*	*0.0157*	*0.0601*	*0.1026*	*0.0564*
Proprietary BMP Technologies	*0.0093*	*0.0673*	*0.0696*	*0.0117*	*0.0150*
Vegetated Roof	*0.1098*	*0.0673*	*0.1126*	*0.1026*	*0.0150*
Minimum Disturbance / Minimum Maintenance	*0.0298*	*0.1555*	*0.1550*	*0.1026*	*0.0564*
Rainwater Capture and Reuse	*0.1042*	*0.1555*	*0.1550*	*0.0565*	*0.0150*

This decision matrix is then multiplied by the previously extracted criteria priority vector from Table 7.10.

Peak Mit.	Capital Costs	Maintenance	Long-term TP Removal	GW Recharge
0.1087	*0.0673*	*0.0360*	*0.0308*	*0.0150*
0.1087	*0.0673*	*0.0360*	*0.1026*	*0.0150*
0.0577	*0.0157*	*0.0138*	*0.1026*	*0.1712*
0.1087	*0.0413*	*0.0360*	*0.1026*	*0.1712*
0.1087	*0.0673*	*0.1199*	*0.1026*	*0.0564*
0.1087	*0.0413*	*0.0360*	*0.0565*	*0.0564*
0.0521	*0.0157*	*0.0138*	*0.1026*	*0.1712*
0.0124	*0.1555*	*0.1199*	*0.0117*	*0.0150*
0.0521	*0.0673*	*0.0360*	*0.0117*	*0.1712*
0.0291	*0.0157*	*0.0601*	*0.1026*	*0.0564*
0.0093	*0.0673*	*0.0696*	*0.0117*	*0.0150*
0.1098	*0.0673*	*0.1126*	*0.1026*	*0.0150*
0.0298	*0.1555*	*0.1550*	*0.1026*	*0.0564*
0.1042	*0.1555*	*0.1550*	*0.0565*	*0.0150*

Criteria
0.27
0.27
0.27
0.12
0.08
0.27

Figure 7.6 Decision Matrix and Criteria Priority Vector – Retrofit Site

The decision matrix is now multiplied by the criteria judgment vector to rank BMP options for the given selection considerations. The results are presented as follows.

Table 7.17 BMP Ranks for Retrofit Application

Extended Dry Detention Pond	0.0358
Wet / Retention Pond	0.0444
Infiltration Trench	0.0571
Infiltration Basin	0.0698
Porous Pavement	***0.0901***
Constructed Wetlands	0.0352
Bioretention	0.0571
Filter Strip	***0.0995***
Vegetated Swale	0.0659
Stormwater Filtering Systems	0.0603
Proprietary BMP Technologies	0.0625
Vegetated Roof	0.0849
Minimum Disturbance / Minimum Maintenance	0.123
Rainwater Capture and Reuse	***0.1143***

Among the feasible BMP alternatives, porous pavement, vegetated filter strips, and rainwater capture strategies appear to be the best options for this site. Closer examination of the individual practices reveals that filter strips are not capable of providing the required peak mitigation. Subsequently, they are discarded from consideration. A site area is not specified, so it is unclear how well rainwater harvesting strategies could be applied. Furthermore, the fundamental need for the implementation of a BMP is due to proposed paving of the parking lot. Logically, the porous pavement system appears to be the optimal BMP option for this site. The performance of a porous pavement system, in terms of the identified selection criteria, is provided below in Table 7.18.

Table 7.18 Performance of Porous Pavement System in Addressing Identified Selection Criteria

Criteria	Porous Pavement Performance
Peak Mitigation	High level of peak mitigation ability
Implementation Cost	Comparable to conventional asphalt paving
Annual Maintenance Costs	$250 annually per acre treated (low)
Long-term Phosphorus Removal	Strong phosphorus removal potential over time
Groundwater Recharge	Moderate recharge provided

Chapter 8.0
Summary of Research Objectives, Findings, and Future Work

Chapter 8 compares the initial research objectives to the tasks accomplished. Significant findings, conclusions, shortcomings, and opportunity for future work are also discussed.

8.1 Review of Stated Research Objectives

The research objectives identified in Chapter 1 are now reviewed.

- **Construction of stand alone matrices that facilitate BMP selection based on long-term pollutant removal performance and annual maintenance cost.**

Arising from this work, two categories of BMP selection matrices were constructed. The first group (Tables 4.35 and 4.36) provides both qualitative and quantitative BMP selection guidance pertaining to removal of total suspended sediment, total phosphorus, and total nitrogen from surface runoff. The second group of BMP selection matrices (Tables 5.11 and 5.12) consists of both a qualitative and quantitative selection matrix expressing anticipated annual maintenance expenditures for each BMP described in Chapter 2.

- **Construction of hierarchal comparisons between alternative BMPs and also between their relevant selection criteria.**

Chapter 6 of this paper details the construction of 20 pairwise comparison templates for use in the AHP optimization algorithm. These templates provide the user with the means by which to quickly, efficiently, and with minimized subjectivity consider a wide array of criteria influencing the BMP selection process.

- **Application of the hierarchal comparisons to the Analytic Hierarchy Process in a BMP selection and design case studies.**

Chapter 7 of this paper applies the templates developed in Chapter 6 to four BMP selection scenarios. Each scenario entails different site conditions and BMP implementation objectives.

8.2 Summary of BMP Pollutant Removal Performance Findings

Three separate databases were utilized in the construction of BMP selection matrices reflecting long-term pollutant removal performance. The results, in general, revealed long-term BMP pollutant removal performance to be lower than what is typically claimed in most literature. This was expected, and, in fact, served as the motivation to construct these matrices. Many reported BMP removal efficiencies are derived from laboratory tests and do not reflect the inevitable decline in BMP performance over time. The National Pollutant Removal Database (Center for Watershed Protection, 2000) and the International Stormwater BMP Database (USEPA, 2006) both provided a significant amount of BMP performance data obtained from field monitoring. This data was analyzed and subsequently employed to provide the foundation of the BMP selection matrices developed in Chapter 4. The MASTEP stormwater technologies clearinghouse lacked significant field-derived data on proprietary practices, but did offer a glimpse into the pollutant removal capabilities of proprietary stormwater technology products.

The most striking revelation in reviewing these databases was the moderate pollutant removal performance exhibited by extended dry detention facilities. Without question, this is the most widely implemented stormwater management BMP throughout the United States. While the practice's peak mitigation capability is among the best of any BMP, the findings of this paper reveal the pollutant removal capability of dry extended detention facilities to be rather modest when compared to other BMP alternatives.

Yet another interesting observation in completing this work was the criticism that has befallen pollutant removal efficiency as a means by which to evaluate BMP performance. The literature reviewed in completing the aforementioned research objectives points to average effluent concentration as being the primary means of BMP evaluation and selection in the future.

Unquestionably, the weakest area of present day BMP performance monitoring relates to the infiltration practices. Generally, these practices are held in high regard in the engineering community and widely reported to exhibit some of the highest pollutant removal levels among all BMPs. However, there is very little data to support or validate these claims. Neither the National Pollutant Removal Database nor the International Stormwater BMP Database addresses infiltration BMPs with a statistically valid sample size. A need exists for increased laboratory and field monitoring of these practices to validate their lofty performance claims.

8.3 Summary of BMP Maintenance Cost Findings

Presently, there is very little data available to analyze, quantify, and subsequently validate the anticipated annual maintenance costs of individual BMPs. A number of reasons exist for the absence of such data. Frequently, the maintenance operations for a privately owned BMP falls under the responsibility of a homeowners association or neighborhood volunteer group. Often, these groups lack the financial resources, manpower, and knowledge to properly carry out BMP maintenance operations. When homeowners associations do attempt to carry out BMP maintenance, the intensity and effectiveness of maintenance can vary immensely. Furthermore, many of these maintenance operations are funded by “door-to-door” solicitation of donations. Such funding endeavors do not lend themselves well to the documentation of maintenance expenditures. Often, state highway departments or municipalities do maintain records of the BMPs for which they are responsible. However, in addition to these maintenance records exhibiting great variability, they are almost always limited in scope to large structural practices such as extended detention dry and wet ponds.

More often than not, BMP maintenance costs are reported as a percentage of implementation cost. However there is no statistically relevant data to support the majority of these claims. A myriad of state stormwater manuals and EPA technology fact sheets report regression-based equations for calculating the anticipated annual maintenance costs associated with various BMPs. However, these equations are almost always derived from the same handful of studies performed in the early to mid 1990s. This paper has updated a number of these reported maintenance cost equations to reflect present day dollar amounts. However, a vast expanse of research opportunity still exists in this field. Current work by the author and committee chair, via contract with the *Virginia Transportation Research Council,* entails compiling BMP maintenance records along with cost data on the various routine and non-routine maintenance operations associated with the various BMPs. The end goal is a database which provides accurate, present day costs associated with an itemized listing of BMP maintenance operations.

8.4 Summary of the Analytic Hierarchy Process in BMP Selection

A seemingly unlimited number of possible criteria influence the choice of a BMP for a particular site or application. As more and more selection criteria are introduced to the selection process, the task of *objectively* and *optimally* selecting a BMP becomes increasingly complex. Chapter 7 of this paper applied the AHP algorithm in a number of BMP selection scenarios. While these application scenarios demonstrate the basic capability of the AHP algorithm in optimizing the BMP selection process, this work is still in its infancy. At least two exciting opportunities for expanding upon this research presently exist.

