THESIS

A MODEL FOR EVALUATING THE EFFECTIVENESS AND LIFE CYCLE COSTS OF STORMWATER BEST MANAGEMENT PRACTICES

Submitted by
Christopher C. Olson
Department of Civil and Environmental Engineering

In partial fulfillment of the requirements
For the Degree of Master of Science
Colorado State University
Fort Collins, Colorado
Spring 2010

TD657
.0576
2010

COLORADO STATE UNIVERSITY

October 28, 2009

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY CHRISTOPHER C. OLSON ENTITLED "A MODEL FOR EVALUATING THE EFFECTIVENESS AND LIFE CYCLE COSTS OF STORMWATER BEST MANAGEMENT PRACTICES" BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

Neil S. Grigg
Neil Grigg, Ph.D., P.E.

John Stednick, Ph.D.

Larry A. Roesner
Advisor Larry Roesner, PhD., P.E.

Luis Garcia
Department Head Luis Garcia, Ph.D.

COLORADO STATE UNIVERSITY LIBRARIES

ABSTRACT OF THESIS

A MODEL FOR EVALUATING THE EFFECTIVENESS AND LIFE CYCLE COSTS OF STORMWATER BEST MANAGEMENT PRACTICES

Structural best management practices (BMPs) are devices designed and implemented for the purpose of reducing or eliminating the effects of urbanization on receiving waters. Structural BMPs each have their own unique effectiveness and costs, however BMPs are rarely evaluated or selected for their long-term cost effectiveness because most of the information required to do so is not readily available to the decision maker. The purpose of this model is to integrate the best available information on BMP costs and effectiveness into a tool that decision makers can use when selecting what type of BMP to implement under certain circumstances.

A spreadsheet model was developed using relatively few required inputs to describe the watershed and BMPs to be implemented. The model computes the number and size of BMPs required for the watershed, the annual pollutant load reduction and runoff volume reduction expected from implementing the BMPs and the net present value of the life cycle costs of the BMPs. These outputs can be used to determine BMP cost effectiveness, computed as cost per pound of pollutant removed or cost per volume of runoff reduced.

The model was applied to two theoretical stormwater management planning scenarios. The first application seeks to determine the unit cost of land at which it is less costly to use underground hydrodynamic separators instead of an extended detention basin in a highly urbanized watershed, assuming that both BMPs meet a minimum water quality requirement. The results show that hydrodynamic separators are less expensive when land costs exceed approximately $1.5 million per acre, however the cost effectiveness ($ per lb of pollutant removed) was not evaluated under this scenario.

In the second application four different BMPs were evaluated to determine the most cost effective at removing 60% of the total suspended solids (TSS) generated from a highly developed watershed. The four BMPs evaluated (hydrodynamic separator, porous landscape detention, sand filter vault and inlet inserts) were chosen because they can be retrofitted into an existing development more easily than many other BMPs. Using an iterative procedure, the BMPs were applied to a certain percentage of the watershed until the annual TSS load discharged to the receiving waters was reduced to approximately 60%. The results suggest that porous landscape detention is the most cost effective BMP at approximately $4.20 per lb of TSS removed annually. Inlet inserts were the second most expensive at $6.00 per lb of TSS removed annually, despite having the lowest initial capital costs. The latter result shows the importance of including long-term operations and maintenance costs when selecting BMPs.

Christopher C. Olson
Department of Civil Engineering
Colorado State University
Fort Collins, CO 80523
Spring 2010

ACKNOWLEDGEMENTS

This work could not have been completed without the assistance and support from many individuals and organizations. I would first like to thank Dr. Larry Roesner for having the confidence in me to take on this project, and for serving as a personal and professional mentor over the past two years.

Mr. Ben Urbonas, formerly of the Urban Drainage and Flood Control District (UDFCD) and now with the Urban Watersheds Research Institute (UWRI), provided endless guidance and mentoring throughout this project. It was great pleasure working with Ben and I tried my best to absorb every piece of stormwater knowledge he threw at me.

