

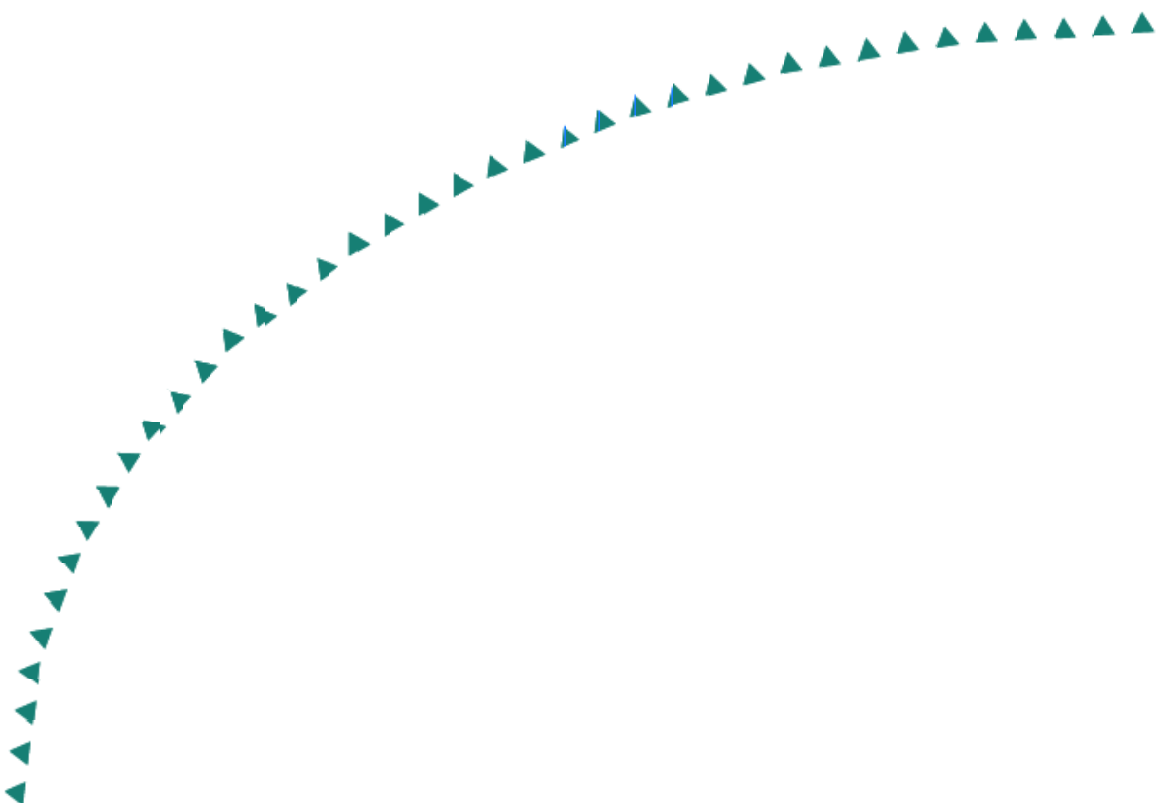
2005-49A

Final Report

**Impact of Alternative Storm Water  
Management Approaches on  
Highway Infrastructure:  
Guide for Selection of Best Management  
Practices – Volume 1**



Research



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**Final Report**

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## **Executive Summary**

It is well-known that storm water runoff from developed areas can degrade the quality of downstream receiving waters in terms of sediment delivery, chemical constituents and elevated water temperature. Storm water runoff volumes and peak flows are also larger from developed areas and this can also adversely impact receiving waters. To protect receiving waters from these negative impacts a variety of storm water best management practices (BMPs) have been developed for use in areas that are already developed and in developing areas. In many instances, storm water BMPs are located adjacent to roadways, some concern has been expressed that these BMPs might have adverse impacts on the roadway function and long-term cost.

The study presented in this report had a goal of evaluating storm water BMPs that are located adjacent to roadway infrastructures. The primary objective was to assess the potential adverse impact of storm water BMPs on the function and long-term operational cost of roadways. A secondary objective was to evaluate a method for assessing the effectiveness of storm water BMPs in controlling storm water runoff volume.

One task of the study was to assess the degree of acceptability of storm water BMPs among professionals most commonly associated with roadway planning, design and maintenance. This assessment was performed through a web-based opinion survey concentrated within the counties of the Twin Cities Metro area. Overall, the conclusion of the survey indicated a high degree of acceptability and satisfaction with the function of storm water BMPs. There was no strong indication that benefits of storm water BMPs are outweighed by the costs.

To evaluate the effectiveness of storm water BMPs with respect to controlling storm water runoff volume, three methods of measuring the infiltration capacities of several types of storm water BMPs were tested in the field. Infiltration measurements, storage capacity, and soil properties were acquired for a total of 24 BMPs. Infiltration capacity data from these measurements were used to assess whether a given storm water BMP would have the capacity to capture and control the volume of storm water generated from a ¼" runoff event. Of the 24 BMPs only six had information about the runoff contributing area. Of these six BMPs two were determined to have insufficient capacity to control the specified runoff volume. Several of the other BMPs characterized were also considered to have insufficient capacity for runoff control because they had persistent standing water, a sign of inadequate capacity.

Cost estimation is a very important step in the decision-making process of any new development. Due to the uncertainty in the data needed to perform an accurate determination of costs, they are estimated in this report following what is known as the top-down approach, which is based on statistical relationships between costs and design parameters, such as the water quality volume or the area of the facility. Maintenance costs are a part of the total costs of a project, and are estimated as a percentage of the construction costs. In order to facilitate comparison between several alternatives, the life

cycle cost of a project is also estimated. The storm water BMPs analyzed include: Dry Ponds, Wet Ponds, Constructed Wetlands, Infiltration Basins, Infiltration Trenches, Sand Filters, Grassed Swales and Bio-retention Areas.

Evaluation of the potential negative impact of storm water BMPs on roadway function and cost was based on the idea that extra moisture introduced into pavement subgrade material from an adjacent BMP would reduce the strength of the pavement foundation, and therefore could decrease pavement life-cycle. This idea was tested in two ways. The first was with observations of pavements in the field using the Mn/DOT distress index represented by the surface rating index (SR). Field measurements of SR's for 45 pavement sections located adjacent to BMPs were compared to control sections (located far from BMPs). Statistical analysis of these data indicated that the BMPs had no measurable adverse effect on the investigated pavements. The limitation of this analysis was that many of the investigated pavements were fairly recently overlaid and therefore it is possible that visible stress might not have had time to be manifested. Field observations should continue to be taken in the future to determine whether pavement stress can be related to the presence of BMPs.

The second way to evaluate the potential negative impact of BMPs on roadways was to use the Mn/DOT pavement design and performance model, MnPAVE. This model allows the direct calculation of pavement longevity as related to subgrade properties. Subgrade moisture content influences pavement foundation strength, and therefore it was possible with MnPAVE to model the tie between a potential increase in moisture content to pavement life-cycle conditions. Within this part of the project it was shown that increases in moisture content, whether from BMPs or other sources of moisture, can significantly reduce a pavement's life-cycle. This reduction leads to an increase in long-term costs for construction and maintenance. Additional work is needed to acquire observations of subgrade moisture contents to determine whether BMPs actually increase subgrade moisture contents in comparison to control sections.



# Chapter 1

## Introduction

### 1.1 Overview of Practices

Storm water management is a key issue in any operation and maintenance program of the Minnesota Department of Transportation not only because highway infrastructure represents a substantial portion of the total impervious areas that generate stormwater runoff, but also because the heavy traffic is a significant source of pollution that affects runoff water quality and, therefore, downstream water bodies (Arika et al, 2005). In northern states additional sources of pollution arise due to the fact that during the cold months of the year, products are applied to pavement surfaces to de-ice them and these products can end up in surface runoff water. Storm water Best Management Practices (BMPs) are practices, techniques, and measures that prevent or reduce water pollution from non-point sources by using the most effective and practicable means of achieving water quality goals (MPCA, 2000). BMPs include, but are not limited to, structural and nonstructural controls, and operation and maintenance procedures (e.g., street sweeping). They temporarily detain and treat storm water runoff in order to control peak discharge rates and reduce pollutant loadings. The mechanisms for pollutant removal are based on gravity, settling, infiltration, adsorption, and biological uptake. Typical BMPs include dry ponds, wet ponds, infiltration trenches, infiltration basins, constructed wetlands, grassed swales, bioretention cells, sand filters, porous pavements, and others (Canelon and Nieber, 2005).

### 1.2 Value of Use

Storm water BMPs have been developed and refined to mitigate some, if not all, of the adverse hydrologic and water quality impacts associated with any kind of development, or redevelopment activity. The capabilities of each BMP are unique. This needs to be recognized along with limitations, and these factors, in addition to the physical constraints at the site, need to be judiciously balanced with the overall management objectives for the watershed in question. At a minimum, a BMP program developed for a site should strive to accomplish the following set of goals (USEPA, 2004a):

1. Reproduce, as nearly as possible, the natural hydrological conditions in the stream prior to development or any previous human alteration.
2. Provide a moderate-to-high level of removal for most urban pollutants as one of a set of BMPs in the watershed working together to achieve desired receiving-water quality.
3. Be appropriate for the site, given physical constraints.
4. Be reasonably cost-effective in comparison with other BMPs.

5. Have a neutral impact on the natural and human environment.

### **1.3 Pervasiveness of Use within U.S.**

For many years, federal and state regulations for storm water management efforts were oriented towards flood control with minimum measures directed towards improving the quality of storm water such as sediments and erosion control and the reduction of pollutants (USEPA, 2004a). The United States government, however, recognized the problem of diffuse pollution many years ago and established provisions in a major amendment to the Clean Water Act in 1987, leading to national programs of action to address the issue. The increased awareness of the need to improve water quality in the last two decades resulted in the concept of storm water BMPs, which refers to operational activities, physical controls or citizen volunteer measures that are applied to reduce the discharge of pollutants and minimize potential impacts upon receiving waters. As a result of the statutes that have been passed and adopted, storm water BMPs are being applied increasingly in developed areas, and in many instances those BMPs are applied adjacent to roadway infrastructure. Naturally, there is some concern, especially among those responsible to maintain the infrastructure that those BMPs might adversely impact the roadway due to the storm water that is held, treated and conveyed by those BMPs.

### **1.4 Costs for Capital Investment and Maintenance**

Storm water BMPs constitute an important item in the general cost structure for any new development or reconstruction of highway infrastructure. They may represent a considerable increase in capital costs if compared to the conventional curb-gutter-sewer approach for storm water management. The estimation of capital costs depends upon the type of BMP under study, and there are several methods available to do it (Mn/DOT, 2005; Canelon and Nieber, 2005). Storm water BMPs also require maintenance programs in order to work properly throughout their scheduled life. The estimation of costs for maintenance is also based on the type of BMP and usually represents a fraction of the investment cost.

### **1.5 Outline for this User Guide**

Chapter 2 describes storm water BMPs in some detail, along with considerations about the selection process for each based on several applicability and performance criteria, such as overbank flood protection and channel protection, groundwater recharge, community acceptance, and pollutant removal. The subject of storm water BMPs maintenance is also treated in that chapter.

Chapter 3 deals with cost estimation of storm water BMPs. Construction costs and maintenance costs are discussed as integral parts of the total life-cycle costs. The estimation of construction costs is made by using equations that relate construction cost

and water-quality volume, which is discussed briefly. The estimation of the maintenance costs, as well as other types of costs, is based on the construction costs.

Chapter 4 describes and presents the conclusions of a survey that was conducted to better understand the perceptions of individuals for employing storm water BMPs for water quality protection. These perceptions were solicited from a range of individuals engaged in the design and maintenance of highway and public utility infrastructure in the metropolitan Twin Cities region of Minneapolis-St. Paul, Minnesota.

Finally, Chapter 5 describes and presents the conclusions of a study conducted using two well-known tools that were applied to evaluate the potential negative impact of storm water BMPs located adjacent to highway infrastructures. The tools used were the Surface Rating (SR) index and the MnPAVE model.

A second volume to this final report contains detailed information about the individual task studies performed in completing the objectives of this research project. A number of citations to that second volume are found throughout the presentations given in the following chapters.

## Chapter 2

### Description of Practices

#### 2.1 Concepts/function

According to the Center for Watershed Protection (CWP, 2000), storm water BMPs can be grouped into five major categories: storm water ponds, storm water wetlands, infiltration practices, filtering practices, and open channels. Within each category, there are several design variations. The following description of common BMPs, including all the pictures and schematics, is based on the report from Sykes et al. (2005).