First, save for a trial and error approach, there is no readily available means by which to apply the AHP algorithm to optimize *combinations* of BMPs. In many localities, when infiltration is not feasible, two (or more) BMPs in series are required. The application of these treatment “trains” is also common in localities requiring high pollutant removal targets. As the AHP presently exists in the realm of optimized 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, its execution 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. New research suggests that the AHP may be used in conjunction with linear and/or non linear programming to facilitate the selection of optimal *combinations* of BMPs, but little work has been carried out on this approach to date.

The second area of significant research opportunity in the BMP optimization field lies in the continued development and refinement of pairwise comparison templates. While this paper details the construction of 20 of these comparison matrices, the opportunity for the construction of many more, reflecting a myriad of influential criteria, exists. Having a wide array of comparison templates at the AHP operator’s disposal reduces the likelihood of a unique site condition arising that cannot be considered in the

BMP selection process. The following is a non-exhaustive list of BMP selection criteria for which the future development of pairwise comparison templates may be considered:

Table 8.1 Future BMP Selection Criteria to be Considered

Applicability for BMP discharge into cold water streams	Ability of BMP to discharge into sediment sensitive streams
Ability of the BMP to provide aquifer protection	Suitability for BMP implementation on sites exhibiting low relief
Suitability of BMP for implementation in Karst geology	Land area requirements of the BMP
Restrictions based on site slopes	Minimum required hydraulic head within the BMP
Intensity of BMP maintenance operations	Ability of the BMP to provide wildlife habitat
Ability of BMP to remove fecal coliform from runoff	Ability of the BMP to remove heavy metals from runoff

In addition to developing templates for additional selection criteria, the value of involving more stakeholders in the construction of these templates cannot be overestimated. The fundamental goal of applying the AHP in this manner is the optimized *unbiased* selection of a BMP which simultaneously satisfies multiple influential selection criteria. As the number of participants and influential criteria increase, the objectivity of the selection process may also be reasonably predicted to increase. The templates developed in Chapter 6 reflect *only* the views, experience, and opinions of the author. The majority of the cell-by-cell BMP comparisons expressed in these templates are founded on quantifiable BMP performance data. However, due to the subjective nature by which the templates were constructed, it is not implied that all bias and subjectivity has been removed from the BMP selection process. Consequently, the templates developed in Chapter 6 must be viewed as merely a starting point in the development of a BMP optimization tool. Ideally, the rankings expressed in the Chapter 6 templates should be subjected to critical scrutiny from a multitude of participants, representing a number of different interests and backgrounds. Future work to refine and improve upon these templates proposes the simultaneous, *independent* construction of pairwise comparison templates by two or more groups, and the subsequent comparison, evaluation, and merging of the results.

Finally, it must again be reiterated that 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. When the AHP is applied in a BMP selection scenario, the algorithm attempts to satisfy *all* selection criteria while adhering to the respective weights assigned to each criterion by the operator. This attempt to simultaneously satisfy potentially conflicting criteria may yield results that do not fully satisfy each criterion. Therefore, the BMP rankings attained by employing the AHP must be further scrutinized. The final step in the BMP selection process must be the evaluation of the potential BMP candidates in terms of each selection criterion to ensure adequacy of the BMP.

Appendix A: **References**

AMEC Earth and Environmental, Center for Watershed Protection, Debo and Associates, Jordan, Jones and Goulding, Atlanta Regional Commission. Georgia Stormwater Management Manual. Atlanta, Georgia, 2001.

Board of Governors of the Federal Reserve System. The Discount Rate. Washington, D.C., 2003.

Brown, W. and T. Schueler. National Pollutant Removal Performance Database of Current Urban Stormwater Best Management Practices. Ellicott City, MD: Center for Watershed Protection, 1997.

Brown, W. and T. Schueler. The Economics of Storm Water BMPs in the Mid-Atlantic Region. Ellicott City, MD: Center for Watershed Protection, 1997.

Center for Watershed Protection. National Pollutant Removal Performance Database for Stormwater Treatment Practices 2nd Edition. Ellicott City, MD, 2000.

Delaware Department of Natural Resources and Environmental Control, The Environmental Management Center of the Brandywine Conservancy. Conservation Design For Stormwater Management – A Design Approach to Reduce Stormwater Impacts From Land Development and Achieve Multiple Objectives Related to Land Use. September, 1997.

Lichten, K. "Grassy Swales." BMP Fact Sheets. Bay Area Stormwater Management Agencies Association (BASMAA),1997.

Livingston, E., E. Shaver, J. Skupien and R. Horner. Operation, Maintenance and Management of Storm Water Management Systems. Ingleside, MD: Watershed Management Institute, 1997.

Maryland Department of the Environment. Water Administration Division. Maryland Stormwater Design Manual. Baltimore, MD, 2000.

Massachusetts Stormwater Treatment Evaluation Program. Stormwater Technologies Clearinghouse. http://www.mastep.net, 2006.

Minneapolis – St. Paul. Metropolitan Council. Urban Small Sites Best Management Practice Manual. Minneapolis, MN, 2001.

Northern Virginia Planning District Commission Department of Environmental Services. Maintaining Your BMP – A Guide for Owners and Operators in Northern Virginia, 2000.

Osmundson, Theodore. Roof Gardens History, Design, and Construction. New York: W.W. Norton & Company, 1999.

Pennsylvania Department of Environmental Protection. Draft Stormwater Best Management Practices Manual. Harrisburg, PA, 2005.

Pennsylvania Department of Environmental Protection. Handbook of BMPs for Developing Areas. Harrisburg, PA, 1998.

Prince George's County, Maryland Department of Environmental Resources. Low Impact Development Design Strategies *An Integrated Design Approach*, June 1999.

Saaty, T.L. The Analytic Hierarchy Process. New York, New York: McGraw-Hill International, 1980.

Schmoldt, Daniel L., et al. The Analytic Heirarchy Process in Natural Resource and Environmental Decision Making. Dordrecht, The Netherlands: Kluwer Academic Publishers, 2001.

Schueler, T. "Developments in Sand Filter Technology to Improve Storm Water Runoff Quality." Watershed Protection Techniques, 1994. (Vol. 1, No.2, pp.47-54).

Southeastern Wisconsin Regional Planning Commission (SWRPC). Cost of Urban Nonpoint Source Water Pollution Control Measures. Waukesha, WI, 1991.

Triantaphyllou, Evangelos, and Stuart H. Mann. "Using The Analytic Hierarchy Process For Decision Making In Engineering Applications: Some Challenges." International Journal of Industrial Engineering Applications: Applications And Practice, 1995. (Vol. 2).

U.S. Department of Transportation. Federal Highway Administration. Evaluation and Management of Highway Runoff Water Quality. Washington, D.C., 1996.

U.S. Environmental Protection Agency and the American Society of Civil Engineers. International Stormwater Best Management Practices (BMP) Database. http://www.bmpdatabase.org, 2005.

U.S. Environmental Protection Agency Office of Water. Preliminary Data Summary of Urban Storm Water Best Management Practices. Washington, D.C., 1999.

U.S. Environmental Protection Agency Office of Water. Storm Water Technology Fact Sheet Bioretention. Washington, D.C., 1999.

U.S. Environmental Protection Agency Office of Water. Storm Water Technology Fact Sheet Porous Pavement. Washington, D.C., 1999.

U.S. Environmental Protection Agency Office of Water. Storm Water Technology Fact Sheet Vegetative Swales. Washington, D.C., 1999.

U.S. Environmental Protection Agency Office of Water. Storm Water Technology Fact Sheet Wetlands. Washington, D.C., 1999.

Virginia Department of Conservation and Recreation. Virginia Stormwater Management Handbook. Richmond, Virginia, 1999.

Virginia Transportation Research Council. VDOT Manual of Practice for Stormwater Management. Charlottesville, Virginia, 2004.

Appendix B
Review of Individual Best Management Practices

B.1 Extended Dry Detention Ponds

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 ponds.* 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 employing a dry extended detention basin has been on peak runoff rate mitigation. 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 pond 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 a forebay and micropool in order to further improve water quality control through increased sedimentation and extended detention / retention of runoff volume from the water quality design storm. 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 2 to 10 years.

When extended dry detention ponds are considered for implementation on a site, a number of key design elements must be considered. Detention basins are major structural BMP 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’s contributing watershed area is less than 10 acres, adequate runoff management is achieved more economically by the use of multiple smaller BMP practices.

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 deep. 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 in residential, commercial, industrial, and highway stormwater management scenarios. 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 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 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 costs, both construction and maintenance, for an extended detention basin can vary considerably depending on basin size and its geographic location. Work by Brown and Schueler (1997) provides the following equation for estimating the construction cost of a detention basin.

$$C = 12.4V^{0.760} \qquad \textbf{(B.1)}$$

Where C is the construction, design, and permitting cost (dollars) and V is the volume of storage needed to control the 10-year return frequency storm (cubic feet). Application of this equation reveals that the initial implementation cost per acre-foot of storage is \$41,600. Annual maintenance costs are estimated to range from three to five percent of this initial implementation cost.

The following tables present typical performance summaries for extended dry detention basins.