I acknowledge the sponsors of this work; UDFCD, the Colorado Stormwater Council and its member agencies and UWRI. The endowment of Mr. Harold H. Short provided funding for the Colorado State University Urban Water Center, through which this work was completed.

Lastly, thanks to my parents who have provided 28 years of unconditional support which has allowed me to reach another substantial personal goal. And of course, to Becky; thank you will never say enough.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AF	Acre-feet
BMP	Best management practices
CCI	Construction Cost Index
cfs	cubic feet per second
CWB	Constructed wetland basin
CWC	Constructed wetland channel
CY	Cubic yards
EDB	Extended detention basin
EMC	Event mean concentration
ENR	Engineering News Record
ET	Evapotranspiration
EURV	Excess urban runoff volume
ft^3	Cubic feet
HS	Hydrodynamic separator
II	Inlet inserts
LCFCTR	Land consumption factor
LID	Low impact development
MDCIA	Minimize directly connected impervious area
MFV	Media filter vault
Model	BMP Effectiveness and Life Cycle Cost Evaluation Model
NRCS	Natural Resources Conservation Service
O&M	Operation and maintenance
PCP	Porous concrete pavement
PLD	Porous landscape detention
PP	Permeable pavements
RGP	Reinforced grass pavement
ROR	Rate of return
RP	Retention pond
SFB	Sand filter basin
SFV	Sand filter vault
SOG	Sediment/oil/grease separator
UDFCD	Urban Drainage and Flood Control District
USDCM	Urban Storm Drainage Criteria Manual
USEPA	United States Environmental Protection Agency
WQCV	Water quality capture volume
VCV	Vault with capture volume

1. INTRODUCTION

1.1. Background

The United States Environmental Protection Agency's (USEPA) National Pollutant Discharge Elimination System stormwater program (Program) requires, in part, that municipalities with urban areas reduce or eliminate pollutant loadings that enter receiving waters from stormwater runoff. To do so, municipalities implement best management practices (BMPs), which are methods or strategies aimed to prevent or treat stormwater pollution. Structural BMPs are one subset of BMPs and are constructed facilities that capture and treat stormwater runoff. Large numbers of structural BMPs have been constructed throughout the US since the Program's establishment and many times, the selection of one BMP over another was based on site constraints, initial (land or construction) costs, or an engineer's or reviewer's familiarity with a particular BMP. However, this BMP selection process disregards the effectiveness of the BMP to mitigate impacts to receiving waters (Urbonas and Jones 2001) and also does not account for the life cycle costs (construction, maintenance and administration) of the BMP. The stormwater community has recognized the need to improve the BMP selection process to include these metrics, however, to this point it has lacked an effective approach for doing so.

Much of work has been done to quantify the effectiveness of BMPs at mitigating the impacts of urbanization. Additionally, a fair amount of research has been done to identify the costs associated with BMP implementation. The problem, however, is that most of the information produced from these works are "buried" within the literature as individual papers and reports, and not readily available to those practitioners that need it. The goal of this project is to synthesize the available information into a tool that can be used and understood by most stormwater professionals to enable improved selection and implementation of structural BMPs based on environmental and financial considerations.

1.2. Objectives and Scope of the Model

The primary objective of the BMP Effectiveness and Life Cycle Cost Evaluation Model (model) is to provide stormwater practitioners and decision makers with a tool for evaluating what effects their BMP selection(s) will have on the long-term fiscal resources of the owners and the environmental resources of the receiving water. Several secondary objectives were also identified, many of which aimed to make the model user-friendly thereby increasing its chances of being widely used. Secondary objectives are described below.

1. The model is built into Microsoft Excel ®, a format most potential users are familiar and have access to.
2. The model is programmed with macros written in Visual Basic for Applications that automate many of the model operations.
3. User inputs are minimized to enable relatively quick and easy learning and use of the model.