##### 2.1.1 Rain Gardens

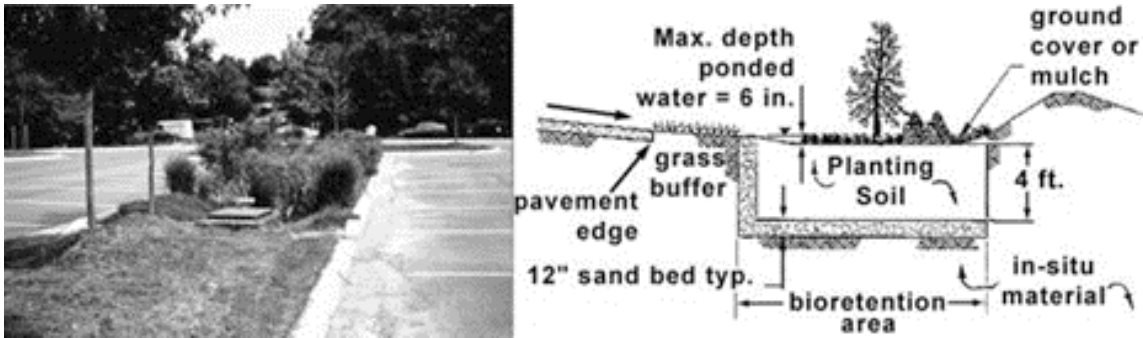
A rain garden (Fig. 2.1) is a small, shallow, normally dry basin, constructed to capture runoff and treat it by exposing it to plant use and infiltration. The floor of the basin is usually planted with a community of plants selected to provide a high degree of plant uptake of water and nutrients, and to promote infiltration. Rain gardens are typically not hydraulically designed, and do not have the constructed artificial soil-profile associated with bioretention. Water outflow is by deep percolation.



**Figure 2.1** Pictures of Rain Gardens

##### 2.1.2 Bioretention Areas

A bioretention area (Fig. 2.2) consists of a shallow, normally dry basin that is designed to capture the first flush of runoff and pass it through a constructed artificial-soil profile two-to-five feet deep put in place beneath the floor of the basin to filter and clean it. The floor of the basin is usually planted with a community of plants selected to provide a high



**Figure 2.2** Picture and Schematic of a Bioretention Area

degree of plant uptake of water and nutrients in addition to the filtering effect of the soil profile. It is hydraulically designed to bypass flows in excess of its treatment capacity. Water leaving the bottom of the soil profile is typically picked up by an underground drain system of perforated pipe and directed to a surface water body. Alternatively, cleaned runoff may be allowed to percolate into undisturbed soil beneath the artificial-soil profile without the presence of an underground drain system.

### 2.1.3 Dry Ponds

A dry pond (Fig. 2.3) is a pond that normally drains completely over a specified extended period of time sufficient to remove settleable pollutants to acceptable levels of concentration. An extended dry detention basin may or may not include features to provide flood-control functions.



**Figure 2.3** Picture of a Dry Pond

### 2.1.4 Wet Ponds

A wet pond (Fig. 2.4) is a pond that normally has water in it and is designed to slowly release water over a specified period of time sufficient to remove settleable pollutants to acceptable levels of concentration. It requires an outlet structure that controls the release velocity of water from the target storm, and enables larger storms to be released at higher rates. A wet pond may or may not include features to provide flood-control functions.



Figure 2.4 Pictures of Wet Ponds

### 2.1.5 Constructed Wetlands

A constructed wetland (Fig. 2.5), also known as storm water wetland, is an artificial wetland specifically constructed to treat runoff water by removing pollutants by sedimentation, plant filtration and plant uptake. It may or may not be an open-water wetland.

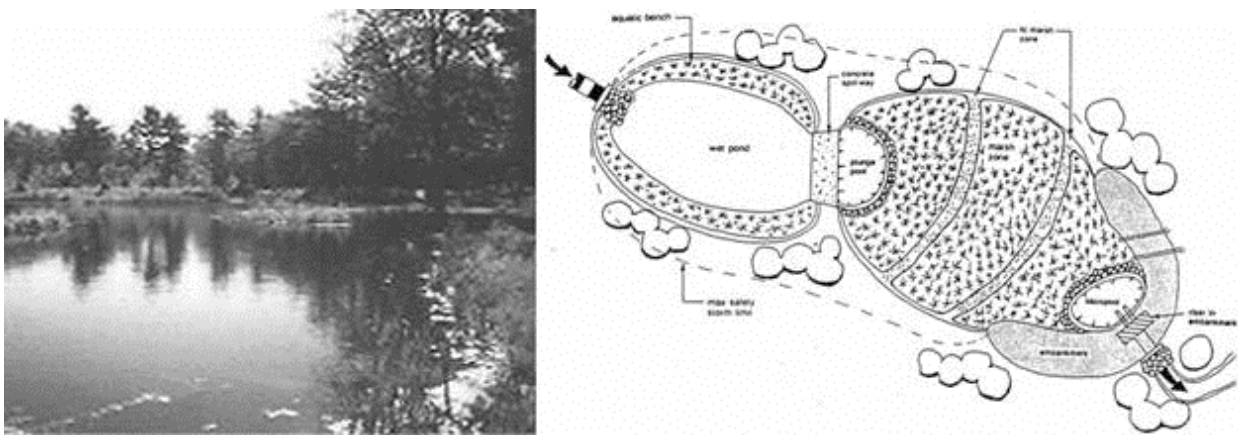


Figure 2.5 Picture and Schematic of a Constructed Wetland

## 2.1.6 Grassed Swales

- Dry Swales

A dry swale (Fig. 2.6a) is a normally dry, vegetated, earth-lined channel constructed to convey runoff flow from specific design storms from one place to another. A dry swale reduces pollution in runoff by passing flows from first-flush runoff in close contact with vegetation leaf and root structures, and by allowing water to infiltrate into the ground as it flows downstream.



**Figure 2.6a** Picture and Schematic of a Dry Swale

- Wet Swale

A wet swale (Fig. 2.6b) is a vegetated, earth-lined channel that normally has standing water in its bottom. It is constructed to convey runoff flow from specific design storms from one place to another. A wet swale reduces pollution in runoff by passing flows from first-flush runoff in close contact with vegetation leaf and root structures, by allowing water to infiltrate into the ground as it flows downstream, and by settling action.



**Figure 2.6b** Picture and Schematic of a Wet Swale

### 2.1.7 Infiltration Trenches

An infiltration trench (Fig. 2.7) is a shallow trench excavated in undisturbed soil to accept runoff and infiltrate it into the soil. The trench is filled with drainage rock or stone to create an underground reservoir. The reservoir should be shielded with geotextile wrapping to prevent sediment from migrating into it. It may or may not have a sacrificial layer on top of it made of pea gravel or other rock to trap oils, sediment and trash.

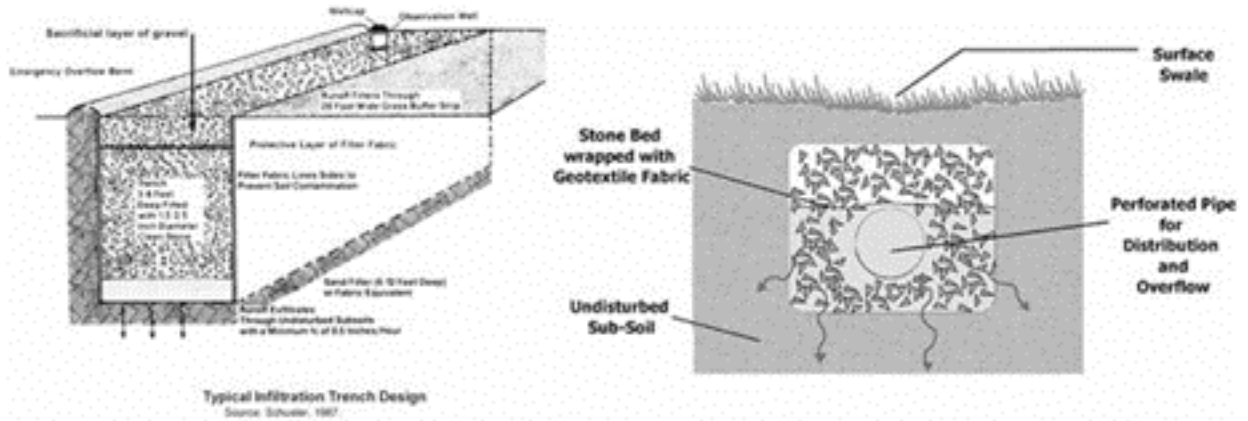


Figure 2.7 Schematics of an Infiltration Trench

### 2.1.8 Infiltration Basins

An infiltration basin (Fig. 2.8) is a normally dry depression or basin constructed in undisturbed soil to capture and infiltrate the first flush of storm water runoff into the ground. The floor of the basin is typically flat and vegetated with grasses. Flows in excess of the first flush are directed to overflow or otherwise bypass the infiltration basin.

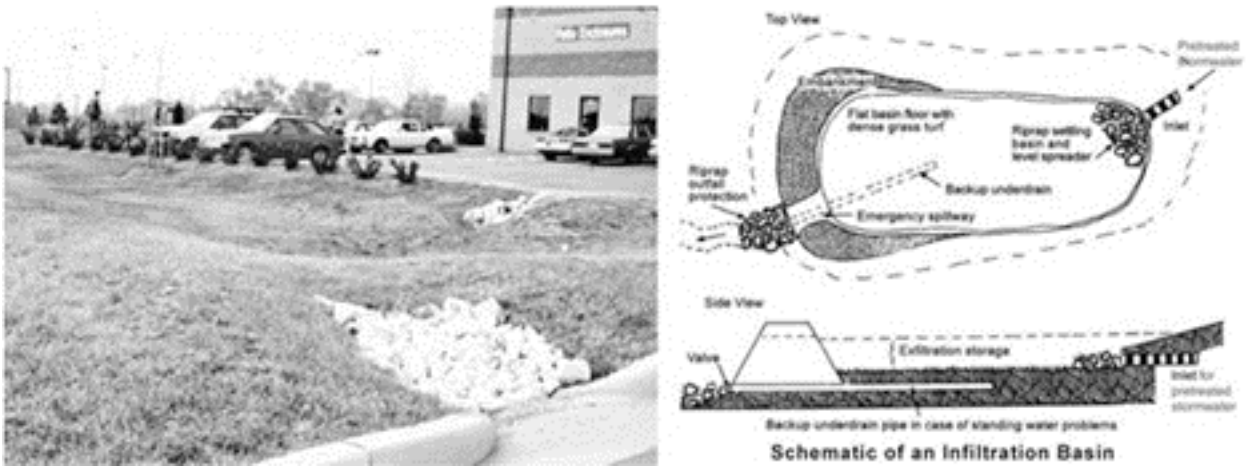
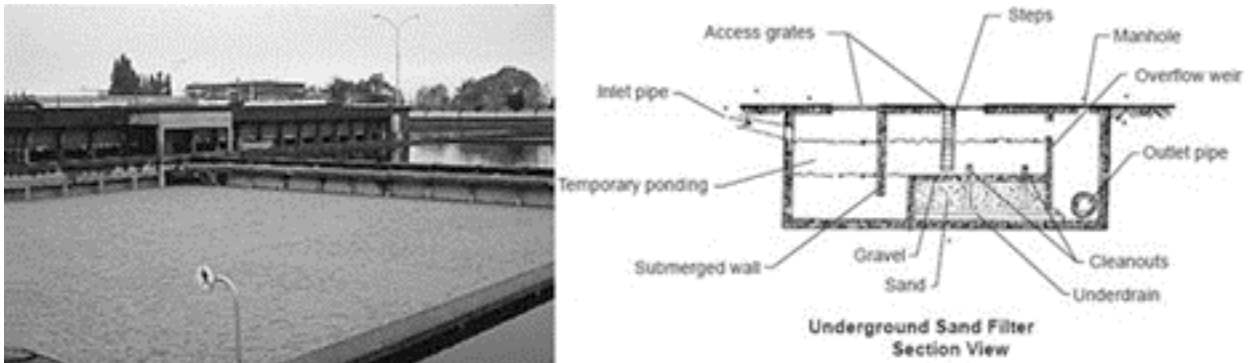


Figure 2.8 Picture and Schematic of an Infiltration Basin



### 2.1.9 Sand Filters

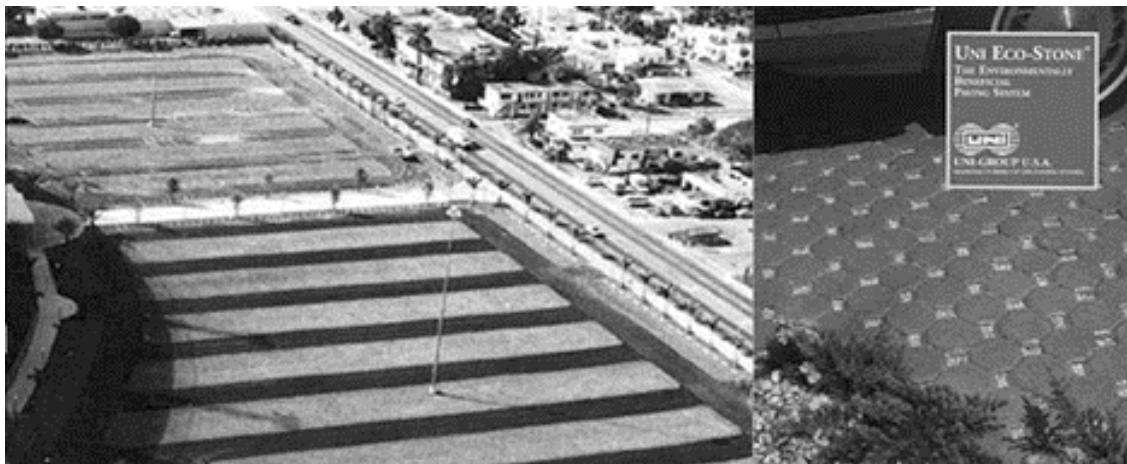
A sand filter (Fig. 2.9) is a device, usually a chamber that cleans runoff water by passing a specified design flow through a bed of sand to reduce the concentration of pollutants to an acceptable level and then discharging it into the surface environment. It may be above ground or below ground and is typically designed to treat the first flush of runoff, bypassing larger flows.