Table B.1 Pollutant Removal Performance – Extended Dry Detention Basins
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	60
TP	40
NO_3	20

Table B.2 Relative Stormwater Management Function – Extended Dry Detention Basins
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.2 Wet / Retention Ponds

Wet ponds are structural BMPs capable of removing sediment, BOD, organic nutrients, and trace metals from stormwater runoff. Wet pond BMP practices, like their dry counterparts, are also capable of providing significant peak mitigation benefits. The recognized water quality benefits of wet ponds are accomplished 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 water, such as nitrate and ortho-phosphorus. Wet ponds also provide aesthetic benefits that many other BMPs do not. Because of this, the inclusion of a wet pond 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 wet detention pond is under consideration for a site, of critical design concern is the presence of an 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 pond 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 wet pond is 10 acres. Typically the maximum contributing drainage area will be limited to 10 square miles. (FHWA, 1996) The designer should consider that between 1 and 3 percent of a contributing drainage area is required for construction of the pond. (FHWA, 1996)

Site soils are a vitally important consideration in the development of a wet pond. 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.

Wet detention ponds achieve their best 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 pond quickly exits the pond before mixing with the permanent pool. Short-circuiting can be discouraged by increasing the pond length to width ratio or by installing baffles near the pond 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 wet detention pond must be maintained within a desirable range. Shallow ponds, in the absence of adequate stabilizing vegetation, possess the ability to easily resuspend sediment as a result of wind. Ponds 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 wet pond’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 wet pond’s perimeter. Vegetation reduces erosion on both the side slopes and the shallow shore areas. Vegetation located near the inlet to the pond 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)

Gradual side slopes should be employed in a wet detention pond design to enhance safety and reduce erosion. Slopes above the permanent pool should be no steeper than 4H:1V while slopes below the permanent pool should be no steeper than 3H:1V. When site topography permits, side slopes of 10H:1V or milder should be considered to encourage use by wildlife and waterfowl. A major advantage of milder slopes is safety and reduction in potential liability. (FHWA, 1996)

When possible, it is desirable to discharge the pond inlet pipe at or below the surface of the permanent pool. Doing so reduces the likelihood of short-circuiting, and improves the mixing of runoff with the permanent pool, thus improving the observed water quality benefits. When the inlet pipe discharges above the permanent pool, an outlet energy dissipater will protect the banks and slopes of the pond from erosion.

Much like dry detention ponds, when a wet pond is considered for implementation on a site, a number of key design elements must be considered. Wet ponds are major structural BMP practices with significant land area requirements, implementation and maintenance costs, and potential safety concerns. Wet ponds require a source of permanent baseflow to ensure that the basin holds a permanent pool even during periods of extended drought. Further, wet ponds 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 wet pond 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 BMP practices.

Wet pond BMP practices are applied throughout the United States in residential, commercial, industrial, ultra urban, and highway stormwater management scenarios. Wet ponds may be restricted in their application on sites exhibiting 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 deep. 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.

The costs, both construction and maintenance, for a wet pond BMP practice can vary considerably depending on basin size and its geographic location. Typical construction costs for a wet pond practice (2004 dollars) range from $25,000 to $50,000 per acre foot of storage. Annual maintenance costs are often estimated to range from three to five percent of this initial implementation cost, though little data presently exists to support this estimate.

Table B.3 Pollutant Removal Performance – Wet Ponds
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	70
TP	60
NO_3	30

Table B.4 Relative Stormwater Management Function – Wet Ponds
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.3 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 is quite significant. (Pennsylvania DEP Draft Stormwater Best Management Practices Manual – January 2005). While different types of infiltration trenches exist, (surface versus subsurface), the core design element of an infiltration trench is in 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 practice may dictate pre-treatment of hotspot runoff. The contributing drainage area to an infiltration trench must be limited to no more than 10 acres. Larger drainage areas produce sediment loading levels in their runoff which can significantly reduce the performance of infiltration practices. Furthermore, with a specific design approach targeted at infiltration of a significant portion of polluted inflow, infiltration practices are subject to a number of unique application restrictions. Sites exhibiting shallow (less than three feet) bedrock and seasonal water table depths are usually not candidates for an infiltration trench BMP. 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 an infiltration trench feasibility study. 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 trench is 12 inches per hour. Generally, hydrologic soil group D is not considered suitable for the construction of infiltration practices. High and moderate infiltration rate soils such as hydrologic soil groups A and B often make desirable soils for infiltration trench construction. During construction operations, care must be taken to avoid the compaction of the soils upon which an infiltration trench is situated. To avoid stagnant conditions, mosquito habitat, and other nuisances, infiltration trenches should be designed such that the surrounding soil provides a complete drawdown of stored water in less than 72 hours.

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 soluble pollutants. Therefore, where pre-treatment is provided and site water table and bedrock depths are sufficient, infiltration trenches are a good consideration for the treatment of hotspot runoff.

Infiltration trenches are often a very economical BMP choice, particularly on smaller sites. Location, configuration, and site-specific conditions lead to great variability in the reported construction costs of infiltration trench practices. Work by Brown and Schueler report the construction cost for an infiltration trench BMP, in 2003 dollars, to range from $4 to $9 per cubic foot of storage provided. Annual maintenance costs are reported to range between 5 and 10 percent of the capital costs.

Table B.5 Pollutant Removal Performance – Infiltration Trench
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	85
TP	85
NO_3	30

Table B.6 Relative Stormwater Management Function – Infiltration Trench
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.4 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. (Pennsylvania DEP Draft Stormwater Best Management Practices Manual – January 2005). The most popular infiltration basin configurations are described as follows:

- *Full infiltration basin* – designed to hold and infiltrate the entire water quality volume from a site. This type of basin is provided with an emergency overflow to safely convey larger storms downstream. Runoff entering the basin exits only by infiltration or by passing through the emergency overflow structure. Full infiltration basins require their bed soils to exhibit extremely high infiltration rates.
- *Off-line basin* – designed to detain and infiltrate only a designated water quality volume. A weir or other flow-splitting device is installed in the storm sewer or on-line conveyance channel allowing only the designated water quality volume to enter the basin. Larger storm events are conveyed downstream to a quantity control BMP such as an extended detention pond.
- *Combined infiltration / detention basin* – designed much like an extended detention pond. The designated water quality volume is provided below the outlet riser's lowest invert and exits the basin only by infiltration. Larger storm events are routed through the riser structure.
- *Side-by-side basin* – functions in the same manner as the combined infiltration / detention configuration, but provides a low-flow channel to accommodate baseflow.

Infiltration basin BMPs are applied throughout the United States in residential, commercial, and industrial settings. 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 when the contributing drainage area is considerably less than this. Larger drainage areas are usually best treated by pond or wetland BMP practices. Sites exhibiting shallow (less than three feet) bedrock seasonal water table depths are usually not candidates for an infiltration basin. When infiltration practices are deemed feasible for a site, they must 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. High and moderate infiltration rate soils such as hydrologic soil groups A and B often make desirable soils for infiltration basin construction. Under no circumstance may an infiltration basin be located on recently placed (less than five years) fill material. During construction operations, care must be taken to avoid the compaction of the soils upon which an infiltration basin is situated. To avoid stagnant conditions, mosquito habitat, and other nuisances, infiltration basins mustbe designed such that the surrounding 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 inflow.

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 high land area requirement when compared to other practices. Additionally, sufficient depth must exist within an infiltration basin to provide sufficient freeboard between the top of embankment and the outfall invert of their overflow structure. The large land area requirement associated with infiltration basins often precludes 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 soluble pollutants. Therefore, on larger sites, where pre-treatment is provided and site water table and bedrock depths are sufficient, infiltration basins are an excellent consideration for the treatment of hotspot runoff.

The location, configuration, and site-specific conditions lead to great variability in the reported construction costs of infiltration basin practices. Excavation costs vary greatly depending on site soils and proposed basin configuration. Vegetative planting of basins typically ranges between $2,500 and $3,500 per acre with piping costs being too basin-specific to attempt to quantify. The Federal Highway Administration ranks the implementation and maintenance costs of an infiltration basin, when compared to other BMP practices, as "medium."

Table B.7 Pollutant Removal Performance – Infiltration Basin
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	85
TP	85
NO_3	30

Table B.8 Relative Stormwater Management Function – Wet Basin
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.5 Porous Pavement Systems

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. (Pennsylvania DEP Draft Stormwater Best Management Practices Manual – January 2005). 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 areas whose 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 are a point-of-contact infiltration practice, and as such may not receive hotspot runoff. These systems may be implemented in cold weather climates, provided that the reservoir layer extends to a depth beyond the frost line. Sites exhibiting shallow (less than three feet) bedrock and seasonal water table depths are usually not candidates for porous pavement infiltration practices. The infiltration bed underlying a porous pavement installation may not be located 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 a critical factor when considering a porous pavement system. The minimum infiltration rate for an infiltration practice to function efficiently is 0.5 inches per hour. Generally, hydrologic soil group D is not considered suitable for the construction of infiltration practices. High and moderate infiltration rate soils such as hydrologic soil groups A and B often make desirable underlying soils for porous surface systems. Under no circumstance may a porous pavement system be located on recently placed fill material. During construction operations, care must be taken to avoid the compaction of the soils upon which an infiltration reservoir or bed is situated.

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 computer 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, including the reduced frequency of need for costly BMP practices such as detention basins, porous asphalt is very comparable in cost to its traditional, impervious counterpart.