4. The model uses hydrologic data, BMP design criteria and cost information, where possible, specific to the metropolitan region of Denver, Colorado.
5. The cost algorithms allow several sizes of BMPs to be evaluated in a single model run.
6. Construction costs reflect economies of scale that typically occur in construction projects.
7. Maintenance costs can be computed using a bottom-up cost estimating procedure based on values input into the maintenance cost tables for the primary factors (frequency, labor, materials, equipment, etc.) that affect maintenance costs. This structure not only allows users to modify the maintenance cost estimates to fit their maintenance program, but also allows for evaluating how adjustments to their maintenance program (such as increasing frequency) will affect costs.
8. Default values for cost and BMP effectiveness parameters are provided, however the user has the option of overriding any of those values with better information.

The model operates by first having the user enter parameters describing the physical characteristics of a watershed and/or subcatchment that affect runoff quality and quantity (e.g., contributing area, land use, imperviousness, etc.). Second, the user selects what type(s) of BMP(s) to apply to the watershed and the number of impervious acres that will runoff to each individual BMP. The model then calculates the size and number of BMPs required to treat the runoff, the average annual pollutant load discharged to the receiving water and the life cycle costs for all of the BMPs applied. A process diagram illustrating how the model works is presented in Figure 1-1.

A list of the BMPs and pollutants that the model can evaluate is presented in Table 1-1.