**Figure 2.9** Picture and Schematic of a Sand Filter

### 2.1.10 Porous Pavement

There are nine categories of materials that fall within the definition of porous pavement (Ferguson, 2005). These include porous aggregate, porous turf, plastic geocells, open-jointed paving blocks, open-celled paving grids, porous concrete, porous asphalt, soft porous surfacing, and decks. An illustration of some porous pavement systems is presented in Fig. 2.10. Storm water infiltrates through the porous upper pavement layer and then into a storage reservoir of stone or rock below. Water from the reservoir either percolates into the soil beneath, eventually recharging groundwater, or is collected by a perforated pipe underdrain system and carried to a surface discharge location.



**Figure 2.10** Pictures of Porous Pavements

## 2.2 Design Requirements

The design process of storm water BMPs includes the selection of the BMP that is appropriate for a specific situation, the sizing of the facility, and its cost estimation. Sizing of BMPs is out of the scope of this guide; detailed information about the subject can be found in several publications, such as MPCA (2000), and USEPA (1999, 2004b). Cost estimation will be treated in the next chapter.

### 2.2.1 BMP Selection

BMP selection is a complex process because there are several minimum requirements to take into account and a large number of BMPs to choose from (EPA, 2004b). New BMPs are being developed on a continual basis, and some BMPs are a combination of individual BMPs, e.g., low-impact development techniques. Thus, selection of one or more BMPs appropriate for a particular situation may be a difficult undertaking. Given the large number of choices, the elimination of inappropriate or less cost-effective BMPs through a series of sequential steps will lead to a much smaller list of the most reasonable choices from which a final decision can be made. These steps include:

- Regulatory considerations,
- Site factors,
- Storm water quantity issues,
- Water-quality performance (such as pollutant removal),
- Cost, reliability, and maintenance issues, and
- Environmental and community acceptance factors.

The Minnesota Pollution Control Agency (MPCA, 2000) proposes a methodology to select and implement BMPs on a system-wide, regional, and water-body basis, to meet the system goals. The appropriate measures are selected and implemented after considering a variety of factors, including:

- The characteristics of the resource to be protected
- The feasibility of implementation
- Public demands and governmental requirements.

According to the Center for Watershed Protection (CWP, 2000), the applicability and performance are key factors in the selection process of BMPs. These factors include the following information:

- Any applicable drainage area requirements/constraints.
- Subjective ranking of ease of maintenance, community acceptance, and cost.
- Whether the practice can be used to meet the requirements for groundwater recharge, pollutant removal (based on being able to provide about 80% removal for TSS), channel protection, and overbank flood protection.

- Pollutant removal capabilities for Total Suspended Solids (TSS), Total Phosphorus (TP), and Total Nitrogen (TN), which are commonly found in urban storm water.

Table 2.1 summarizes the methodology proposed by CWP (2000) to assess the applicability and performance of most BMPs, which are grouped into five main categories. Each practice was ranked with a score from 1 (positive) to 5 (negative) indicating how much maintenance is required, the general community acceptance of the practice and the cost of the practice. A lower score indicates either a high benefit or a low drawback, and a higher score indicates either a low benefit or a high drawback.

**Table 2.1** Applicability and Performance of Common BMPs  
(data taken from CWP, 2000)

<b>BMP</b>	<b>DA</b>	<b>CA</b>	<b>MR</b>	<b>CC</b>	<b>Re</b>	<b>Cp</b>	<b>WQ</b>	<b>Qp</b>	<b>TSS</b>	<b>TP</b>	<b>TN</b>
<b>Stormwater Ponds</b>											
Micropool ED Pond	> 10 ac	3.0	3.5	1.0		X	?	X	50	30	30
Wet Pond	> 25 ac	1.5	1.5	2.0		X	X	X	79	49	32
Wet ED Pond	> 25 ac	2.0	2.0	2.0		X	X	X	80	55	35
Multiple Pond System	> 25 ac	1.5	2.0	3.0		X	X	X	91	76	ND
Pocket Pond	< 5 ac	3.0	4.0	1.5		X	X	X	87	78	28
<b>Stormwater Wetlands</b>											
Shallow Marsh	> 25 ac	2.0	3.5	3.0		X	X	X	83	43	26
ED Shallow Wetland	> 25 ac	2.5	3.0	3.0		X	X	X	69	39	56
Pond/Wetland System	> 25 ac	1.5	2.0	3.0		X	X	X	71	56	19
Pocket Marsh	< 5 ac	3.0	4.0	2.0			X	?	57	57	44
Submerg. Gravel Wetland	< 5 ac	4.0	4.0	3.0			X	?	83	64	19
<b>Infiltration</b>											
Infiltration Trench	< 5 ac	2.0	5.0	3.5	X	?	X	?	100	42	42
Infiltration Basin	< 10 ac	4.0	5.0	3.0	X	?	X	?	90	65	50
Porous Pavement	< 5 ac	1.0	5.0	3.0	X	?	X	?	95	65	83
<b>Filtering</b>											
Surface Sand Filter	< 10 ac	2.5	3.5	4.0	X	X	?		87	59	32
Underground Sand Filter	< 2 ac	1.0	4.0	4.5			X		80	50	35
Perimeter Sand Filter	< 2 ac	1.0	3.5	4.0			X		79	41	47
Organic Filter	< 10 ac	2.5	3.5	4.0			X		88	61	41
Pocket Sand Filter	< 2 ac	2.5	4.0	3.0			X		80	40	35
Bioretention Cell	< 2 ac	2.0	2.0	2.5	X		X		ND	65	49
<b>Open Channels</b>											
Dry Swale	< 5 ac	1.5	2.0	2.5	X		X		93	83	92
Wet Swale	< 5 ac	1.5	2.0	2.0			X		74	28	40

In Table 2.1, **DA** is the Drainage Area, **Re** is the Groundwater Recharge Capability, **WQ** is the Pollutant Removal Capability, **CP** is the Channel Protection Capability, **QP** is the Overbank Flood Protection, **TSS** are the Total Suspended Solids, **TP** is the Total

Phosphorus, **TN** is the Total Nitrogen, **M** is the Maintenance score, **CA** is the Community Acceptance score, and **CC** is the Construction Cost score.

As an example of the meaning of the values shown in Table 2.1, a Micropool ED Pond (a storm water pond BMP) meets the criteria for both overbank flood protection and channel protection (**X**), and potentially for water quality (?), but not for groundwater recharge ( ). It has a low construction cost (**1.0**), but is not highly accepted by the community (**3.0**). A micropool ED pond provides roughly 50% TSS removal, and 30% removal for TP and TN.

There are BMPs that do not fully meet water-quality volume requirements by themselves, but can be combined with other management practices to provide groundwater recharge, pretreatment, or water quality volume requirements. Those BMPs are: water quality inlets, dry extended detention ponds, filter strips, grass channels (biofilters), dry wells, and deep sump pits.

Several of the listed BMPs are not currently recommended by CWP (2000), such as conventional dry ponds, porous pavements, oil/grit separators, and infiltration basins. Dry ponds and oil/grit separators were found not to provide meaningful pollutant removal capability, while infiltration basins have been found to have very high rates of failure. Porous pavements were also shown to have high failure rates and maintenance requirements, and cannot be used if sand is applied to the surface for protection against ice in freezing periods. However the CWP study did not distinguish among asphalt porous pavement and other types such as unit paver systems and porous concrete. Porous asphalt has been found to be self sealing over time (CWP, 2000). Sand can be a problem with porous concrete. Neither of these problems has been reported for unit paver systems.

## **2.3 Maintenance Requirements**

According to the State of Rhode Island Storm Water Design and Installation Standards Manual (SRI, 1993), the key to successful long-term operation of storm water BMP facilities is proper maintenance procedures on a regularly scheduled basis. The most carefully designed and constructed storm water BMP will be subject to eventual failure in the event of poor or inadequate maintenance. Failure of a BMP results in costly repairs or replacement of a system, therefore it is imperative that the responsible parties conduct maintenance as provided on the final site development plans. Very often, maintenance of BMPs is incorporated into the state and local approval process for land development. Accordingly, the following recommendations should be adhered to where applicable.

- A maintenance schedule for each type of BMP must be included in the application package and in the final site construction documents.
- An area should be set aside within the development site for the purpose of sediment disposal (where applicable).
- Proper erosion and sediment control practices must be implemented during all phases of construction and until the site is satisfactorily stabilized.

- Grasses (e.g., conservation seed mixture) must be planted around and within basins immediately following construction to stabilize the slopes and prevent erosion.
- Side-slopes, embankments, and the upper stage of basins should be mowed at least once per growing season, to prevent unwanted woody growth.
- All trash and litter and other debris shall be removed from any storm water facility, including inlet and outlet structures.
- Sediments should be removed from any basin immediately following site stabilization and thereafter in accordance with the specific maintenance plan.
- If blockage of a basin outlet structure occurs it may be necessary to dewater the pond for access to the blockage.
- Pools of stagnant water in detention basins indicate failure due to erosion and scouring of the basin bottom, particularly near an inlet device.
- All outlet structures and outflow channels should be inspected annually.
- The grassed areas of any basin should be inspected at least twice per year to check for erosion problems.
- Inspections of all catch basins on-site should occur on an annual basis to check for debris removal (sediment and hydrocarbons) and structural integrity or damage.
- Repairs or replacement of inlet/outlet structures, rip-rap channels, fences, or other elements of the facility should be done within 30 days of deficiency reports.

Best management practices require a variety of periodic maintenance activities in order to enhance performance (USEPA, 2004a). These activities include sediment removal, vegetation maintenance, periodic maintenance and repair of outlet structures if needed, periodic replacement of filter media, and others. Regular inspection of control measures is essential in order to maintain the effectiveness of post-construction storm water BMPs. The inspection and maintenance of BMPs can be categorized into two groups: expected routine maintenance, and non-routine (repair) maintenance. Routine maintenance involves checks performed on a regular basis to keep the BMP in good working order and aesthetically pleasing and is an efficient way to avoid the health and safety threat inherent in BMP neglect (e.g., prevent potential nuisance situations, reduce the need for repair maintenance, reduce the chance of polluting storm water runoff by finding and correcting problems before the next rain). Additional detailed information for each type of BMP regarding reliability, required maintenance activities, recommended maintenance intervals, as well as consequences of failing to perform maintenance can be found in USEPA (2004b).

## Chapter 3

### Cost of Practices

#### 3.1 Introduction

The implementation of BMPs to treat storm water produced by either residential/commercial developments or highway infrastructure is costly. However, these BMPs will provide additional benefits to the less expensive curb-gutter sewer approach because of the removal of pollutants. Several documents that address cost estimating for BMPs have been published; however, most of these reports treat only construction costs (Young et al., 1996); Sample et al., 2003). In addition, costs are often documented as base costs and do not include land costs which, according to the USEPA (1999), is the largest variable influencing overall BMP cost. Land costs are not included in this work.