Table B.9 Pollutant Removal Performance – Porous Pavement
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	85
TP	85
NO_3	30

Table B.10 Relative Stormwater Management Function – Porous Pavement
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.6 Constructed Wetlands

Constructed Wetlands are shallow marsh areas planted with a diverse mix of emergent vegetation, capable of treating stormwater runoff. (PADEP, 2004) 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, 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)

A number of variations exist among Constructed BMP Wetlands, however. The four most common are as follows:

- Shallow wetlands – large surface wetlands whose primary means of water quality improvement is through displacement of the permanent pool.
- Extended detention wetlands – similar to shallow wetlands but use extended detention as another mechanism for water quality and peak rate control.
- Pocket wetlands – smaller wetlands that serve drainage areas between 5 and 10 acres and are constructed at or near the water table.
- Pond / Wetland systems – a combination wet pond and constructed wetland.

In addition to providing significant water quality benefits, constructed wetlands offer aesthetic benefits, wildlife habitat, and erosion control. However, wetlands also exhibit certain disadvantages. First, a continuous baseflow is required through the wetland area. Should the wetland area become dry or stagnant, problems such as algae blooms and undesirable odors will arise. Furthermore, dry conditions can lead to accumulated salts and scum that may become resuspended and flushed out by large storm events. Wetlands also require more rigorous maintenance than do other BMPs. Maintenance operations such as plant harvesting are crucial to maintaining the proper functioning of the wetland. (FHWA, 1996)

The first issue to be considered in the design of a constructed wetlands area is the average depth to the water table. As previously stated, wetlands require a perennial source of baseflow. Therefore, the presence of a shallow water table, or a water table that meets the ground surface, is a desirable condition. In the absence of a shallow water table, the wetland is dependant upon surface runoff for its baseflow. This dependence may lead to water level fluctuations within the wetland that make it difficult to establish vegetation. Hydrologic studies must be conducted to determine if flooding or frequent inundation occurs, and if saturated soils are present in the proposed wetlands area. Frequent, natural inundation is a desirable condition. (FHWA, 1996) When wetland practices are being considered, a water balance study *must* be performed to ensure that a stormwater wetland can withstand a 45 day drought at summer evaporation rates without completely drawing down. (MDE, 2000)

Wetland soils should ideally consist of loose loam or clay in order for wetlands-specific vegetation to take root and sustain itself. Clay soils underlying the wetland will help prevent percolation of inflow to groundwater (FHWA, 1996). Whenever possible, the presence of organic soils should be capitalized upon and used for constructed wetlands. Organic soils serve particularly well as a sink for pollutants and generally have high water holding capacities (PADEP, 2004). Hydrologic soil groups C and D are usually suitable for wetlands construction without modification. The presence of hydrologic soil groups A and B may require a wetland area to be equipped with a clay or synthetic liner.

The control of sediment is critical to sustaining functioning stormwater wetlands. A sediment forebay must be located at all inlet points to the wetland. Forebays are usuall sized to accommodate10-15% of the computed water quality volume from the entire inflow-contributing area. Typically, the wetland forebay pool depth will range from three to six feet. Additionally, a three to six foot deep micropool must be located at the wetland outlet to protect the low flow pipe from clogging and to prevent sediment resuspension (MDE, 2000). The best functioning wetlands are designed such that the flowpath from the inflow point(s) to outflow point(s) are maximized. Flowpaths of 1.5:1 (length relative to width) and irregular shapes are recommended to increase hydraulic residence time and reduce the likelihood of sediment resuspension. Additional methods used to attain increased wetland flowpath lengths include internal berms and microtopography (MDE, 2000).

Usually, the minimum surface area required for a stormwater wetlands area is one percent of the contributing drainage area to the facility. Shallow wetlands may require a minimum surface area of 1.5 percent of the contributing drainage area. At least 25% of the total water quality treatment volume should exist as deepwater zones (defined as having a minimum depth of four feet) within the wetland. The sediment forebays and micropool are commonly considered as part of this volume. A minimum of 35% of the total surface area of the wetland should exhibit a daily average depth of six inches or less, and at least 65% of the total surface area is typically shallower than 18 inches.

Wetlands require a near-zero longitudinal slope. If zero slope is not feasible within the main wetland channel, the slope of the wetland is kept gradual enough to ensure that the flow velocity for the 2-year return frequency inflow through the pond does not exceed 2.5 ft/sec. This velocity is determined by using a Manning's *"n"* value of 0.03 and a flow depth of 3-5 feet. (FHWA, 1996) The inability of a constructed wetlands system to demonstrate flow velocities less than 2.5 ft/sec may prohibit its implementation, thus requiring other BMP practices to serve runoff treatment needs. Such slope restrictions often preclude the use of wetlands BMP practices in mountainous terrain.

Wetlands carry perhaps the greatest potential liability of all BMP measures. Because wetlands are often applied in residential and commercial settings, numerous safety measures have been introduced similar to those required for extended dry detention ponds and wet detention ponds. Safety measures unique to wetlands areas include requiring that all pools in the wetland area deeper than four feet have two safety benches, each four to six feet wide (PADEP, 2004). One of these benches must be placed 1 – 1.5 feet above the normal water elevation, and the other 2 – 2.5 feet below the water surface.

Wetlands costs vary considerably depending on their configuration, geographic location, and, other site-specific elements. The USEPA Wetlands Fact Sheet, 1999, reports an approximate wetlands construction cost of $30,000 to $65,000 per acre of surface area. The most influential cost factors are the amount of earthwork required and the diversity and density of the vegetative plantings. Plant harvesting and care, sediment removal, and other routine maintenance costs result in the average annual wetlands maintenance costs to range as high as five percent of the construction cost.

Table B.11 Pollutant Removal Performance – Constructed Wetlands
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	85
TP	85
NO_3	30

Table B.12 Relative Stormwater Management Function – Constructed Wetlands
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.7 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.*

First, *Off-Line Bioretention BMPs* are areas consisting 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 way 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 in Section 2.3.4. Local ordinances often prohibit the construction of bioretention areas 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. A number of unique design guidelines also affect the consideration of bioretention BMPs. Bioretention BMPs should *not* be used under the following circumstances:

- Mature trees would have to be removed in constructing the bioretention area
- Site slopes are 20 percent or greater
- An unstable soil stratum is present in vicinity of site

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. (Pennsylvania DEP <u>Draft Stormwater Best Management Practices Manual</u> – January 2005).

To ensure manageable sediment loading, rigorous guidelines exist in establishing a bioretention surface area and the allowable drainage area directed to a bioretention practice. The Pennsylvania DEP <u>Draft Stormwater Best Management Practices Manual</u> (2005) states that the drainage area to bioretention area ratio be a maximum of 5:1. The Federal Highway Administration document, <u>Evaluation and Management of Highway Runoff Water Quality</u>, further recommends that the *minimum* size of an off-line bioretention area shall be 15 ft wide by 40 ft long. For bioretention areas to function optimally, the length-to-width ratio is 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.

Critical to the long-term performance of a bioretention practice is the selection of vegetation. These plantings should replicate, as closely as possible, a terrestrial forest community ecosystem. This is accomplished by including trees, a shrub layer, and a herbaceous layer. Planting shall resemble the random, *natural* placement of plants rather than a landscaped approach with trees and shrubs placed in an organized row or other orderly fashion. The vegetation must be able to withstand ponding, variable soil moisture conditions, and the pollution found in urban stormwater runoff. Appendix H (Tables H-2 and H-3) of the <u>Pennsylvania Handbook of Best Management Practices for Developing Areas</u>, 2004 provides a listing of plant species well suited for implementation in bioretention areas.

Often, bioretention areas are equipped with an upstream buffer strip. The purpose of a grass buffer strip/energy dissipation area is to reduce the potentially erosive velocities that may exist prior to entering the bioretention area. The required length of the grass buffer strip is a function of the land cover of the contributing drainage area and its slope. Usually, the minimum length of a grass buffer strip is 10 ft. In addition to the grass buffer area, an optional sand filter may be located immediately upstream of a bioretention area. Inclusion of a sand filter further slows the runoff entering the bioretention facility, assists in dispersing the runoff evenly, provides filtering benefits, provides positive drainage to prevent anaerobic conditions in the planting soil, and enhances exfiltration from the basin. Anaerobic conditions are avoided even during periods of saturation as the water present in the sand is migrant and constantly draining during periods of no inflow.

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. Bioretention areas, specifically rain gardens, exhibit construction costs ranging from approximately $5 to $7 per cubic foot of storage.