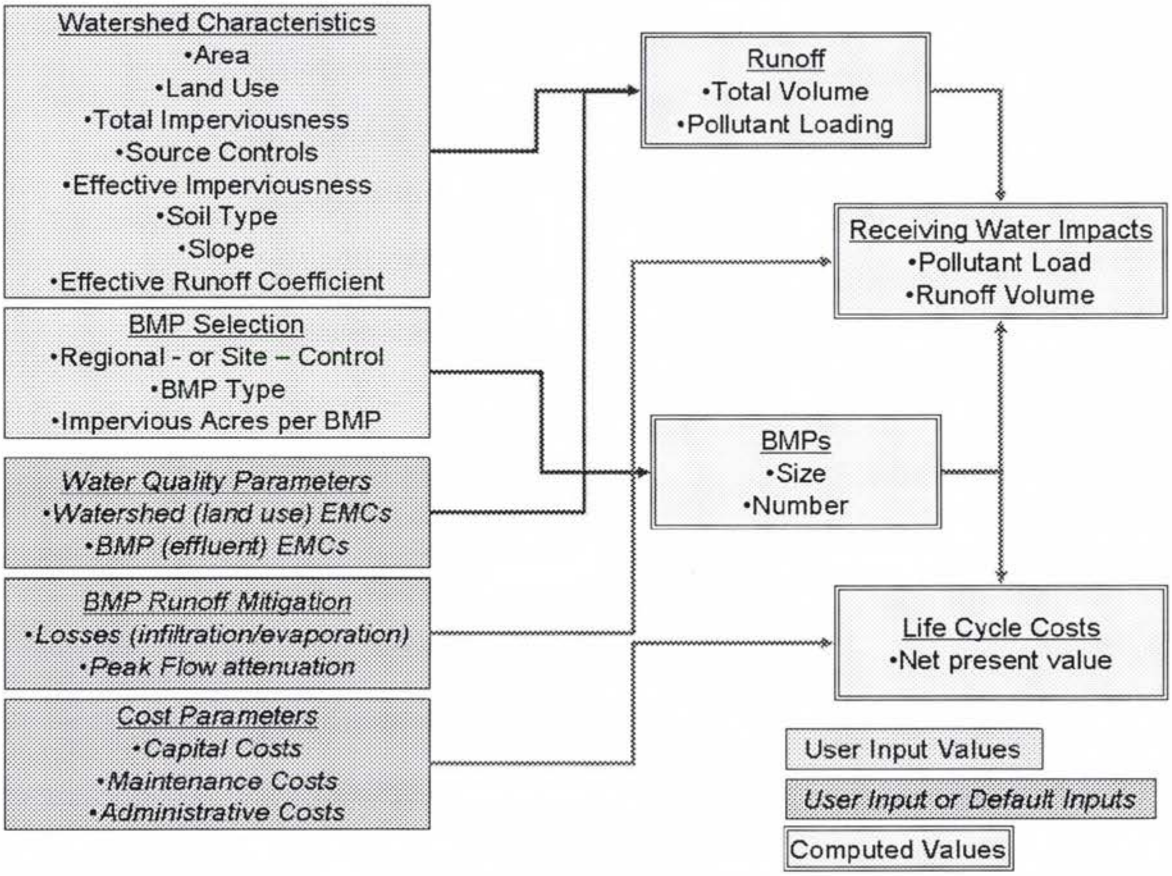


Figure 1-1: Diagram of model processes

1.3. Appropriate Use

The model was developed as a deterministic, planning-level model, where some output accuracy is sacrificed in order to make the model easy-to-use and require minimal data inputs. As such, the model uses several simplifying assumptions which are further described throughout this thesis. *The model results should not be used as a substitute for,* *nor as a comparative resource for, final BMP designs, more intensive rainfall-runoff modeling techniques or "engineer's estimates".*

The model uses many of the recommendations and methods provided in the Urban Drainage and Flood Control District's (UDFCD) Urban Storm Drainage Criteria Manual (USDCM) (UDFCD 2004). Application of the model outside of jurisdictions accepting those methods should be used with caution.

Table 1-1: BMPs and pollutants evaluated in the model

BMPs	Pollutants
Constructed Wetland Basin	Total Suspended Solids
Constructed Wetland Channel	Total Phosphorus
Extended Detention Basin	Total Nitrogen
Hydrodynamic Separator	Total Kjeldahl Nitrogen
Inlet Inserts	Total Zinc
Media Filter Vault	Dissolved Zinc
Porous Landscape Detention	Total Lead
Retention (Wet) Pond	Dissolved Lead
Sand Filter Basin	Total Copper
Sand Filter Vault	Dissolved Copper
Sediment/Oil/Grease Separator	
Vault with Capture Volume	
Porous Concrete Pavement[1]	
Porous Gravel Pavement[1]	
Reinforced Grass Pavement[1]	
Concrete Grid Pavers[1]	
Permeable Interlocking Concrete Pavers[1]	

Notes:

[1] – collectively referred to as permeable pavements

1.4. Organization of Thesis

This thesis is organized into seven sections, identified below.

Section 1: Background and scope of the project.

Section 2: Results of a literature review.

Section 3: The equations and algorithms developed for computing BMP effectiveness and life cycle costs.

Section 4: Model set up and instructions for how to use it.

Section 5: Results from model application to two theoretical stormwater management problems

Section 6: Summary and conclusions

Section 7: Recommendations for future work

Section 8: Literature cited.

2. LITERATURE REVIEW AND DATA SOURCES

This section presents the results of a literature review focused on revealing past research findings that provide data or recommended methods for estimating BMP cost effectiveness.

2.1. Methods for Cost Estimating

The United States Department of Defense classified four types of common cost estimating techniques, which were summarized in USEPA (2004) and reproduced below for reference.

> **Bottom-Up Method**
> The bottom-up approach estimates costs on an item-by-item basis. Detailed methods typically rely on quantity take-offs and compiled sources of unit cost data for each item, taken from either a built-in database or other sources (e.g., cost-estimating references). This method is used when design information is available.
>
> **Analogy Method**
> This technique uses the cost of previously completed projects, as a comparison to the cost of the proposed project, to arrive at a final cost estimate. The actual costs from the completed project are extrapolated to estimate the cost of the proposed project. This method provides estimates by using the system or component level, which are obtained from using actual project costs from past experiences. The disadvantage of this method occurs when projects similar to the one in question do not exist, or the accuracy of the available data is questionable, or extrapolating the entire project cost does not accurately reflect evenly scaled costs.
>
> **Expert Opinion Method**
> Experts in this field can be consulted to provide a cost estimate for the project based upon their past experience and understanding of the

proposed undertaking. The advantage of this method is that the experts have the knowledge to account for the differences between past project experiences and the proposed project requirements, pointing out areas contributing to the cost estimate that may be overlooked. They can also factor in the impacts produced by new technologies or applications. The disadvantage of this technique is that the estimate is confined by the judgment and expertise of the consulted experts.