According to USEPA (2004c), there are four approaches of BMPs cost estimation that are commonly used; they are the Bottom-Up method, the Analogy method, the Expert Opinion method, and the Parametric method. Canelón and Nieber (2005) presented a cost analysis using the Parametric Method, which relies on relationships between cost and design parameters. A summary of that work is presented next.

The elements considered in the analysis are **Total Costs** and **Life-Cycle Costs**. Total Costs include both capital (construction and land) and annual Operation and Management costs. Life Cycle Costs refers to the total project costs across the life span of a BMP, including design, construction, O&M, and closeout activities.

**Capital Costs** are those expenditures that are required to construct a BMP. Typically this can be estimated using equations based on the size or volume of water to be treated, such as  $C = a \cdot P^b$  (USEPA, 2004c; Mn/DOT, 2005).

**Design, Permitting, and Contingency Costs** include costs for site investigations, surveys, design and planning of a BMP. Contingency costs are unexpected costs during construction of a BMP. This type of cost will be estimated as a 32% of the capital costs, which also include erosion and sediment control cost (USEPA, 2004c).

**Operation and Maintenance Costs** are those post-construction costs necessary to ensure or verify the continued effectiveness of a BMP. These costs are seldom estimable on a comprehensive basis and, therefore, have been expressed as a fraction of capital costs. That fraction can vary between 1% and 20%, depending on the BMP under consideration (USEPA, 2004c; Mn/DOT, 2005).

**Land Costs** are site specific and extremely variable both regionally and by surrounding land use. They will not be taken into account in this report.

**Inflation and Regional Cost Adjustments** are needed for inflation and regional differences. For the Twin Cities area, this adjustment factor is approximately 1.04, which comes from the ratio between the regional adjustment factor (1.16) and a precipitation adjustment factor (1.12) (USEPA, 2004c).

**Life Cycle Costs** refer to the total project costs across the life span of a BMP, including design, construction, operation and management (O&M), and closeout activities. They include the initial capital costs and the present worth of annual O & M costs, less the present worth of the salvage at the end of the service life. Life-cycle cost analysis can be used to choose the most cost effective BMP from a series of alternatives so that the lowest long-term cost is achieved. The present worth (PW) of a series of future payments is calculated using the following equation:

$$PW_{\text{total}} = \sum_{t=1}^{i=n} \frac{x_t}{(1+i)^t} \quad (3.1)$$

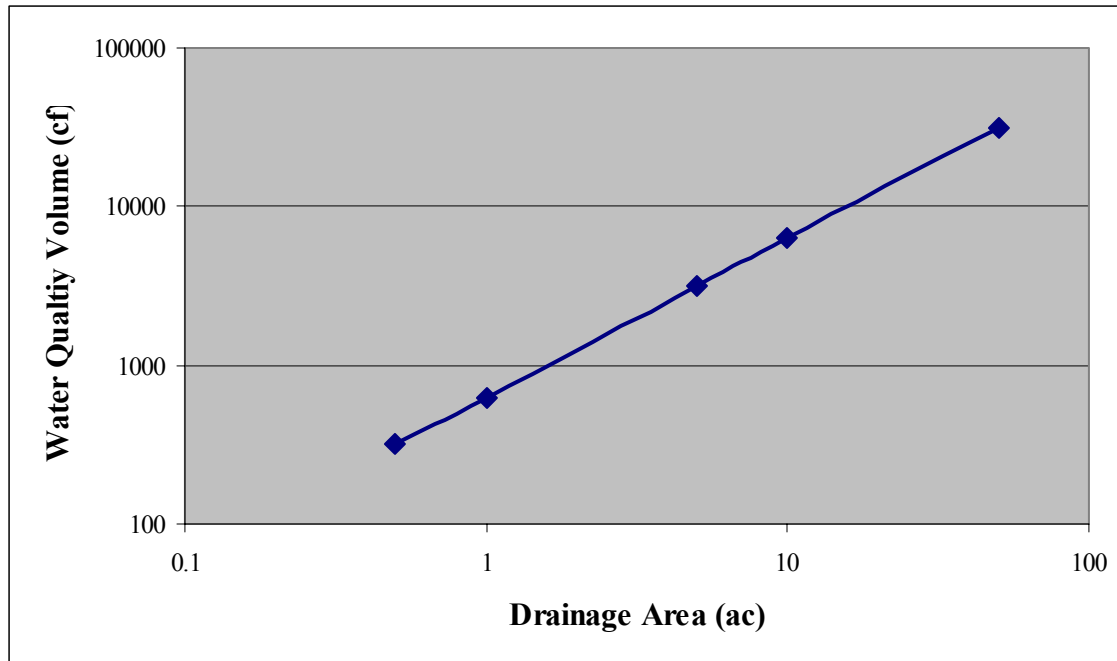
where  $x_t$  is the payment in year  $t$ ,  $i$  is the discount rate and  $n$  is the period of time considered.

### 3.2 Construction Cost

The construction cost of any BMP depends upon the size of the facility, and this size usually is based on the volume of water the facility will treat. This volume of water is called the Water Quality Volume (WQV), and can be calculated as follows (Mn/DOT, 2005):

$$WQV = \left( \frac{43560}{12} \right) \cdot P \cdot R_v \cdot A \quad (3.2)$$

where  $P$  is the design precipitation depth (in),  $R_v$  is the ratio of runoff to rainfall in the watershed, and  $A$  is the watershed area (ac). Figure 3.1 shows the estimation of WQV for a rainfall depth of 1 inch in the Twin Cities area (Canelon and Nieber, 2005).



**Figure 3.1** Water Quality Volume  
(Canelon and Nieber, 2005)

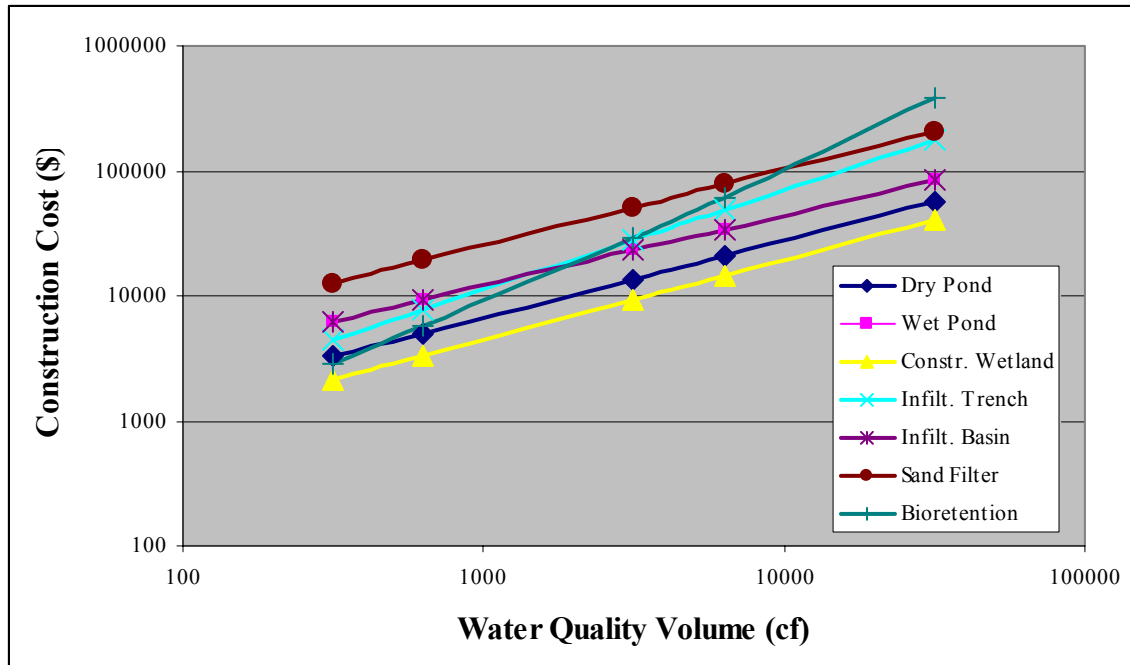
The following equations can be used to estimate construction costs for common BMPs. Data needed to develop them was taken from the excellent work developed by Weiss *et al.* (Mn/DOT, 2005), about the cost and effectiveness of storm water BMPs. The equations presented here correspond to the best fit of the data available; the Mn/DOT, however, also shows values for the 67% confidence interval.

- Dry Pond  $CC = 97.338 \cdot WQV^{-0.3843}$
- Wet Pond  $CC = 230.16 \cdot WQV^{-0.4282}$
- Constructed Wetland  $CC = 53.211 \cdot WQV^{-0.3576}$
- Infiltration Trench  $CC = 44.108 \cdot WQV^{-0.1991}$
- Sand Filter  $CC = 389.00 \cdot WQV^{-0.3951}$
- Bioretention  $CC = 0.0001 \cdot WQV + 9.00022$
- Grass Swales  $CC = 21.779 \cdot \ln(A) - 42.543$

where CC is the construction cost expressed in dollars per unit of water-quality volume (WQV) or BMP area A(ac). More equations can be found in Table 6.1, USEPA (2004c).

Figure 3.2 shows values of construction cost for selected BMPs, related to water quality volume to be treated.





**Figure 3.2** Construction Cost for Selected Storm Water BMPs

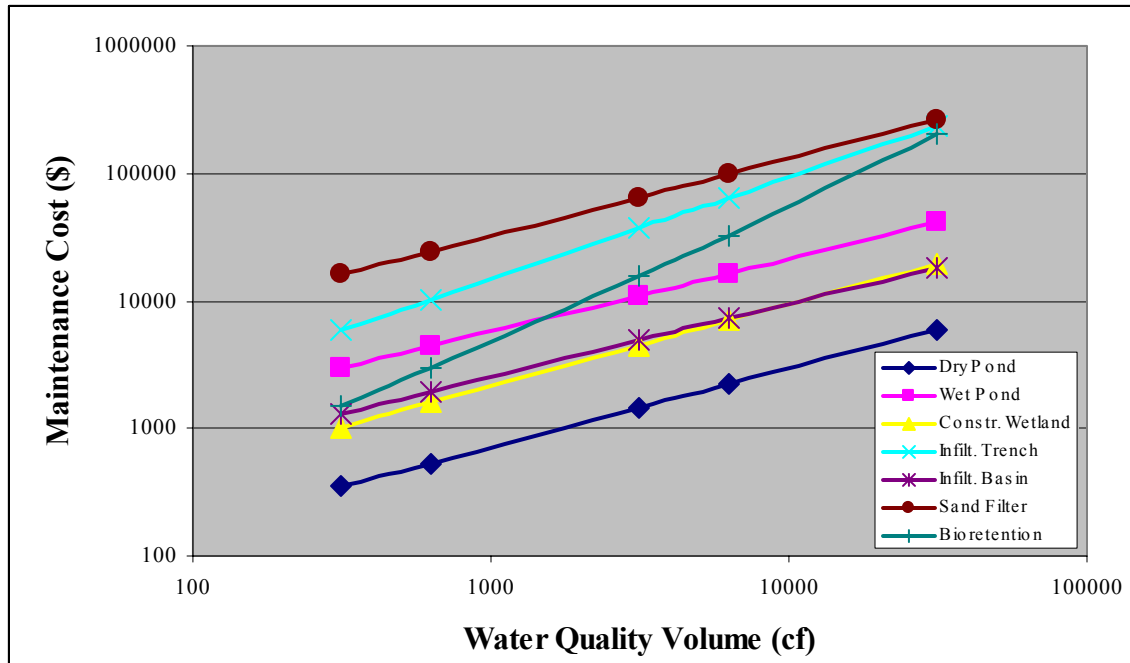
### 3.3 Maintenance Cost

As stated above, maintenance cost is usually estimated as a fraction of construction cost, and this fraction depends upon the BMP under consideration. The annual percentage of construction costs used for common BMPs are as follows (USEPA, 2004c):

- Dry Pond <1%
- Wet Pond 3 to 6%
- Constructed Wetland 3 to 6%
- Infiltration Trench 5 to 20%
- Infiltration Basin 1 to 3%
- Sand Filter 11 to 13%
- Bioretention 5%

Mn/DOT(2005) collected data from several sources and, in some cases, found considerable differences with respect to values from USEPA (2004c).

Figure 3.3 shows values of maintenance cost for selected BMPs, related to water quality volume to be treated. Values for return period of analysis and discount rate were taken from USEPA (2004c).



**Figure 3.3** Present Worth Maintenance Costs for Selected Storm Water BMP, for a period of analysis (n) of 20 years and a discount rate (i) of 7% (Canelon and Nieber, 2005)

### 3.4 Life Cycle Cost

As stated before, life-cycle costs refer to the total project costs across the life span of a BMP, including design, construction, and operation and maintenance costs. As an example, Table 3.1 shows the procedure followed and the values obtained for the life cycle of Dry Ponds; for other selected BMPs, see Appendices A-1 through A-7.