Table B.13 Pollutant Removal Performance – Bioretention
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	85
TP	85
NO_3	30

Table B.14 Relative Stormwater Management Function – Bioretention
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.8 Vegetated Filter Strips

Vegetated filter strips are "permanent, maintained strips of planted or indigenous vegetation located between nonpoint sources of pollution and receiving water bodies for the purpose of removing or mitigating the effects of nonpoint source pollutants such as nutrients, pesticides, sediments, and suspended solids." Vegetated filter strips often serve as one component of an integrated stormwater runoff management system or BMP "train." Properly constructed and maintained, strips are capable of reducing runoff velocity, reducing runoff volume (slightly), improving runoff quality, contributing to groundwater recharge, 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 BMP filter strip. As with many filtration BMP practices, the first of these criteria is that of site soil considerations. 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 the 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 is not an issue, the maximum contributing drainage area to a vegetated filter strip should not exceed five acres. During the design process, careful attention must be given to hydraulically examine the anticipated flow regime carefully for drainage areas approaching the five acre maximum to ensure that runoff entering the filter strip is 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, the concern of the BMP land area requirements becomes negligible, as a portion of the site is not "lost" to the BMP practice. 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 levels, the hydraulic residence time of the water quality volume entering a filter strip is typically maintained at nine minutes or greater, and is under no circumstances permitted to 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 must not produce a depth of flow exceeding one half inch. (FHWA, 1996)

When the filter is located such that the width of the contributing drainage area is greater than that of the filter, runoff must first be directed into a level spreader. This ensures that the runoff entering the filter strip area is introduced uniformly and under sheet flow conditions. Runoff that is directed to the level spreader may be sheet flow or concentrated flow. However, the purpose of the level spreader is to ensure that runoff fills the spreader evenly and flows over the level lip as uniformly as possible. The downstream edge of the level spreader and the top edge of the filter strip must follow the same elevational contour. If a section of the strip dips below this established contour, runoff will tend to form a channel. The level spreader width must extend the entire width of the filter strip, leaving a maximum of 10 feet open on each end. This requirement potentially increases the construction cost and land area requirements of the filter strip.

To increase ponding and hydraulic residence time in a vegetated filter strip, a pervious berm is often installed along the strip's downstream edge. This berm must be constructed using a moderately permeable soil such as ASTM ML, SM, or SC. Soils meeting USDA sandy loam or loamy sand texture, with a minimum of 10% to 25% clay may also be used. Additional loam may be used on the berm (25% +/- of the total berm volume) to help support vegetation. If a berm is employed, an armored overflow is also provided to allow the passage of larger storms without overtopping and erosion of the berm. Filter strip's employing a downstream berm must possess sufficient surface area to avoid ponding depths in excess of one foot.

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 phenomenon, 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 construction cost of a filter strip practice includes grading, sodding, planting, the construction of a permanent level spreader, and possibly the construction of a permeable berm. Construction costs for filter strip practices range as high as $50,000 per acre. Their annual maintenance costs range from $100 to $1,400 per acre, but much of this maintenance cost overlaps with standard site landscaping costs.

Table B.15 Pollutant Removal Performance – Vegetated Filter Strip
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	30
TP	20
NO_3	10

Table B.16 Relative Stormwater Management Function – Vegetated Filter Strip
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.9 Vegetated Water Quality Swales

Vegetated swales are another category of filtration BMP practices. Engineered BMP stormwater conveyance systems 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 multiple BMP “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. Another variety of filter is characterized by a 12 to 24 inch deep aggregate layer underlying the vegetated upper band. The void space found in the aggregate leads to a significant reduction in the volume of runoff observed from a site. A typical vegetated swale is shown below in Figure 2.16.

A number of different criteria influence the design of an engineered grassed 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 the channel design 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, 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 must not be greater than 2H:1V. In the design of stormwater conveyance channels, the concept of the *best* *hydraulic section* is often employed. The best hydraulic section is the channel configuration for which the minimum area is required to convey the desired flow. The best hydraulic section exhibits side slopes of 0.58:1. These excessively steep side slopes lend themselves well to concrete or other manmade systems, but are usually impractical for vegetated swales. While potentially useful as a starting design point, employment of best hydraulic section methodology will usually be impractical in the design of a grass swale.

The required depth of a swale is governed, ultimately, by the volume of water for which treatment is planned. The ponded volume 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 rule, 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 to consider when considering implementation of an engineered grassed swale is that of anticipated flow velocity. The flow velocity should be as low as practically possible 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. The following maximum design velocities must be met for a conveyance swale to function as a water quality BMP:

Table B.17 Vegetated Swale Permissible Velocities By Return Period

Source: Virginia Department of Conservation and Recreation Stormwater Management Handbook, 1999

Design Flow	Permissible Velocity (fps)
2-year	4
10-year	7

Along with channel geometry, another factor influencing flow velocities in a vegetated swale is that of the channel's longitudinal slope. The generally accepted minimum constructible slope is 0.75%. The slope of the proposed grassed swale 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 velocity requirements previously discussed. 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.

Swale configurations do exist that provide positive water quality benefits with the use of no check dams. The primary purpose of the check dams is to level the grade, decrease erosion, and increase the contact time for the flow as it passes through the vegetative cover. Most vegetated swales must provide inflow with a minimum hydraulic residence time of 9 minutes for significant pollutant removal to occur. Without check dams to induce ponding, the equivalent swale length must increase. For many sites, this alternative will not be feasible because of the excessive length required to achieve an acceptable hydraulic residence time for the flow entering the channel. When vegetated grassed swales employ check dams, ponding results in easy attainment of the 9 minute hydraulic residence time. In the absence of check dams, infiltration of runoff in the swale is negligible. Thus, BMP swales without check dams are intended to serve only as a treatment step in a series of multiple BMPs.

Generally, vegetated swales are one of the lowest cost BMP measures 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 expected lifespan exhibited by vegetated swales, they remain a very financially attractive runoff management option. Table 2.18 compares the costs associated with a vegetated swale to those associated with underground piping and curb and gutter runoff conveyance systems.

Table B.18 Cost Comparison – Vegetated Swale Vs. Underground Piping and Curb & Gutter

Source: Bay Area Stormwater Management Association, June 1997

	Swale	Underground Pipe	Curb & Gutter
Construction Cost (per linear foot)	\$4.50 - \$8.50 (from seed) \$15 – 20 (from sod)	\$2 per foot per inch of diameter (e.g. a 12″ pipe would cost \$24 per linear foot)	\$13 – 15
Annual O&M cost (per linear foot)	\$0.75	No data	No data
Total annual cost (per linear foot)	\$1 (from seed) \$2 (from sod)	No data	No data
Lifetime (years)	50		20

Table B.19 Pollutant Removal Performance – Vegetated Swale

Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	50
TP	50
NO_3	20

Table B.20 Relative Stormwater Management Function – Vegetated Swale

Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.10 Stormwater Filtering Systems

Constructed stormwater filter systems are structures or areas containing a layer of sand, compost, organic material, peat or other filter media that reduces the observed pollutant levels in the runoff that enters the filter. Constructed filter BMPs are used in commercial, industrial, ultra urban, and highway settings to reduce or remove the sediment and pollutants found in the first flush of runoff from pavement or other impervious surfaces. Unlike most BMPs, the performance of a stormwater filter may improve over time as a mat of bacterial slime develops within the filter. (FHWA, 1996)

In most applications, runoff flows through an open air “pretreatment” chamber prior to entering the filter chamber. This process allows large particles and debris to settle out. Surface vegetation is another option for pretreatment. Runoff entering the filter chamber passes through the filter media where pollutants are filtered out. Next, runoff is collected in an under-drain and then returned to the conveyance system, receiving waters, or infiltrated into the soil mantle. (PADEP, 2005) Filtering systems are not designed to reduce the peak rate of stormwater runoff. Consequently, stormwater filters are typically combined with a separate facility to accomplish peak runoff rate mitigation. The Maryland Department of the Environment identifies five types of stormwater filters (excluding bioretention facilities).

- Surface sand filters
- Underground sand filters
- Perimeter sand filters
- Organic filters
- Pocket sand filters

Stormwater filtering BMPs are subjected to several constraints not present in the design of many other BMP measures. The primary cause of stormwater filter failure is premature clogging which may arise from elevated sediment levels in the runoff directed to the filter. To prevent excessive sediment loading, the maximum drainage area that may be directed to a single filter is limited to 10 acres. Stormwater filtering BMPs are usually further limited in application to watersheds with an impervious fraction greater than 75%. When drainage areas with impervious fractions less than this are directed to a filter, full pretreatment of the runoff must occur to protect the filter from sediment. A dense and vigorous vegetative cover must be established over all non-impervious contributing surfaces prior to directing runoff to the filter. Surface sand filters, organic filters, and pocket sand filters are often equipped with a grass cover to aid in pollutant adsorption. The species of grass selected must be able to withstand frequent periods of inundation.

To afford the filter with an added measure of protection from excessive sediment loading, runoff entering the filter typically passes through a pretreatment chamber. Pretreatment of runoff occurs in the sedimentation basin immediately upstream from the filtration basin. The sedimentation chamber may be designed as a full or partial sedimentation basin. Full sedimentation chambers are sized to accommodate the entire water quality volume and release it into the filtration chamber over some period of time, typically 24 hours. Partial sedimentation basins operate more as a flow-through device, and are designed only to hold a portion of the designated water quality volume. Partial sedimentation basins, as their name implies, only remove a portion of the incoming sediment, thus allowing more sediment to reach the filter bed. (FHWA, 1996) Depending on available space and other constraints, pretreatment of the entire water quality volume may not be feasible. Pretreatment of a minimum of 25% of the computed water quality volume is recommended by the Maryland Department of Environment and this should occur immediately upstream of the filter media (MDE, 2000). This minimum level of pretreatment is accomplished, most commonly, by a sedimentation basin whose minimum length-to-width ratio is 2:1. The need for adequate pretreatment increases the total land area required for the filtering practice.

Filtering practices are not used as online BMP practices. When runoff from a storm sewer is directed to a filtering practice, a flow regulator (splitter or diversion weir) is employed to direct only the water quality volume to the filter bed. When a diversion weir is in place to control the total *volume* of runoff directed to a filtering practice, provisions for an emergency overflow bypass are not needed. However, when the runoff volume entering the filter bed cannot be controlled, as is the case when the bed receives inflow from r overland sources, the filter bed must be equipped with an overflow system capable of safely bypassing at least the 10-year return frequency inflow.