Parametric Method

The parametric approach relies on relationships between cost and design parameters. These relationships are usually statistically-based or model-based. Statistically-based approaches rely on "scaled-up" or "scaled-down" versions of projects where historical cost data are available. Model-based approaches utilize a generic design that is linked to a cost database and adjusted by the user for site-specific information. This method, also known as top-down estimating, is used when design information is not available.

2.2. Life Cycle Cost Estimating

The life cycle cost is the sum of all costs that occur during the planning horizon of a project. This method of cost estimating has gained so much popularity in the construction and engineering fields over the past 10 to 20 years that the American Society of Civil Engineers (ASCE 2006) passed ASCE Policy 451 in 2006 encouraging the use of life cycle cost analysis for all civil engineering projects. Generally, the components of the life cycle cost for a constructed facility will include construction costs, engineering/permitting costs, land costs, operation and maintenance costs, major rehabilitation costs, and salvage costs. In addition, Urbonas (2008) recommends that the administrative costs of managing maintenance activities also be included as a long-term cost. Reporting life cycle costs in terms of net present value (NPV) is an effective method for comparing mutually exclusive alternatives (Newnan 1996).

2.3. Construction Costs

The literature contains a wide variety of cost estimates reported for many of the BMPs in the model. Some studies produced parametric cost equations based on a sample of many individual BMPs, some reported a range of costs and others have simply reported a single unit cost. Some of the more prevalent BMPs had more than one cost estimate reported. Each cost estimate, its source and any other information that is pertinent to the selection and/or modification of the cost estimate to meet the model objectives is discussed in the following sections.

2.3.1. Constructed Wetland Basin

Construction cost estimates for constructed wetland basins were reported by Wossink and Hunt (2003) and the USEPA (2008). Wossink and Hunt (2003) developed Equation (2-1) relating construction costs to the size (area) of the watershed contributing to the BMP.

$$C = 3{,}852X^{0.484} \tag{2-1}$$

Where $C =$ construction costs (2003\$) and $X =$ the area of the watershed (acres). The equation was based on the costs of 15 constructed wetlands located in North Carolina, with contributing areas ranging in size from 4-200 acres. Neither the imperviousness of the contributing watersheds, nor the storage volume of the wetlands was reported.

The USEPA, citing a lack of reported construction costs for wetlands, assumes that constructed wetlands cost 25% more than wet ponds of an equivalent volume (USEPA 2008). Using this assumption, USEPA (2008) suggests increasing the wet pond construction cost estimate reported by Brown and Schueler (1997) by 25%, resulting in Equation (2-2).

$$C = 30.6V^{0.705} \tag{2-2}$$

Where C = construction, design and permitting costs (1997\$) and V = storage volume required for the 10-year storm (ft^3). The equation referenced by USEPA (2008) is not a construction-only cost (it includes design and permitting) and also is the equation reported by Brown and Schueler (1997) for all ponds (wet and dry) and wetlands evaluated in their study, not wet ponds only.

2.3.2. Constructed Wetland Channel

No construction cost estimates were found in the literature for constructed wetland channels (CWC).

2.3.3. Extended Detention Basin

Brown and Schueler (1997) developed Equations (2-3) and (2-4) for estimating construction costs of dry extended detention ponds (basins).

$$C = 8.16V^{0.78} \tag{2-3}$$

$$C = 14.93WQCV^{0.788} \tag{2-4}$$

Where C = construction costs (1997\$), V = storage volume required for the 10-year storm (ft^3) and $WQCV$ = water quality capture volume (ft^3). These equations were developed using cost data from 18 dry EDB's located in the mid-Atlantic region of the United States. The authors found the cost relationship based on the 10-year storage volume to be significant (R^2-value = 0.93), however the cost relationship based on the WQCV was not significant (R^2-value = 0.72).