**Table 3.1** Cost Estimation for Dry Ponds, for a period of analysis (n) of 20 years and a discount rate (i) of 7% (Canelon and Nieber, 2005)

<b>BASIC DATA AND EQUATIONS</b>					
<b>LFC = CC + DC + MC</b>		<b>LFC</b> is the life cycle cost (\$)			
		<b>CC</b> is the construction cost (\$)			
		<b>DC</b> is the design, permitting, erosion control, and contingency cost (\$)			
<b>CC = 97.338 Q<sub>v</sub><sup>-0.3872</sup></b>		<b>CC</b> in \$/cf		<b>DC = 32% CC</b>	
<b>MC = 1% CC x MDF</b>		<b>MDF</b> is the multiyear discount factor			
$\text{MDF} = \sum_{t=1}^{t=n} \frac{1}{(i + 1)^t}$		<b>i</b> is the discount rate (fraction) <b>t</b> is the period of analysis (year)			
<b>DRAINAGE AREA</b>					
<b>COST TYPE</b>	<b>0.5 ac</b>	<b>1 ac</b>	<b>5 ac</b>	<b>10 ac</b>	<b>50 ac</b>
<b>Q<sub>v</sub> (cf)</b>	315	630	3151	6302	31511
<b>CC (\$)</b>	3306	5056	13556	20730	55582
<b>DC (\$)</b>	1058	1618	4338	6634	17786
<b>MC (\$)</b>	350	536	1436	2196	5888
<b>LCC (\$)</b>	4715	7210	19330	29560	79257

## **Chapter 4**

### **Survey of Practices in Minnesota**

#### **4.1 Introduction**

In order to help assess the applicability and performance of the storm water BMPs that have been implemented in the State of Minnesota, a survey was conducted (Sykes et al., 2005) in the Twin Cities area. This survey involved responses from a range of individuals engaged in the design and maintenance of highway infrastructure. The idea was to compare the opinions held by those in a position to influence BMP use with respect to their effect on elements of adjacent infrastructure, with the factual information in this regard presented by BMPs under operation. The results obtained represent opinions of BMP performance only, not results of objective measurements of actual BMP performance. Additional information about the survey, as well as a summary of the conclusions obtained with its application, is presented next.

#### **4.2 Survey Design**

The survey was conducted through the use of a world-wide-web-based survey instrument that allowed participants to directly enter their responses with keystrokes or the click of a mouse. To recruit participants, e-mail messages were sent to a list of people gleaned from various sources. The list was constructed to focus on key individuals in public works departments and related organizations with responsibility for, interest in and technical capability to attend to the use of storm water BMPs in the course of their work. The contact list included 105 individuals.

The survey comprised a total of 13 questions grouped in several categories. Questions 1 and 2 were focused on defining the categories of individuals responding based on job type and level. Question 3 identified the specific BMP types that the respondent had critically observed as constructed examples in the field. Questions 4 through 6 were used to further measure observer experience by practice type and to understand the perspective of the observer. Questions 7 through 11 focused on measuring opinions as to impact on adjacent infrastructure and the general quality of BMP design, function and maintenance. Question 12 allowed open-ended comments by the respondents. Question 13 enabled the respondent to allow follow-up contact.

Each of the questions asked in the survey about specific BMP types inventoried responses for fourteen BMP types: Infiltration Basins, Infiltration Trenches, Infiltration Beds, Porous Pavements, Sand Filters, Peat/Sand Filters, Oil/Grit Separators, Dry Swales, Wet Swales, Extended Detention Dry Ponds, Wet Ponds, Bioretention, Rain Gardens, and Storm Water Wetlands. To help insure that the respondents were clear about the definition and use of terms for each BMP, the Web survey provided respondents a web-based mechanism to assess their understanding. The Web site allowed respondents, at any

point in the survey, to select a link to the name of the BMP about which they had a question that gave a definition and showed an image or images of the BMP.

### **4.3 Summary of Conclusions**

The results of the survey are summarized in the following ten statements. Detailed analysis of the results and conclusions are found in Sykes et al. (2005).

1. To the extent sufficient responses were obtained in any single BMP type category to represent a general opinion, the viewpoint represented is that of the most local level of government officials.
2. Individually, only those BMP types that clustered in the “broadest experience” category had a broad enough representation of the response pool (>60% of the respondents) on which to base reasonably reliable conclusions as to general opinion about them.
3. From the responses to question 4, the observers surveyed are generally quite experienced about the design, construction and maintenance issues of the BMP types for which they entered responses.
4. Although the observations were not systematically gathered, the number of observations suggests a very significant depth of experience base is represented in the pool of survey respondents.
5. The base of observations from which respondents formed their opinions of impacts on infrastructure appears to be balanced in terms of BMP proximity to infrastructure element.
6. By a large margin – more than 4 to 1 – opinion represented in this survey regards the group of BMPs surveyed as productive of positive impacts on infrastructure.
7. By a substantial margin (nearly 2:1), opinion represented in this survey regards BMPs as generally NOT productive of negative impacts on infrastructure.
8. Opinion about the quality of the design of BMPs observed can be regarded as positive for BMPs in general. However, with respect to individual BMPs, quality of design varies widely.
9. Opinion about the quality of the functioning of BMPs observed can be regarded as positive for BMPs in general, but slightly less positive than quality of design. However, with respect to individual BMPs, quality of functioning varies widely.
10. Opinion about the maintenance costs associated with BMPs in general leans toward regarding them as acceptable, and in some cases better than average compared with those for the range of typical infrastructure items. Infiltration basins and infiltration beds are notable exceptions to this generalization.

## Chapter 5

### Assessment of Stormwater Practice Effectiveness

#### 5.1 Introduction

The stormwater practices considered in this guide all involve some sort of infiltration as a major part of the operation of the practice. Therefore it is of value to determine how effective a particular practice is in meeting the goal of stormwater control. One approach for evaluating the effectiveness of a particular practice is to measure the infiltration capacity of the soil within the boundaries of the practice. Details of how to perform this infiltration capacity assessment are presented by Johnson et al. (2005). A summary of the approach is illustrated in the following by using a study site. Also illustrated is an analysis of the stormwater capacity of the site. The details of how to perform an assessment of stormwater capacity of a site are given by Johnson and Nieber (2005).

#### 5.2 Measuring Infiltration

One approach to assessing the infiltration capacity of a stormwater practice is to make a number of point-wise measurements of infiltration within the borders of the practice. Naturally, some variability of the infiltration capacity will exist within the borders of a practice due to the variability of soil profile characteristics and surface cover conditions.

Point-wise infiltration capacity can be measured by a number of different methods, but we have attempted to use three methods, including the Guelph permeameter (GP) method, the tension infiltrometer (TI) method, and the Philip-Dunne (PD) permeameter method. Of these three, the Philip-Dunne method is by far the lowest cost and simplest to implement. The PD method will be briefly described here. Details of how to use this method and the other two methods are presented in Johnson et al. (2005).

The tube for the PD method is generally about 15 inches long and 4 inch diameter, and can be composed of acrylic, metal, or PVC material. Prior to running the test the moisture content of the soil near the measurement location is measured gravimetrically. The tube is driven into the soil to a depth of two or three inches. The inserted tube is then filled with water, and the time required for the water level in the tube to reach the half-full point, and the completely empty point is measured. After the infiltration is completed the soil moisture beneath the tube is measured gravimetrically. With these data it is possible to calculate the important properties of the soil related to infiltration capacity, using the following relations,

$$\tau_{\max} = 0.73(t_{\max} / t_{\text{med}}) - 1.112 \quad t_{\max} / t_{\text{med}} < 5.4$$

$$\tau_{\max} = 8K_{f_s} t_{\max} / \pi^2 R$$

$$\log \psi_{\text{wf}} = -13.503 + 19.678(t_{\max} / t_{\text{med}})^{-1/2}$$

$$S = (2K_{f_s} \psi_{\text{wf}} \Delta\theta)^{1/2}$$

$$\Delta\theta = \theta_{\text{post}} - \theta_{\text{pre}}$$

where  $t_{\text{med}}$  is the time when the tube is half empty,  $t_{\max}$  is the time for the tube to empty completely,  $\theta_{\text{pre}}$  is the soil moisture content measured prior to infiltration,  $\theta_{\text{post}}$  is the soil moisture content measured after infiltration,  $K_{f_s}$  is the saturated hydraulic conductivity of the soil,  $S$  is the soil sorptivity, and  $\psi_{\text{wf}}$  is the wetting front suction. While the  $S$  and the  $\psi_{\text{wf}}$  enter into infiltration capacity calculations, for most practical situations it is sufficient to use only  $K_{f_s}$  in assessing infiltration capacity as it will give a conservative value. How to use these parameters in infiltration calculations is described in the next section and in Johnson and Nieber (2005).

Infiltration measurements with the three methods were performed on a total of 24 sites where stormwater control systems were in place. The types of stormwater practices represented included infiltration basins, swales, and rain gardens. As expected, there was a wide range of values of  $K_{f_s}$  determined for these practices. For the PD measurements, the value of  $K_{f_s}$  ranged from 0.362 in/hr to 2.55 in/hr for the infiltration basins, 1.53 in/hr to 4.9 in/hr for the swales, and 1.19 in/hr to 6.02 in/hr for the rain gardens. A sample of the details of information collected at the stormwater practice sites is given in Figure 5.1 for a rain garden located near Como Park. Note that there are large differences between the three methods of measurement. Summary results for other sites studied are presented by Johnson et al. (2005).

### 5.3 Assessing Effectiveness of the Practice

The effectiveness of a stormwater practice is assessed based on how well the practice controls the stormwater runoff that occurs within a design storm event. To perform this assessment it is necessary to know what volume of runoff water is directed into the practice, and how much of that water is infiltrated. The design storm considered for the assessment is that associated with a 1/4" runoff event.

For the rain garden outlined in Figure 5.1, this area accepts runoff from a 3.5-acre watershed. Runoff enters the garden on the west end from a pipe that sends water from the steep-topography above the basin (Nebraska Ave). The garden consists of two separate sections, which are separated by a higher elevation "dike" near the middle of the

Area = 0.08 ha  
 Distance to infrastructure = 10 ft  
 Elevation difference between practice and infrastructure = 2.5-5 ft

Soil texture within practice

Depth	Texture
0-6	Sandy loam
6-12	Sand
12-18	Sand
18-24	Coarse sand and gravel
24-30	Coarse sand and gravel
30-36	Coarse sand and gravel

Soil texture between road and practice

Depth	Texture
0-6	Loam
6-12	Clay loam
12-18	Sand and gravel
18-24	Sand and gravel
24-30	Sand and gravel
30-36	Sand and gravel

<b>Field-saturated hydraulic conductivity</b>	
TI:	2.31E -04 cm/sec = .327 in/hr
PD:	2.93E -03 cm/sec = 4.15 in/hr
GP:	2.00E -03 = 2.83 in/hr
TI:	1.12E -03 cm/sec = 1.59 in/hr
PD:	2.35E -02 cm/sec = 33.3 in/hr

**Figure 5.1** Characteristics of the Rain Garden Located SE of the Lexington Pkwy N and Nebraska Ave Intersection, St. Paul.

practice. Measurements were taken in the west portion where the water enters. Terry Noonan, of the Capitol Region Watershed District, indicated that runoff has never overflowed the dike into the second portion of the rain garden (Terry Noonan, personal communication, 2004). Previous monitoring of the garden has indicated an infiltration rate of about 5 in/hr.

Soil textures within the garden ranged from sandy loam on the surface to coarse sand and gravel below.  $K_{fs}$  values ranged from 0.33 in/hr to 33.3 in/hr from measurements taken with the PD and TI. The highest value (33.3 in/hr) was measured using a PD and was much larger than other measurements, demonstrating the variability of  $K_{fs}$ . The mean value of  $K_{fs}$  for this site was about 9 in/hr. Using this value it is determined that it takes about 0.45 hour to infiltrate the runoff generated on the 3.5-acre area. This practice is considered to be functioning per its intended purpose. This conclusion is confirmed by monitoring results provided by Terry Noonan (personal communication, 2004).