Constructed stormwater filters are most commonly equipped with a perforated underdrain piping system. Inflow that has passed through the filter media is collected in this underdrain and conveyed to a downstream link in the stormwater conveyance network or the terminus receiving water. However, filters can be constructed as *infiltration* practices on sites where the surrounding soil mantle exhibits a suitable rate of permeability. The minimum infiltration rate for an infiltration bed to function efficiently is 0.5 inches per hour. Typically, the maximum allowable infiltration rate for the soil mantle is 12 inches per hour. Generally, hydrologic soil group D is not considered suitable for the construction of infiltration practices. High and moderate infiltration rate soils such as hydrologic soil groups A and B often make desirable site soils when infiltration of inflow is planned for the filter practice. Sites exhibiting shallow (less than three feet) bedrock seasonal water table depths are usually not candidates for infiltration practices. When infiltration practices are deemed feasible for a site, they must 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. Whether the filter is equipped with underdrain piping or infiltration of inflow is planned, filter beds should be designed and maintained such that complete drawdown of stored water is observed within a maximum of 72 hours.

Stormwater filters are a maintenance intensive BMP practice. Filtering practices typically function very well upon installation, but their performance has the potential to rapidly decline as sediment accumulates on the filter. To ensure an acceptable level of performance, filters must be inspected a minimum of four times per year, and maintenance performed accordingly. In addition to quarterly inspections, filters must receive maintenance any time standing water is observed on the filter more than 72 hours after a runoff producing event and when film or discoloration is observed on any surface of the filter material. The presence of excessive film or discoloration is indicative of the filter becoming clogged by organic debris. Routine maintenance may range from simple operations such as removal of trash and debris to a complete overhaul of the filtering medium.

Filter types and materials vary too greatly to provide a useful estimate of their cost. Factors such as material (sand, peat, compost), the amount of site area dedicated to the practice, the extent of excavation, and the magnitude of inlet and outlet structures all introduce great variability into the cost of filtering BMP practices. Typically, the construction of a filtering practice underground significantly increases its cost. Furthermore, when the rigorous maintenance required of a filtering practice is considered, the costs of such practices are considered high compared to other BMP measures.

Table B.21 Pollutant Removal Performance – Constructed Filters
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

Pollutant	Removal Percentage
TSS	85
TP	85
NO_3	30

Table B.22 Relative Stormwater Management Function – Constructed Filters
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

**Medium when constructed as an infiltration practice*

B.11 Proprietary Stormwater Technologies (Hydrodynamic / Swirl Separators and Water Quality Filtering Units

Proprietary BMP practices are a structural category of BMP using some form or combination of settling and filtration to remove particulate pollutants from turbulent flow. Proprietary practices vary widely in size and function. The most common types of proprietary BMP measures 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, 2000) These manufactured systems are designed as flow-through structures, and do not provide significant detention volume. In contrast to conventional BMP measures 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. (VADCR, 2000)

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 separators are not intended for the removal of dissolved or emulsified oils and pollutants such as coolants, soluble lubricants, glycols and alcohols. (GASWM, 2001) Hydrodynamic separators are presently limited in application by the following:

- Throughout the United Stages, a widely implemented target removal percentage for suspended sediment is 80 percent. Hydrodynamic separators cannot *alone* achieve the 80% removal of TSS.
- Dissolved or emulsified pollutants are not effectively removed by these types of BMPs.
- Frequent maintenance is required to maintain desired pollutant removal performance levels.
- Hydrodynamic separators do not provide mitigation of peak rate of runoff to pre-developed levels.

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. When a manufactured hydrodynamic separator is being considered for a particular site development, the site design specifications and plan drawings must be reviewed by the BMP manufacturer to ensure that the system is adequately sized and located. Watersheds producing excessively high sediment loads in their runoff are of particular detriment to the performance of oil / water separation BMPs. Due to this concern, hydrodynamic separators are typically limited in use to drainage areas of less than five acres. To further protect the device from excessive sediment loading, it is typically recommended that the contributing drainage area to any single separator be limited to one acre or less of impervious cover. 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.

Separation devices are sized based on *rate* of runoff. This design criteria contrasts with most BMPs, which are sized for a designated runoff *volume*. Hydrodynamic separators are typically designed to bypass runoff flows in excess of their design flow rate. This bypass may be accomplished by an internal bypass mechanism or a diversion weir or flow splitter located upstream of the separator in the runoff conveyance system. As with all runoff control structures, an adequately stabilized outfall must be provided at the separator’s discharge point. Separation BMPs serve only water quality benefit. Additional BMP measures must be applied when mitigation of runoff rate is required.

Hydrodynamic separators require a much more intensive maintenance schedule than other BMP measures to ensure desirable performance levels. A typical maintenance schedule is shown as follows:

Table B.23 Typical Maintenance Activities for Gravity Separators
Source: State of Georgia Stormwater Management Manual, 2001

Activity	Schedule
Inspect the gravity separator unit.	Quarterly
Clean out sediment, oil and grease, and floatables, using catch basin cleaning equipment (vacuum pumps). Manual removal of pollutants may be necessary.	As needed on storm by storm basis

The individual performance, design guidelines, and cost of proprietary hydrodynamic separators vary greatly. The pollutant removal efficiency and cost of various hydrodynamic separators are discussed, at length, in Chapters 4 and 5 respectively.

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, 2005) 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, 2005) 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, 2005) 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.

The design and implementation process for a specific water quality inlet or catch basin insert must begin with a review of various vendor publications and the use of preliminary sizing guidelines provided by the vendor. The specific design criteria for the proprietary system being considered must be obtained from the manufacturer or vendor to ensure that the latest design and sizing criteria are used. In most applications, the design for a particular site should be reviewed by the manufacturer to ensure that the system is adequately sized and located. Specific site conditions must be matched with manufacturer/vendor guidelines and specifications to assure desirable performance levels. Geographic location and land govern the specific pollutants and their associated loading rates found in runoff. Catch basin inserts and water quality inlets, like hydrodynamic separators, are pass through BMP structures. They serve only to improve the quality of runoff and require additional BMP measures when peak mitigation is required.

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, 2005) 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. During construction operations, water quality inlets should be inspected a minimum of once per week, and cleaned as needed. Following construction, they should be emptied when full of sediment and trash / debris. Thorough cleaning of the inlet filter media should take place at least twice per year. Water quality inlets and catch basins equipped with filtering devices should also be inspected after all heavy runoff producing events.

The individual performance, design guidelines, and cost of catch basin and water quality inserts vary greatly. The pollutant removal efficiency and cost of various catch basin inserts and water quality inlets are discussed, at length, in Chapters 4 and 5 respectively.

B.12 Low Impact Development Strategy – Vegetated Roof Systems

Low impact development (LID) strategies encompass a category of best management practices which try to preserve a site's pre-development land cover and hydrologic runoff patterns as closely as possible during the development process. LID measures may range from *structural practices* such as vegetated roofs to *design strategies* such as a minimum maintenance / minimum disturbance site development approach.

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, January 2005) 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, January 2005) 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. These deep intensive systems usually are considered roof gardens. 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. Only extensive systems are considered a BMP practice. 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 / protection layer, 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, phosphorous and nitrogen 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.

Table B.24 Relative Stormwater Management Function – Vegetated Roofs
Source: Pennsylvania DEP Draft Stormwater Best Management Practices Manual, 2005

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

B.13 Low Impact Development Strategy – Minimum Disturbance / Minimum Maintenance

Minimum Disturbance / Minimum Maintenance (MD/MM), also termed *site fingerprinting or footprinting*, is an approach to site development where clearing of vegetation and disturbance of soil is carefully limited to a prescribed distance from proposed structures and improvements. The application of minimum disturbance / minimum maintenance site design as a best management practice is most commonly found on sites which possess existing vegetation in the form of tree cover. However, the term *existing vegetation* may also encompass any natural vegetative cover. Furthermore, a site's tree cover does not have to be in the form of a mature stand of forest for MD/MM to be considered. Scrub vegetation is capable of providing significant water quality and quantity benefits. Developed sites where clearing has already taken place may still be candidates for MD/MM practices, provided that revegetation and reforestation are planned. (DEDNREC, September 1997) It is important to note that, whenever feasible, retaining natural / native vegetation is preferred to artificial landscaping. Native, established vegetation is preferred because it does not require fertilization as does newly planted landscaping. The fertilization required of new plantings is subject to wash off, and is often a significant source of non-point source pollution. This approach to site development has the dual benefit of minimizing the effects of land disturbing activities (increased rate of stormwater runoff, increased levels of pollutants), and also preserving natural areas of vegetation, thus retaining all of their natural stormwater management function.