2.3.4. Hydrodynamic Separators

The USEPA (1999) reported costs and treatment design rates for three proprietary hydrodynamic devices that are manufactured offsite. (Information for a fourth device is also available; however costs were reported as a function of storage volume, not design flowrate). A summary of the cost information is provided in Table 2-1.

Table 2-1: Summary table of hydrodynamic separator costs

Device	Flowrates (cfs)	Cost per Unit (1999$)	Cost per cfs (1999$)
Continuous Deflective Separation	3-62	-	\$2,300-\$7,200
Downstream Defender	0.75-13	\$10,000-\$35,000	\$2,700-\$13,300
Vortechs	1.6-25	\$10,000-\$40,000	\$1,600-\$6,250
Summary	**0.75-62**		**\$1,600-\$13,300**

2.3.5. Inlet Inserts

The Interagency Catch Basin Insert Committee (ICDIC 1995), comprised of members from several stormwater agencies in the Seattle, WA region, reported inlet insert (II) costs ranging from $100-1,500 each for units sized to treat approximately 0.25 acres of impervious area. The cost range includes several proprietary devices with various levels of design sophistication and different targeted pollutants (i.e. sediments or hydrocarbons), however the cost for each device was not stated. The costs for disposable-type inserts ranged from $50-$110 on two stormwater project sales websites (Adsorbants Online, 2009 and Bowhead Environmental & Safety, 2009).

2.3.6. Media Filter Vault

No cost estimates were available specifically for media filter vaults, however it is generally recognized that the construction costs are similar to those of sand filter vaults (USDOT 2002a).

2.3.7. Porous Landscape Detention

Brown and Schueler (1997) and Wossink and Hunt (2003) both reported equations for estimating construction costs for bioretention BMPs, also known as porous landscape detention (PLD) or raingardens. Brown and Schueler's study yielded Equation (2-5) based on 11 bioretention BMPs located in the mid-Atlantic region of the US.

$$C = 5.67WQCV^{0.99} \tag{2-5}$$

Where C = construction costs (1997$) and $WQCV$ = water quality capture volume (ft^3). The relationship of construction cost to WQCV was considered significant (R^2-value = 0.92).

Wossink and Hunt developed two different cost equations, based on the soil type in which the BMP was constructed. Equation (2-6) is applicable to bioretention BMPs constructed in clay soils and Equation (2-7) for sandy soils.

For clayey soils:

$$C = 10{,}162X^{1.088} \tag{2-6}$$

For sandy soils:

$$C = 2{,}861X^{0.438} \tag{2-7}$$

Where C = construction costs (2003$) and X = watershed area (acres). These equations were developed based on cost data from 18 bioretention BMPs located in North Carolina, with watershed areas ranging from 0.3-9.2 acres. The study did not report either watershed imperviousness or storage volume for BMP.

2.3.8. Retention (Wet) Pond

Construction cost equations for retention (wet) ponds (RP) have been reported by Brown and Schueler (1997), Southeastern Wisconsin Regional Planning Commission (SEWRPC 1991) and Wossink and Hunt (2003).

Brown and Schueler developed Equations (2-8) and (2-9) based on cost data from 11 wet extended detention ponds located in the mid-Atlantic region of the US.

$$C = 8.50V^{0.75} \qquad \textbf{(2-8)}$$

$$C = 74.64WQCV^{0.611} \qquad \textbf{(2-9)}$$

Where C = construction costs (1997$), V = storage volume required for the 10-year storm (ft^3), and $WQCV$ = water quality capture volume (ft^3). Neither equation fit the cost data significantly (R^2-values of 0.69 and 0.59, respectively). Also worth noting is that the authors separated the ponds used to develop these equations from other wet ponds that contained considerable "ornamental" storage volumes.

SEWRPC developed a range of cost estimates (low, medium, high) for four different sizes of wet ponds, as presented in Table 2-2.