## Chapter 6

### Impacts on Infrastructure

#### 6.1 Introduction

Storm water BMPs have been gaining acceptance both in the State of Minnesota and other states, because they favor infiltration and, therefore, decrease peak flow rates and allow pollutant removal. However, a concern about the use of BMPs, is the possibility that a negative impact on roadway pavement may be produced by BMPs that are located adjacent to the roadways. If the pavements adjacent to storm water BMPs show signs of failure, these failures can possibly be attributed to these facilities. In order to address this concern, Otto and Nieber (2005a, 2005b) conducted a study based on the applications of two well-known procedures to assess road conditions. The first tool was the Surface Rating (SR) index (Mn/DOT, 2003), and the second one was the MnPave model (Chadbourn et al., 2002). A brief description of the study, as well as the conclusions obtained, is presented next.

#### 6.2 The Surface Rating (SR) Index

The details of this study are presented by Otto and Nieber (2005a). A summary of the study and the results and conclusion are presented in the following.

##### 6.2.1 Description

The Surface Rating (SR) index is a crack-and-surface distress index applied by the Minnesota Department of Transportation (Mn/DOT, 2003). The SR uses a rating scale, from 0 to 4, where the highest number indicates the least distress. To evaluate the potential impact of existing storm water BMPs on roadway infrastructure, a total of 45 analyses were completed on roadway pavements adjacent to storm water BMPs. Those BMPs adjacent to roadways included 20 rain gardens, 12 dry swales, 7 infiltration basins, 2 depressed parking lot islands, 2 bioretention facilities, 1 dry pond, and 1 wet pond. To test the possibility that any distress identified was a result of the adjacent BMP and not poor pavement construction or faulty pavement material, each of the 45 pavements adjacent to alternative storm water BMPs was compared to similar, if not identical, pavement with no adjacent BMP (control). The hypothesis to be tested was that there will be no difference between the SR calculated for pavement adjacent to an alternative storm water control facility and the SR calculated for the control.

##### 6.2.2 Results and Conclusions

Many of the SRs calculated, both SR-Adjacent to BMP and SR-Control, were equal to 4.0, the highest value possible for the SR, indicating that there was little or no distress

present. This result might have been expected because many of the pavements analyzed were recently constructed and have not had time to display any surface distresses. The lowest SR value calculated was 2.3 for the SR-Control, at one site, and the corresponding SR-Adjacent to BMP calculated at that site was 2.5 and was for a dry swale.

The data were of a form to allow the testing of the difference between the two treatments (BMP versus control sections). The hypothesis for the test was that the mean of the SR-Difference is not statistically different from zero. The analysis of the data led to acceptance of this hypothesis at a level of significance of  $\alpha = 0.01$ .

Based on the analyses using the Surface Rating pavement quality index and statistical test of the hypothesis developed, there is no impact of existing storm water BMPs on the adjacent roadway infrastructure. However, it should be noted that many of the BMPs used in the study were relatively new and perhaps sufficient time to manifest a negative impact on the pavement had not passed.

### **6.3 The MnPAVE Model**

The details of this study are presented by Otto and Nieber (2005b). A summary of the study and the results are presented in the following.

#### **6.3.1 Description**

The MnPAVE model (Chadborn et al., 2002) is a model typically used by Mn/DOT to design flexible pavements given climatic conditions, pavement structures, material properties, and traffic volumes. The software can also estimate pavement design life for the same inputs. The model was applied in this study in an attempt to evaluate the potential negative impact of existing storm water BMPs on roadway pavements. This was done by modeling the performance of the roadway pavement under a range of possible subgrade moisture conditions that might be experienced if located adjacent to a storm water BMP. In particular, the point of interest is the impact of increased water contents in the pavement subgrade soil due to the proximity of an adjacent BMP.

While there is no direct way to model the effects of increased subgrade soil water contents using MnPAVE, there is the ability to model the effects of variable subgrade soil resilient modulus ( $M_r$ ) on pavement life. The  $M_r$  is a representation of the stiffness of a soil and, as water content increases, the  $M_r$  of most fine-grained soils decreases. Using calculated values of  $M_r$ , MnPAVE was used to perform two separate analyses to determine the effect of increased subgrade soil water contents on pavement life.

#### **6.3.2 Methodology**

The  $M_r$  at optimum water content for four subgrade soil types was calculated as the mean of the  $M_r$  values at the lowest degree of saturation (S) for each subgrade soil type from Drumm et al. (1997). The  $M_r$  at optimum water content for each subgrade soil type was

then modified by increasing the subgrade soil water content in one percent (1%) increments using the resilient modulus gradient of Drumm et al. (1997). Using the Mr values, MnPAVE was used to perform two separate analyses to determine the effect of increased subgrade soil water contents on pavement life. Both analyses were performed in MnPAVE's Research Mode and used MnPAVE's default climatic values for the Minneapolis-St. Paul metro area. The traffic volumes for both MnPAVE analyses were calculated using a First-Year Design Lane Average Annual Daily Traffic (AADT) of 1000 vehicles, design life of 20 years, zero percent (0%) growth rate, and a Low-Volume Traffic-Type Load Spectrum.

For the first analysis, two actual pavement structures adjacent to rain gardens in Maplewood and Lake Elmo, Minnesota, were modeled. The Mr at the various water contents for the four aforementioned subgrade soil types was then input as the Mr for the Engineered Soil in MnPAVE's intermediate design mode to observe the effects on MnPAVE's predicted pavement life.

For the second analysis, a hypothetical pavement structure for each of the four subgrade soil types was designed. These hypothetical pavement structures were designed to have a MnPAVE-predicted design life of 20 years. This was done by holding the thickness of hot mix asphalt (HMA) and engineered soil (EngSoil) constant at 3.5 and 12.0 inches, respectively, and then finding the thickness of aggregate base (AggBase) necessary for MnPAVE to predict a design life of 20 years. The optimum water content Mr for the four classes of engineered soil was used in this procedure.

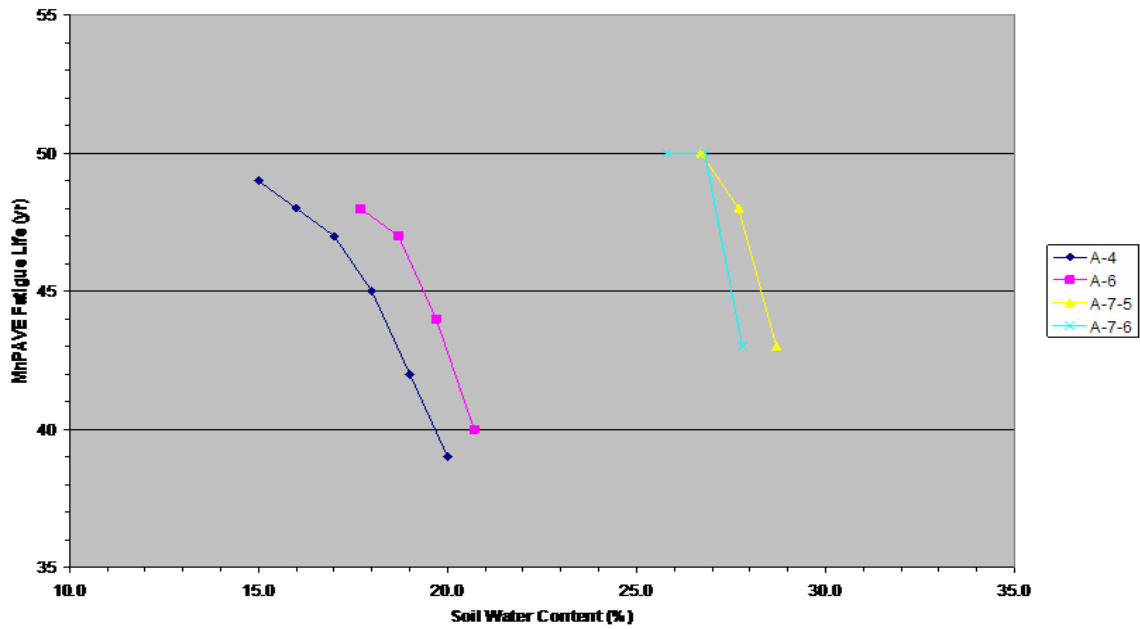
Next, the Mr at the various water contents for the four subgrade soil types from Drumm et al (1997) was applied as the Mr for the Engineered Soil in MnPAVE's intermediate design mode. After that, the HMA layer thickness was increased while holding the AggBase layer thickness constant to observe the HMA layer thickness increase required to maintain a 20-year design life at the various water contents and Mr. The same procedure was performed holding the HMA layer thickness constant and increasing the AggBase layer thickness.

### **6.3.3 Results and Conclusions**

From the results of the first MnPAVE analysis, it can be observed (e.g., Figs. 6.1 and 6.2) that as subgrade soil water content increases and Mr decreases, the fatigue and rutting lives predicted by MnPAVE decrease. On the other hand, from the results of the second MnPAVE analysis, it can be observed that as subgrade soil water content increases and Mr decreases, the thickness of HMA and AggBase required by MnPAVE to maintain a 20 year design life increases (e.g., see Figs. 6.3 and 6.4).

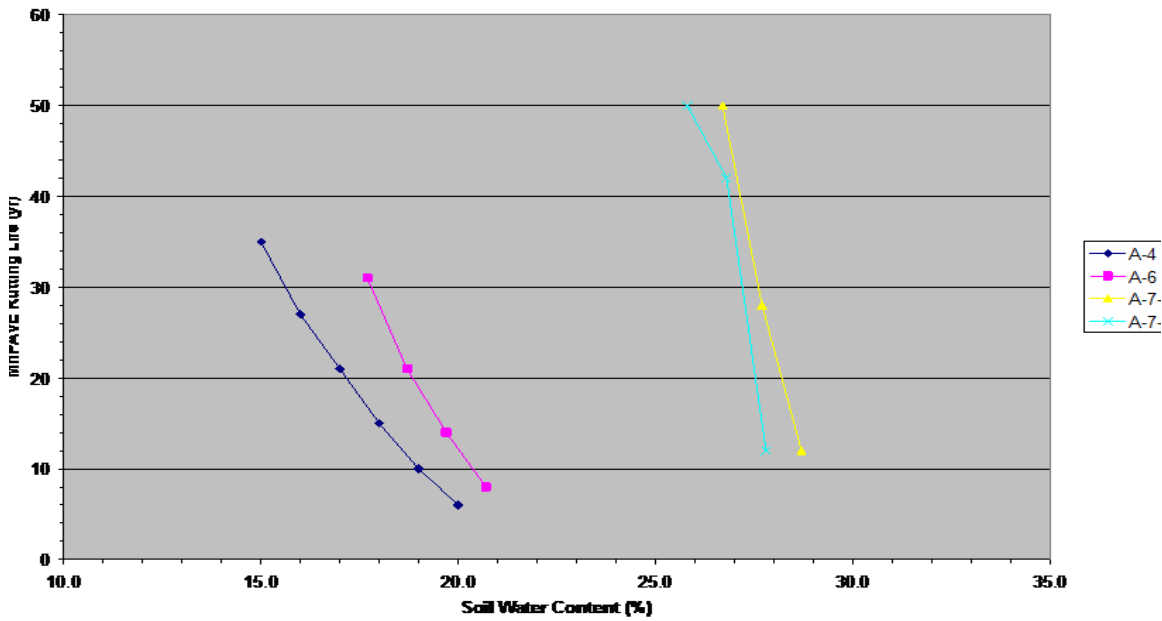
Based on these two analyses using the MnPAVE software, it is possible to conclude that there is the potential for decreased pavement performance, in the form of reduced design life, if the subgrade soil water content is increased. A storm water BMP might increase the adjacent subgrade soil water content and, as a result, be responsible for the potential increase in the cost of maintenance since the road will cost more in order to overcome the