The first step to consider when implementing an MD/MM design is to establish the limit of disturbance (LOD), also termed the *site envelope*. A development project's LOD must be considered from the very infancy of the site design process with joint input from the plan reviewing authority, the design engineer, and if possible the contractor. Additionally, the site envelope must be established by integrating MD/MM considerations with local subdivision ordinances and building codes. The site envelope reflects the minimum clearing zone required for the construction of the proposed site improvements. Establishment of the LOD must consider reasonable construction techniques, and must also consider physical constraints unique to the site and proposed development, such as slopes and the type of proposed structure(s) and roadway(s). For example, a 10 foot LOD buffer surrounding proposed structures may be feasible from a construction standpoint for a low-density residential development, whereas a 25 foot or larger buffer may be required on sites where larger construction equipment must be employed. LOD distances can vary by type of development, size of site, and by specific development features. (DEDNREC, September 1997) MD/MM methodology and considerations must continue throughout the design and preparation process. Procedurally, the LOD must be established early on in the plan preparation process, and should be clearly delineated on the site design drawings.

In addition to minimizing the total disturbed area of a proposed development, MD/MM design also considers a 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 contributes to the establishment of the site envelope by attempting to preserve 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.

A number of design elements and approaches exist to minimize the amount of impervious area arising from development of a site. The first is simply to consider reduced 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 attempted preservation of natural runoff patterns and drainage ways, curb and gutter may not be required. In addition to reducing the width of proposed roadways, attention to their layout orientation can greatly reduce the total amount of impervious area arising from a development project. The disturbance of natural / native vegetation can be further minimized by locating proposed structures and roadways along existing contours and ridge lines. Site earthwork and clearing can be 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. Earthwork can also be reduced by permitting steeper cuts and grades. Innovative trenching procedures also now exist which can reduce the amount of site disturbance required for the installation of utility lines by as much as 50 percent.

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 impervious portions of a site *disconnected*.

Disconnection of site impervious areas provides an opportunity for infiltration and evaporation, while also reducing the volume of concentrated stormwater runoff from a given site. Methods of disconnecting impervious areas are presented as follows (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.

The impact on stormwater runoff from a MD/MM design approach compared to a conventional design approach is highly variable by site, and is difficult to quantify. Even when MD/MM practices are implemented, peak post-development runoff rates must be examined and measures taken to ensure they do not exceed ordinance-based target rates. This may include the use of conventional, structural BMP measures capable of detaining and/or infiltrating runoff from the developed site. However, the employment of MD/MM design will inherently reduce the number and size of detention practices required to achieve allowable runoff rates from a site. Because the primary objective of MD/MM design is to maximize retention of natural vegetative cover on a site, the post-development curve number (CN) will be less than if conventional site development methods were employed. Even if a site's native vegetation is nothing more than "scrub" growth or meadow, it will exhibit a lower post-development CN than if the site were cleared, graded, and then revegetated in the form of a 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 less than ideal permeabilities 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. Additional research found that the concentration of phosphorus in urban lawns was higher than any other non-point source. In addition to fertilizers, the application of pesticides to developed landscape areas presents a significant problem for aquatic biota. Storm events occurring shortly after the application of these types 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 BMP measures to control runoff quality and quantity, the benefit to cost ratio of such a design strongly supports its implementation. In situations where a conventional BMP measure or measures must be implemented alongside MD/MM features, such an analysis is difficult to make. However, when site aesthetics and the reduced amount of site work (site clearing, grubbing, rough and fine grading, and final landscaping) for an MD/MM design are considered, research shows that the benefit to cost ratio of an MD/MM approach is significantly greater than that of a conventional site design. By retaining natural areas on a site, which in turn can be used for stormwater management, additional cost savings result. During construction operations, an MD/MM design approach is highly favored over a conventional approach because of the reduced need for erosion and sediment control features such as silt fence, sediment traps and basins, and storm drain inlets. When long-term site maintenance and operations costs are considered, the MD/MM design approach demonstrates even more compelling cost benefits. Studies reveal that maintenance costs for a typical developed site, such as mowing and fertilization, can range from $1,000-$5,000 per year (DEDNREC, September 1997). If commercial services are employed to fulfill these needs, the costs can increase considerably. The elimination or significant reduction in these costs arising from an MD/MM design makes the approach quite appealing to developers and land owners.

B.14 Low Impact Development Strategy – Rainwater Capture and Reuse

Capture and Reuse BMP 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 capture and reuse systems is typically not found in highway settings. In addition to reducing stormwater runoff, the intercepted water is ideal for fire protection and irrigation. (PADEP, January 2005) 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 employed as storage for fire protection, the storage volume is dictated by applicable codes. The design and sizing of vertical storage units and fat downspouts must be accomplished by working closely with both the architect and structural engineer.

The first step when considering a capture and reuse 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 capture and reuse 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 C: Data Summary – National Pollutant Removal Database, 2000

Table C.1 – NPR Database Summary – Extended Dry Detention Pond

Extended Dry Detention Pond						
			% Mean Removal Efficiency			Calc. Method
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**	
Oakhampton, MD	16.8	9	87	26	-	O
Maple Run, TX	28	17	30	18	35	O
Hawthorn Ditch, OR	512	11	47	21	-	O
London Commons, VA	11.4	27	51.5	48	42.5	O
Stedwick, MD	34	25	70	13	24	O
Greenville, NC	200	8	71	14	26	M

Table C.2 – NPR Database Summary – Wet Pond

Wet Pond						
			% Mean Removal Efficiency			Calc. Method
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**	
Davis, NC	1258	22	60.4	46.2	16	M
Piedmont, NC	1220	25	19.6	36.5	35.1	M
Woodhollow, TX	381	14	54	46	39	O
EG Business Park, WA	320	18	87	79	-	C
Harding Park, Ontario	41.5	10	80	37	28	C
Lake Tohopekaliga, FL	75	6	-	85	-	C
?, TX	12	17	83	52	55	C
East Barrhaven, Ontario	2139	-	52	47	-	O
Kennedy-Burnett, Ontario	395	6	98	79	54	O
Ontario	860	5	82	69	-	O
Tampa, FL	6.5	20	69	75	28	M

Table C.2 Cont'd.						
			% Mean Removal Efficiency			Calc. Method
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN	
Tampa, FL	-	21	71	62	-	M
Rouge River, Ontario	320	18	87	79	-	M
Wisconsin	238	-	90	65	-	O
St Elmo, TX	27.1	5	93	87	50	C
Washington	98.8	17	61	19	-	C
Timbercreek, FL	122	9	68	55	12	C
Florida	26.3	6	54	69	-	M
West Pond, MN	76	8	65	25	-	M
Buckland, CT	20	7	61	45	-	M
Westleigh, MD	48	32	81	54	37	O
Grace Street, MI	-	18	32	12	6	O
Unqua, NY	-	8	60	45	-	O
Waverly Hills, MI	-	29	91	79	62	O
Michigan	4872	6	32	18	-	O
Lake Ellyn, IL	-	23	84	34	-	O
Florida	41.6	22	54	30	16	C
Seattle, WA	-	5	86.7	78.4	-	O
Washington	1.8	5	99	91	-	O
Mercer, WA	7.6	5	75	67	-	O
St Joes Creek, FL	1280	6	45	45	-	O
Heritage, Park, Ontario	130	11	80	80	-	M
Florida	41.6	11	83	37	30	M
McCarrons, MN	583	21	93	79	76	M
Lake Ridge, MN	315	20	90	61	41	O
McKnight, MN	725	16	85	48	30	M
Burke, VA	27.1	29	-33	39	32	O
Virginia	51.4	-	85	86	34	O
Shop Creek, CO	437	11	62	36	-	M
Lakeside Pond, NC	65	11	93	45	-	M

Table C.3 NPR Database Summary – Infiltration Trench

Infiltration Trench						
			% Mean Removal Efficiency			
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN	Calc. Method
Blacksburg, VA	-	-	-	4.5	3.4	C
Blacksburg, VA	-	-	-	100	50.5	C
Blacksburg, VA	-	-	-	100	42.3	C

Table C.4 NPR Database Summary – Porous Pavement

Porous Pavement						
			% Mean Removal Efficiency			Calc. Method
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN	
Prince William, VA	-	13	82	65	80	M
Rockville, MD	-	-	95	65	85	M
Cottage Lake, WA	-	9	97	94	-	O

Table C.5 NPR Database Summary – Extended Detention Constructed Wetlands

Extended Detention Wetlands						
			% Mean Removal Efficiency			Calc. Method
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN	
Mays Chapel, MD	97	-	24	16	-	O
Clear Lake, MN	1070	-	76	54	-	O
Tanner's Lake, MN	413	10	62	24	36	O
Ben Franklin, VA	40	23	62	76	76	M
Lake Jackson, FL	2230	-	96	90	75	O
FDOT, FL	41.6	22	-24	-9	-25	C
Long Lake, ME	18	11	95	92	-	O
Auckland, New Zealand	24	6	78	79	-	M
Florida	41.6	11	61	33	13	M
Greenwood, FL	522	11	68.3	61.5	-11	M
McCarrons, MN	608	21	96	70	58	M
McCarrons, MN	736	35	66	4	33	M
Carver Ravine, MN	170	15	46	24	15	O
Shop Creek, CO	550	36	72	51	19	O

Table C.6 NPR Database Summary – Bioretention

Bioretention / Organic Filter						
			% Mean Removal Efficiency			
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN	Calc. Method
Beltway Plaza, MD	-	15	-	65	49	M
Lake Stevens, WA	0.69	8	48	-78.5	-	C
Wisconsin	0.25	5	98	88	-	C
Texas	1.5	16	84	48	30	C
McGregor Park, TX	-	21	90	73		M