Table 2-2: Summary of wet pond construction costs reported by SEWRPC (1991)

Pond Size (acres)	Pond Volume (ft^3)[1]	Construction Cost (1989$)[2]		
		Low	Medium	High

0.25	54,450	\$10,609	\$22,459	\$34,306
1	217,800	\$30,079	\$57,506	\$84,929
3	653,400	\$90,089	\$165,275	\$240,460
5	1,089,000	\$150,341	\$273,478	\$396,642

Notes:

[1] - computed based on 5 foot basin depth

[2] – not including 25% engineering/contingencies reported in the total cost

Using cost data from 13 wet ponds located in North Carolina, Wossink and Hunt developed Equation (2-10).

$$C = 13{,}909X^{0.672} \qquad \textbf{(2-10)}$$

Where C = construction costs (2003\$) and X = watershed area (acres). The ponds surveyed had watershed areas ranging from 0.75 to 67 acres, however neither the watershed imperviousness, nor the storage volume of the ponds were reported.

2.3.9. Sand Filter Basin

For this model, a sand filter basin (SFB) is an excavated basin that contains a sand bottom that filters the stormwater before infiltrating into the soil or draining through underdrains. In many parts of the US, these BMPs are also known as infiltration basins.

Young et al (1996), as reported in USEPA (2004), developed Equation (2-11) for construction costs of infiltration basins.

$$C = 16.9V^{0.69} \qquad \textbf{(2-11)}$$

Where C = construction costs (1996\$) and V = storage volume (ft^3). USEPA did not provide details of how the cost estimate by Young et al was developed.

SEWRPC (1991) generated three construction cost curves for infiltration basins, each curve representing a low, medium, or high estimate. Table 2-3 summarizes construction costs for four sizes of infiltration basins from those curves.

2.3.10. Sand Filter Vault

A sand filter vault (SFV) is sand filter that is located underground and is also referred to as a perimeter sand filter or underground sand filter. Wossink and Hunt (2003) developed Equation (2-12) based on a survey of 11 perimeter sand filters located in the mid-Atlantic region.

$$C = 47{,}888X^{0.882} \tag{2-12}$$

Where C = construction costs (2003$) and X = watershed area (acres). The watershed areas for the 11 perimeter sand filters studies ranged from 0.5-9 acres. Neither the storage volume nor the imperviousness of the watersheds were reported, however the authors acknowledged that sand filters are generally implemented in areas with high imperviousness.

Table 2-3: Summary of infiltration basin cost estimates reported by SEWRPC (1991)

Pond Size (acres)	Pond Volume (ft^3)[1]	Construction Cost (1989$)[2] Low	Medium	High
0.25	32,670	$9,505	$18,804	$28,100
1	130,680	$30,741	$58,105	$85,469
3	392,040	$97,500	$187,500	$277,500
5	653,400	$142,500	$255,000	$375,000

Notes:

[1] - computed based on 3 foot basin depth

[2] – not including 25% engineering/contingencies reported in the total cost

2.3.11. Sediment/Oil/Grease Separator

There were no construction cost estimates reported for sediment/oil/grease separators (SOG) in the literature.

2.3.12. Vault with Capture Volume

A vault with capture volume (VCV) is synonymous with underground detention BMPs. Table 2-4 summarizes costs for six underground detention facilities installed across the US reported by USEPA (2001).

Table 2-4: Costs of underground detention facilities (USEPA, 2001)

Material	Storage Volume (ft^3)	Total Cost (2000$)[1]	Construction Costs (2000$)[2]	Cost per Unit Storage ($/$ft^3$)
CSP	868,380	$9,000,000	$6,750,000	$7.80
Aluminum	251,336	$1,200,000	$900,000	$3.60
HDPE	50,126	$250,000	$187,500	$3.70
HDPE	2859.3	$28,190	$21,200	$7.40
Concrete	16026.2	$267,000	$200,300	$12.50
Concrete	3741.8	$85,000	$63,800	$17.00

Notes:

[1] – total costs assumed to include 25% engineering and contingencies

[2] – computed not including engineering and contingencies

2.3.13. Permeable/Porous Pavements

The Low Impact Development Urban Design Tools website, operated by the LID Center (LID Center 2009) reported the unit cost ranges presented in Table 2-5 for installation of various permeable pavements.

Table 2-6 summarizes all of the BMP construction costs discussed in this section.