**Effect of Soil Water Content on MnPAVE Fatigue Life-Pavement #1**



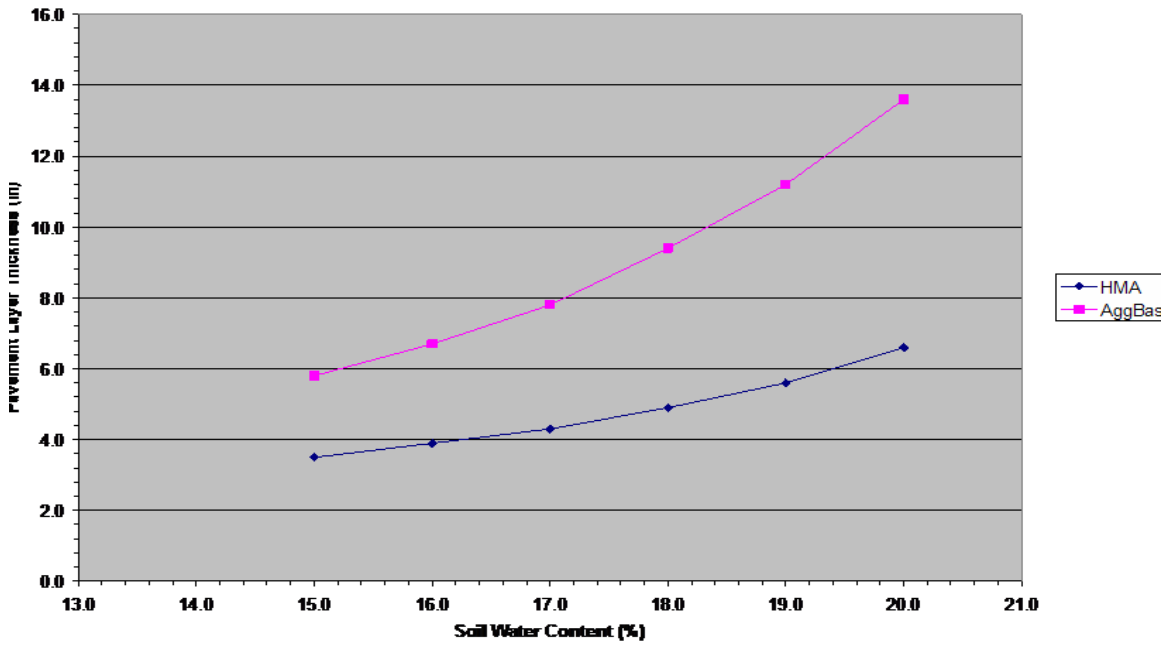
**Figure 6.1** Effect of Soil Water Content on MnPAVE Fatigue Life – Exp. 1 (Otto and Nieber, 2005b)

**Effect of Soil Water Content on MnPAVE Rutting Life-Pavement #1**



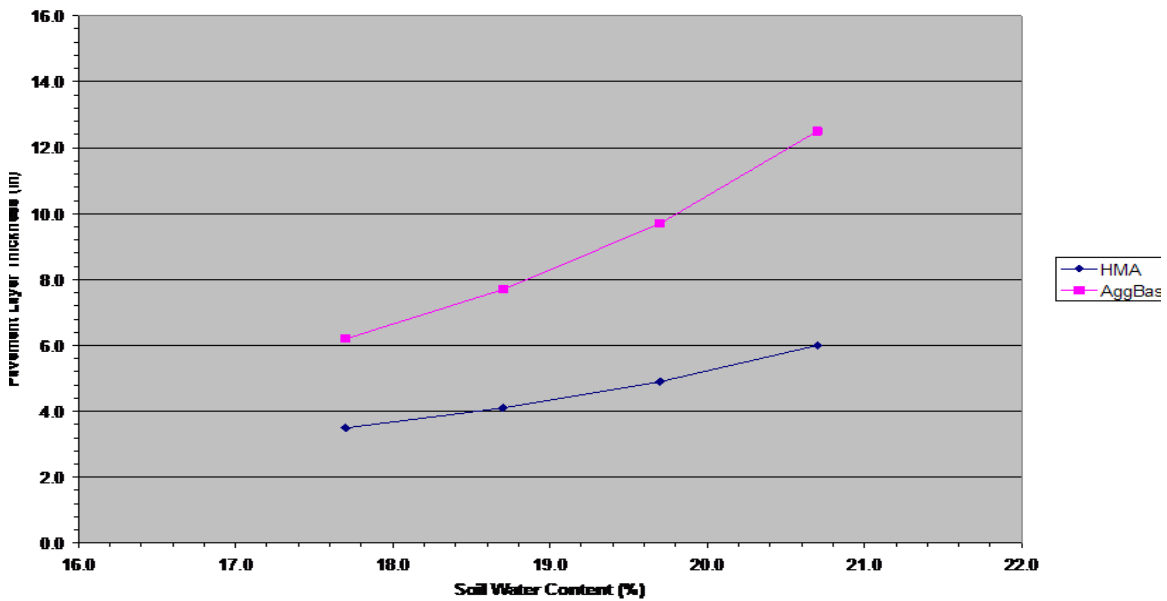
**Figure 6.2** Effect of Soil Water Content on MnPAVE Rutting Life – Exp. 1 (Otto and Nieber, 2005b)

**Effect of Soil Water Content on MnPAVE Pavement Layer Thickness-AASHTO A-4 Soil**



**Figure 6.3** Effect of Soil Water Content on MnPAVE Pavement Layer Thickness-AASHTO A-4 Soil (Otto and Nieber, 2005b)

**Effect of Soil Water Content on MnPAVE Pavement Layer Thickness-AASHTO A-6 Soil**



**Figure 6.4** Effect of Soil Water Content on MnPAVE Pavement Layer Thickness-AASHTO A-6 Soil (Otto and Nieber, 2005b)

limitations of the higher moisture content. However, no field data were collected within this study to allow the testing of this simulated result. Additional work will be necessary to further test this idea in the field.

#### 6.4. Estimating the Cost of Infrastructure Impact

The increase in pavement maintenance costs due to the potential increase in water content caused by a BMP located adjacent to the pavement can be estimated based on the increase in overall construction costs. Three alternative approaches are suggested for making this estimate of cost increase, and these are described in the following.

**Approach 1:** To install tile drains in the vicinity of the BMPs adjacent to roads, either edge drains or centerline drains. By doing this, the water content of the subgrade material will not increase due to the presence of the BMPs. Alternatively, an impermeable barrier could be constructed between the pavement and the BMP to prevent the water from flowing into the subgrade material. The construction cost of the road will increase because of installation cost of the drains or the barrier.

**Approach 2:** To increase the thickness of the pavement to avoid decrease in both the Fatigue Life and the Rutting Life of the pavement. By doing this, the estimated lifetime of the road will not decrease even if water content increases. The construction cost of the road will increase because more material is needed to build it.

**Approach 3:** To estimate the decrease in fatigue life of the road due to the increase in water content in the subgrade material. By doing this, it will be possible to determine the actual lifetime of the road and, therefore, forecast how often the pavement needs to be replaced. The construction cost will increase, in the long term, because the pavement will be replaced more frequently than would be required if the moisture content were not affected.

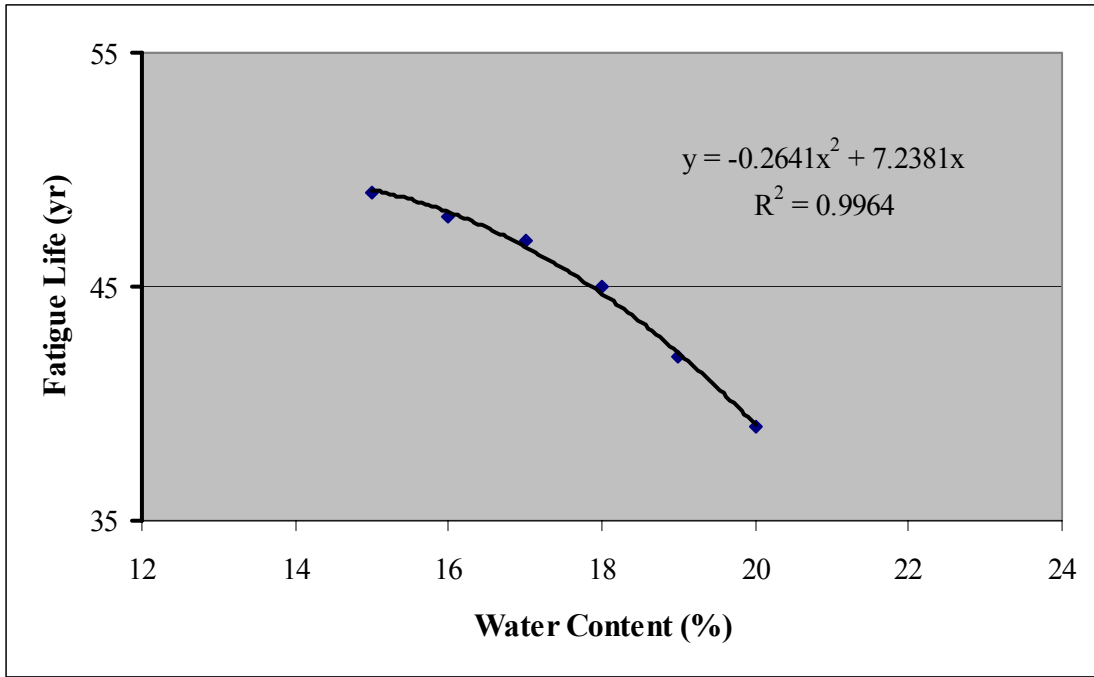
In the following analysis, the cost estimate of BMP impacts will be based on the use of Approach 3.

From Otto and Nieber (2005b) it can be observed that the fatigue life of the road decreases consistently when the water content of the subgrade increases (Fig. 6.5). In other words, any relative increase in water content of the pavement subgrade can be associated with a relative decrease in fatigue life of it (Fig. 6.6).

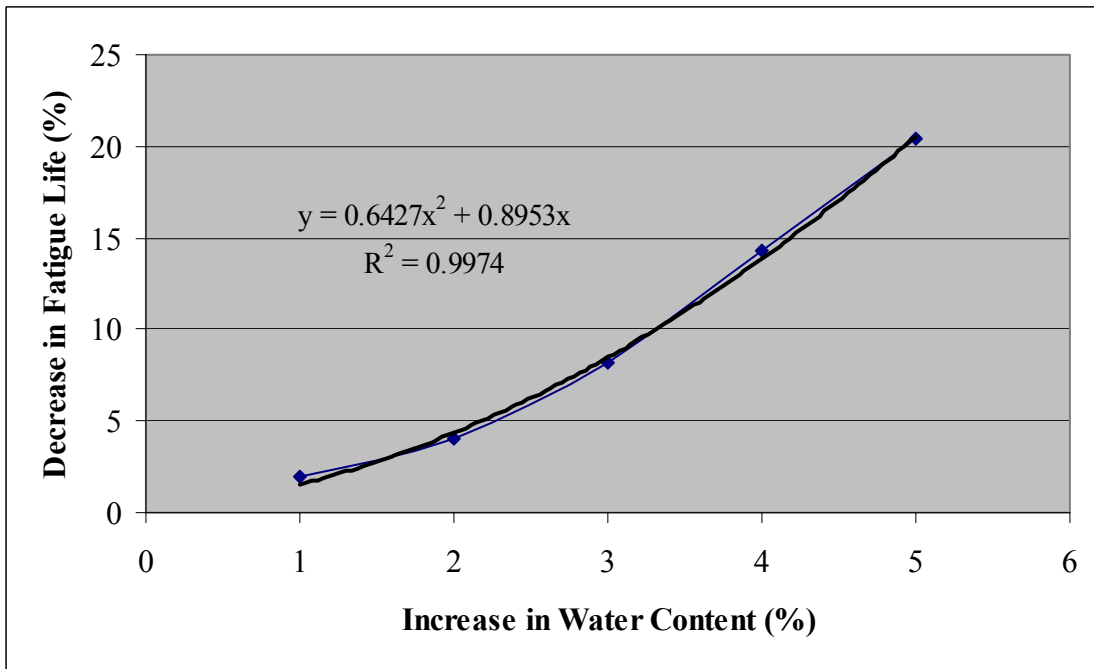
The cost analysis of a road is commonly based on its estimated lifecycle and a market discount rate using the following equation:

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1} \quad (6.1)$$

where,



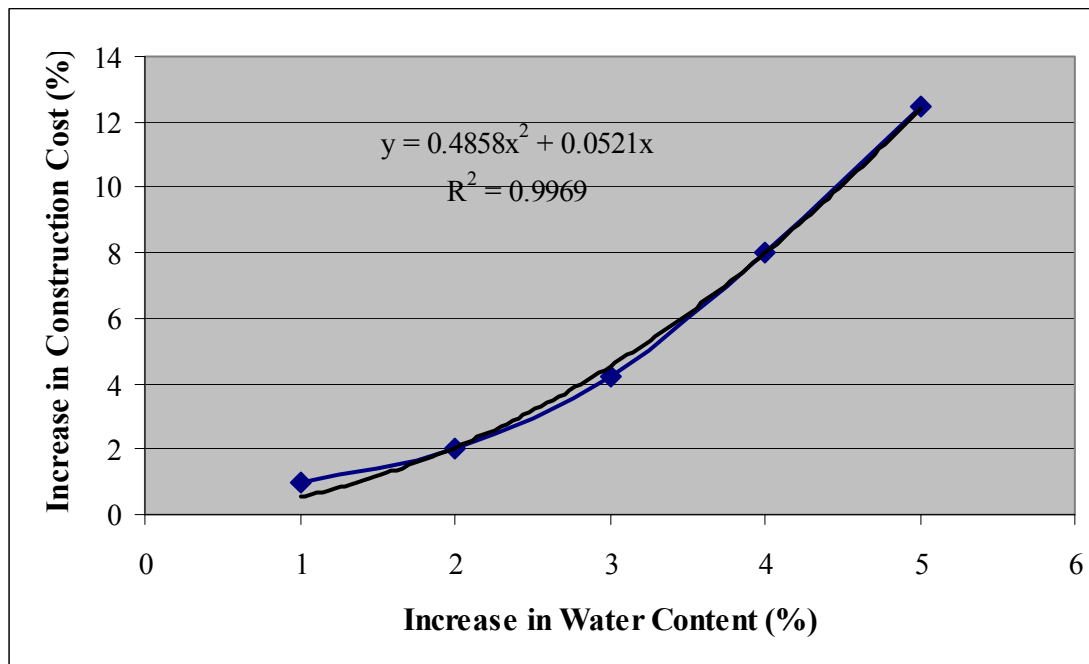
**Figure 6.5** Relationship between Fatigue Life and Water Content (Canelon and Nieber, 2005)



**Figure 6.6** Decrease in Fatigue Life with Increase in Water Content (Canelon and Nieber, 2005)

CRF is the capital recovery factor  
*i* is the market discount rate  
*n* is the lifecycle of the road

Using this equation, it is possible to calculate the annual construction cost of the road during its lifecycle. So, if the decrease in fatigue life of the road, from Fig. 6.6, is associated with a similar decrease in its lifecycle, it would be possible to calculate a new CRF and, therefore, determine the increase in the construction cost of the road. In other words, if the lifecycle decreases, the CRF will increase and, accordingly, the annual construction cost of the road will also increase, such as it is shown in Fig. 6.7.