Table C.6 Cont'd.						
			% Mean Removal Efficiency			
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN	Calc. Method
Alabama	-	13	83	-	-	C
Minocqua, WI	2.5	7	85	80	-	C
Washington	73.9	7	95	41	-	C

Table C.7 NPR Database Summary – Vegetated Swales

Vegetated Swale						
			% Mean Removal Efficiency			
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN	Calc. Method
Dayton Avenue, WA	90	8	67.8	4.5	-	C
Mountlake Terrace, WA	15.5	6	83	29	-	C
Mountlake Terrace, WA	15.5	6	60	45	-	C

Table C.8 NPR Database Summary – Stormwater Filters

Stormwater Filters						
			% Mean Removal Efficiency			
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN	Calc. Method
Seton Pond, TX	83	10	98	66	-	M
Joleyville, TX	9.5	16	87	61	32	M
Brodie Oaks, TX	50	17	92	80	71	M
Barton Creek, TX	79	18	75	59	44	M
Highwood, TX	3.1	18	86	19	31	M
Barton Ridge, TX	2.95	8	89	59	17	M
Florida	-	33	98	61	-	M
Barton Creek, TX	80	22	78	27	27	M
Virginia	0.7	20	79	65.5	47	M
Washington	1.5	6	8	20	-	C

Table C.8 Cont'd						
			% Mean Removal Efficiency			
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**	**Calc. Method**
Washington	0.64	14	83	41	-	C
Texas	4.93	8	55	45	15	C
Danz Creek, TX	5.21	10	60	-	-	M

Table C.9 NPR Database Summary – Hydrodynamic Separators

Oil Water Separator						
			% Mean Removal Efficiency			
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**	**Calc. Method**
Maryland	1.01	13	-7.5	-41	-	C
Wisconsin	4.3	45	25	19	-	O

Appendix D: Data Summary – International Stormwater Best Management Practices Database

Table D.1
ISB Database Summary –Extended Detention Pond

Extended Dry Detention Pond					
			% Mean Removal Efficiency		
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**
San Diego, CA	-	12	-14	44	7
Seattle, WA	18	7	-	28	82
Greenville, NC	-	8	75	27	35
Oak Hampton, MD	16.8	10	88	33	9
Escondido, CA	-	15	70	70	25
Bellevue, WA	76	13	-30	-	-
Cerritos, CA	-	11	22	-81	26
Tallahassee, FL	-	4	0	13	0
Encinitas, CA	-	14	2	52	10

Table D.2

ISB Database Summary – Wet Pond

Wet Pond					
			% Mean Removal Efficiency		
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**
DeBary, FL	-	33	99	70	10
Tampa, FL	-	22	59	56	62
Ann Arbor, MI	-	5	0	40	-
Woodbury, MN	-	29	89	44	28
Maplewood, MN	-	28	86	40	26
Orlando, FL	-	12	4	28	12
Tallahassee, FL	-	3	97	75	42

Table D.2 Cont'd.					
			% Mean Removal Efficiency		
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**
Pinellas Park, FL	-	6	-78	40	-42
Jacksonville, FL	-	11	12	-50	-1
Ann Arbor, MI	-	7	42	15	-
Charlotte, NC	-	-	92	37	-
Roseville, MN	-	24	78	31	23
Lansing, MI	-	32	-3	57	30
Austin, TX	-	9	-754	-29	69
Suwanee, GA	-	7	-9	65	20
Ruskin, FL	-	24	51	64	2
Talahassee, FL	-	4	60	48	31
Bellevue, WA	-	12	59	18	-
Madison, WI	-	24	89	60	70
Birmingham, AL	-	6	99	-	-
Birmingham, AL	-	6	65	-	-
Charlotte, NC	-	8	64	29	-
Glen Ellyn, IL	-	16	-31	66	62

Table D.3

ISB Database Summary – Extended Detention Wetlands

Extended Detention Wetlands					
			% Mean Removal Efficiency		
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**
Tampa, FL	15	81	70	62	73
Clinton, MD	100	19	28	-35	-53
Chesterfield, VA	-	7	50	66	-

Table D.3 Cont'd.					
			% Mean Removal Efficiency		
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**
Chantilly, VA	40	34	71	16	-8
Sperryville, VA	-	3	20	32	-
Portland, OR	50	7	84	11	-
Centreville, MD	100	47	72	27	-27
Ann Arbor, MI	-	6	75	46	-

Table D.4

ISB Database Summary – Vegetated Swale

Vegetated Swale					
			% Mean Removal Efficiency		
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**
Cerritos, CA	-	4	30	-649	-
Cerritos, CA	-	4	39	-11	-
Lakewood, CA	-	4	-12	-186	-
Portland, OR	-	4	-15	16	-
Vista, CA	-	5	8	-155	-
Tampa, FL	-	23	18	-19	-29
Austin, TX	-	19	-29	-84	-10
Portland, OR	-	6	44	22	-
Tampa, FL	-	20	70	-79	2.4
Portland, OR	-	6	42	19	-
Charlottesville, VA	-	8	2	-17	-
Carlsbad, CA	-	6	59	-1.1	-
Portland, OR	-	6	-10	5	-
Portland, OR	-	4	70	27	-

Table D.4 Cont'd.					
			% Mean Removal Efficiency		
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**
Downey, CA	-	3	69	-67	-
Seattle, WA	-	8	69	-5	31

Table D.5

ISB Database Summary – Vegetated Filter Strip

Vegetated Filter Strip					
			% Mean Removal Efficiency		
Facility Location	**Contributing Drainage Area (ac)**	**Number of Storms Sampled**	**TSS**	**TP**	**TN**
Sacramento, CA	-	13	57	15	-
San Onofre, CA	-	6	14	-122	-
San Onofre, CA	-	9	37	-118	-
San Onofre, CA	-	10	36	-76	-
Sacramento, CA	-	20	53	32	-
Moreno Valley, CA	-	7	-144	10	-
Sacramento, CA	-	15	64	12	-
Orange, CA	-	6	-8	-106	-
Orange, CA	-	10	-94	-50	-
Orange, CA	-	10	-4	-50	-
San Rafael, CA	-	19	71	-6	-
Orange, CA	-	4	80	-35	-
Orange, CA	-	6	59	-45	-
Shasta, CA	-	15	78	38	-
Moreno Valley, CA	-	8	-295	25	-
Shasta, CA	-	15	92	31	-
Sacramento, CA	-	15	55	35	-

Table D.5 Cont'd.					
			% Mean Removal Efficiency		
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN
Clayton, NC	-	8	83	-4	9
Cerritos, CA	-	6	46	-523	-
Shasta, CA	-	15	41	-498	-
Altadena, CA	-	6	69	-121	-
Shasta, CA	-	15	77	-439	-
Moreno Valley, CA	-	8	-785	-40	-
Orange, CA	-	4	64	-154	-

Table D.6

ISB Database Summary – Surface Sand Filters

Surface Sand Filters					
			% Mean Removal Efficiency		
Facility Location	Contributing Drainage Area (ac)	Number of Storms Sampled	TSS	TP	TN
Norwalk, CA	-	4	93	36	-
Vista, CA	-	9	95	45	-
Whittier, CA	-	10	79	26	-
Monrovia, CA	-	12	87	42	-
Carlsbad, CA	-	8	94	56	-
Tallahassee, FL	-	28	85	75	55
Tallahassee, FL	-	14	96	75	83
Alexandria, VA	-	20	79	67	52
Lakewood, CO	-	3	81	78	-55
Birmingham, AL	-	4	86	-	-
Escondido, CA	-	7	83	49	-

Appendix E: Glossary

AHP – Analytic Hierarchy Process

ASCE – American Society of Civil Engineers

BMP -- Best Management Practice

CWP – Center for Watershed Protection

DDNREC – Delaware Department of Natural Resources and Environmental Control

EDD – Extended Dry Detention

EMC – Event Mean Concentration

FHWA – Federal Highway Administration

HSG – Hydrologic Soil Group

ISBD – International Stormwater Best Management Practices Database

MASTEP – Massachusetts Stormwater Technologies Evaluation Program

MDE – Maryland Department of the Environment

NoVA PDC – Northern Virginia Planning District Commission

NPRD – National Pollutant Removal Database

PADEP – Pennsylvania Department of Environmental Protection

STP – Stormwater Treatment Practice

TARP – Technology Acceptance and Reciprocity Partnership

TN – Total Nitrogen

TP – Total Phosphorus

TSS – Total Suspended Solids

USACE – United States Army Corps of Engineers

USEPA – United Stated Environmental Protection Agency

VADCR – Virginia Department of Conservation and Recreation

WQ_V – Water Quality Volume

VITA

Kevin Young was born in Blacksburg, Virginia in 1974. Kevin is the son of David and Almeta Young. Upon graduating from Blacksburg High School in 1992, Kevin enrolled at New River Community College in the Drafting and Mechanical Design curriculum. Obtaining an A.A.S. degree in 1994, Kevin took a design technician position at Anderson & Associates, Inc. Kevin entered the Civil Engineering program at Virginia Tech in 1996, and graduated with honors in 2000. Holding a B.S., Kevin was promoted to project engineer at Anderson & Associates, Inc. In 2001, Kevin became one of two company-wide hydraulic and hydrology engineers, a position he held until 2003 when becoming a graduate student at Virginia Tech. Kevin is a licensed professional engineer in the Commonwealth of Virginia, and this thesis concludes his requirements for the degree Master of Science.