**Figure 6.7 Increase in Construction Costs Due to Increase in Water Content**  
 (Canelon and Nieber, 2005)

As an example, for an increase of water content of 5%, the decrease in fatigue life of the road and, therefore, in its lifecycle, will be about 20%. For a normal lifecycle of 20 years, the reduced lifecycle will be now around 16 years. Using a market discount rate (*i*) of 0.07, the new CRF will be 0.1062, instead of 0.0944, representing an increase in construction costs of about 12.5%. For an increase of water content of 8%, the new lifecycle will be about 10.5 years (from Figure 6.6), and the increase in the construction cost will be about 32% (from Figure 6.7).



Whether stormwater BMPs adjacent to pavements will significantly increase the water content of pavement subgrades remains to be evaluated. This can be done by measuring moisture content in the pavement subgrade at locations of storm water BMPs. It could also be done by using computer modeling of the flow of moisture from BMP locations to pavement subgrades. This work remains to be done in future research activities.

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## **Appendix A**

### **Cost Estimation Formulas for Storm Water Best Management Practices**

**Appendix A.1 Cost Estimation for Wet Ponds**  
(Canelon and Nieber, 2005)

<b>BASIC DATA AND EQUATIONS</b>					
<b>LFC = CC + DC + MC</b>		<b>LFC</b> is the life cycle cost (\$)			
		<b>CC</b> is the construction cost (\$)			
		<b>DC</b> is the design, permitting, erosion control and contingency cost (\$)			
<b>CC = 230.16 Qv<sup>-0.4282</sup></b>		<b>CC</b> in \$/cf	<b>DC = 32% CC</b>		
<b>MC = 4.5% CC x MDF</b>		<b>MDF</b> is the multiyear discount factor			
$\text{MDF} = \sum_{t=1}^{t=n} \frac{1}{(i + 1)^t}$		<b>i</b> is the discount rate (fraction) <b>t</b> is the period of analysis (year)			
<b>COST TYPE</b>	<b>DRAINAGE AREA</b>				
	<b>0.5 ac</b>	<b>1 ac</b>	<b>5 ac</b>	<b>10 ac</b>	<b>50 ac</b>
<b>Qv (cf)</b>	315	630	3151	6302	31511
<b>CC (\$)</b>	6175	9179	23038	34243	85950
<b>DC (\$)</b>	1976	2937	7372	10958	27504
<b>MC (\$)</b>	2944	4376	10983	16325	40975
<b>LCC (\$)</b>	11095	16491	41393	61526	154429

**Appendix A.2 Cost Estimation for Constructed Wetlands**  
(Canelon and Nieber, 2005)

<b>BASIC DATA AND EQUATIONS</b>					
<b>LFC = CC + DC + MC</b>		<b>LFC</b> is the life cycle cost (\$)			
		<b>CC</b> is the construction cost (\$)			
		<b>DC</b> is the design, permitting, erosion control and contingency cost (\$)			
<b>CC = 53.211 Qv<sup>-0.3576</sup></b>		<b>CC</b> in \$/cf	<b>DC = 32% CC</b>		
<b>MC = 4.5% CC x MDF</b>		<b>MDF</b> is the multiyear discount factor			
$\text{MDF} = \sum_{t=1}^{t=n} \frac{1}{(i + 1)^t}$		<b>i</b> is the discount rate (fraction) <b>t</b> is the period of analysis (year)			
<b>COST TYPE</b>	<b>DRAINAGE AREA</b>				
	<b>0.5 ac</b>	<b>1 ac</b>	<b>5 ac</b>	<b>10 ac</b>	<b>50 ac</b>
<b>Qv (cf)</b>	315	630	3151	6302	31511
<b>CC (\$)</b>	2143	3345	9406	14682	41287
<b>DC (\$)</b>	686	1070	3010	4698	13212
<b>MC (\$)</b>	1022	1595	4484	6999	19683
<b>LCC (\$)</b>	3850	6010	16900	26380	74181

**Appendix A.3 Cost Estimation for Infiltration Trenches**  
(Canelon and Nieber, 2005)

<b>BASIC DATA AND EQUATIONS</b>					
<b>LFC = CC + DC + MC</b>		<b>LFC</b> is the life cycle cost (\$)			
		<b>CC</b> is the construction cost (\$)			
		<b>DC</b> is the design, permitting, erosion control and contingency cost (\$)			
<b>CC = 44.108 Q<sub>v</sub><sup>-0.1991</sup></b>		<b>CC</b> in \$/cf		<b>DC = 32% CC</b>	
<b>MC = 12.5% CC x MDF</b>		<b>MDF</b> is the multiyear discount factor			
$\text{MDF} = \sum_{t=1}^{t=n} \frac{1}{(i + 1)^t}$		<i>i</i> is the discount rate (fraction) <i>t</i> is the period of analysis (year)			
<b>COST TYPE</b>	<b>DRAINAGE AREA</b>				
	<b>0.5 ac</b>	<b>1 ac</b>	<b>5 ac</b>	<b>10 ac</b>	<b>50 ac</b>
<b>Q<sub>v</sub> (cf)</b>	315	630	3151	6302	31511
<b>CC (\$)</b>	4421	7702	27953	48700	176739
<b>DC (\$)</b>	1415	2465	8945	15584	56556
<b>MC (\$)</b>	5855	10200	37017	64491	234046
<b>LCC (\$)</b>	11691	20367	73915	128774	467341



**Appendix A.4 Cost Estimation for Infiltration Basins**  
(Canelon and Nieber, 2005)

<b>BASIC DATA AND EQUATIONS</b>					
<b>LFC = CC + DC + MC</b>		<b>LFC</b> is the life cycle cost (\$)			
		<b>CC</b> is the construction cost (\$)			
		<b>DC</b> is the design, permitting, erosion control and contingency cost (\$)			
<b>CC = 230.16 Q<sub>v</sub><sup>-0.4282</sup></b>		<b>CC</b> in \$/cf	<b>DC = 32% CC</b>		
<b>MC = 2% CC x MDF</b>		<b>MDF</b> is the multiyear discount factor			
$\text{MDF} = \sum_{t=1}^{t=n} \frac{1}{(i + 1)^t}$		<i>i</i> is the discount rate (fraction) <i>t</i> is the period of analysis (year)			
<b>COST TYPE</b>	<b>DRAINAGE AREA</b>				
	<b>0.5 ac</b>	<b>1 ac</b>	<b>5 ac</b>	<b>10 ac</b>	<b>50 ac</b>
<b>Q<sub>v</sub> (cf)</b>	315	630	3151	6302	31511
<b>CC (\$)</b>	6175	9179	23038	34243	85950
<b>DC (\$)</b>	1976	2937	7372	10958	27504
<b>MC (\$)</b>	1308	1945	4881	7255	18211
<b>LCC (\$)</b>	9460	14061	35292	52457	131666

**Appendix A.5 Cost Estimation for Sand Filters**  
(Canelon and Nieber, 2005)

<b>BASIC DATA AND EQUATIONS</b>					
<b>LFC = CC + DC + MC</b>		<b>LFC</b> is the life cycle cost (\$)			
		<b>CC</b> is the construction cost (\$)			
		<b>DC</b> is the design, permitting, erosion control, and contingency cost (\$)			
<b>CC = 389 Qv<sup>-0.3951</sup></b>		<b>CC</b> in \$/cf		<b>DC = 32% CC</b>	
<b>MC = 12% CC x MDF</b>		<b>MDF</b> is the multiyear discount factor			
$\text{MDF} = \sum_{t=1}^{t=n} \frac{1}{(i + 1)^t}$		<b>i</b> is the discount rate (fraction) <b>t</b> is the period of analysis (year)			
<b>COST TYPE</b>	<b>DRAINAGE AREA</b>				
	<b>0.5 ac</b>	<b>1 ac</b>	<b>5 ac</b>	<b>10 ac</b>	<b>50 ac</b>
<b>Qv (cf)</b>	315	630	3151	6302	31511
<b>CC (\$)</b>	12626	19203	50835	77314	204676
<b>DC (\$)</b>	4040	6145	16267	24741	65496
<b>MC (\$)</b>	16051	24412	64626	98288	260200
<b>LCC (\$)</b>	32718	49759	131729	200343	530372

**Appendix A.6 Cost Estimation for Bioretention Areas**  
(Canelon and Nieber, 2005)

<b>BASIC DATA AND EQUATIONS</b>					
<b>LFC = CC + DC + MC</b>		<b>LFC</b> is the life cycle cost (\$)			
		<b>CC</b> is the construction cost (\$)			
		<b>DC</b> is the design, permitting, erosion control and contingency cost (\$)			
<b>CC = 0.0001 Q<sub>v</sub> + 9.0002</b>		<b>CC</b> in \$/cf	<b>DC = 32% CC</b>		
<b>MC = 5% CC x MDF</b>		<b>MDF</b> is the multiyear discount factor			
$\text{MDF} = \sum_{t=1}^{t=n} \frac{1}{(i + 1)^t}$		<i>i</i> is the discount rate (fraction) <i>t</i> is the period of analysis (year)			
<b>COST TYPE</b>	<b>DRAINAGE AREA</b>				
	<b>0.5 ac</b>	<b>1 ac</b>	<b>5 ac</b>	<b>10 ac</b>	<b>50 ac</b>
<b>Q<sub>v</sub> (cf)</b>	315	630	3151	6302	31511
<b>CC (\$)</b>	2846	5712	29353	60692	382894
<b>DC (\$)</b>	911	1828	9393	19421	122526
<b>MC (\$)</b>	1508	3026	15548	32149	202819
<b>LCC (\$)</b>	5264	10565	54295	112262	708239

**Appendix A.7 Cost Estimation for Vegetated Swales**  
(Canelon and Nieber, 2005)

<b>BASIC DATA AND EQUATIONS</b>					
<b>LFC = CC + DC + MC</b>		<b>LFC</b> is the life cycle cost (\$)			
<b>DC = 32% CC</b>		<b>CC</b> is the construction cost (\$)			
		<b>DC</b> is the design, permitting, erosion control, and contingency cost (\$)			
<b>CC = \$0.50 A</b>		<b>A</b> is the surface area of the swale (sf)			
<b>MC = 6% CC x MDF</b>		<b>MDF</b> is the multiyear discount factor			
$\text{MDF} = \sum_{t=1}^{t=n} \frac{1}{(i + 1)^t}$		<b>i</b> is the discount rate (fraction) <b>t</b> is the period of analysis (year)			
<b>DRAINAGE AREA</b>					
<b>COST TYPE</b>	<b>0.5 ac</b>	<b>1 ac</b>	<b>5 ac</b>	<b>10 ac</b>	<b>50 ac</b>
<b>A (sf)</b>	218	436	2178	4356	21780
<b>CC (\$)</b>	109	218	1089	2178	10890
<b>DC (\$)</b>	35	70	348	697	3485
<b>MC (\$)</b>	69	138	692	1384	6922
<b>LCC (\$)</b>	213	426	2130	4259	21297