Table 2-5: Unit cost ranges for permeable pavements (LID Center 2009)

Product	Cost per Square Foot (2001$)
Porous Concrete	$2.00-$6.50
Grass/Gravel Pavers	$1.50-$5.75
Interlocking Concrete Paving Blocks	$5.00-$10.00

Table 2-6: BMP construction costs reported in the literature

BMP	Cost Equation	Year$	Source	Notes
Constructed Wetland Basin	$\$3,852(X)^{0.484}$	2003	Wossink and Hunt (2003)	
	$\$23(V)^{0.705}$	1997	Brown and Schuler (1997)	As reported in USEPA (2008); not including eng./permitting costs
Constructed Wetland Channel	-	-	-	None reported
Extended Detention Basin	$\$8.16(V)^{0.78}$	1997	Brown and Schuler (1997)	
Hydrodynamic Separator	$1,600(F) – $13,300(F)	1999	USEPA (1999)	Range reported for a variety of proprietary devices
Inlet Inserts	$100(E) - $1,500(E)	1995	ICDIC (1995)	Range reported for a variety of products
Media Filter Vault	-	-	-	None reported
Porous Landscape Detention	$\$5.67(WQV)^{0.99}$	1997	Brown and Schueler (1997)	
	$\$10,162(X)^{1.088}$	2003	Wossink and Hunt (2003)	For PLDs constructed in clayey soils
	$\$2,861(X)^{0.438}$	2003	Wossink and Hunt (2003)	For PLDs constructed in sandy soils
Retention (Wet) Pond	$\$8.50V^{0.75}$	1997	Brown and Schuler (1997)	
	$0.14(V)- $0.63(V)	1989	SEWRPC (1991)	
Retention (Wet) Pond	$\$13,909(X)^{0.672}$	2003	Wossink and Hunt (2003)	

BMP	Cost Equation	Year$	Source	Notes
Sand Filter Basin	$16.9V^{0.69}$	1996	Young et al (1996)	As reported in USEPA (2004)
	\$0.22(V)- \$0.86(V)	1989	SEWRPC (1991)	
Sand Filter Vault	$47,888(X)^{0.882}$	2003	Wossink and Hunt (2003)	
Sediment/Oil/Grease Separator	-	-	-	None reported
Vault with Capture Volume	\$3.70(V) - \$17.00(V)	2000	USEPA (2001)	Range reported for a variety of structures (concrete, CSP, etc.)
Porous Concrete Pavement	\$2.00(SF) – \$6.50(SF)	2001	The LID Center (2009)	Installed costs.
Grass/Gravel Pavers	\$1.50(SF)- \$5.75(SF)	2001	The LID Center (2009)	Installed costs
Interlocking Concrete Paving Blocks	\$5.00(SF)- \$10.0(SF)	2001	The LID Center (2009)	Installed costs

Notes:
E = each
F = design flowrate (cfs)
SF = surface area (ft^2)
V = storage volume (ft^3)
WQV = water quality volume (ft^3)
X = watershed area (acres)

2.4. Contingency/Engineering/Administrative Costs

Contingency/engineering/administrative (CEA) costs occur prior to and during construction, and include the costs commonly associated with design of the BMP, permitting, site surveying, erosion and sediment control, contract preparation and any other unforeseen costs. They are usually estimated as a percentage of the construction costs, with reported values ranging from 25-32% (USEPA 2004). Urbonas (2008) estimated CEA costs to be approximately 40% of construction costs in the metropolitan region of Denver, Colorado.

2.5. Land Costs

There are two components to estimating the land costs associated with structural BMPs; one is the cost of the land itself and the second is the area of land required for the BMP. Land costs can vary considerably from site to site. If a BMP is to be constructed within an area of open space, easement, public park, etc; then that land may be considered "free". But if the land required for the BMP could have been developed, then the land cost could be considered equal to the market value of that land (Strecker et al 2005) or the opportunity costs (future returns) that are foregone from not developing the land (Sample et al 2003).

Estimates of urban land costs as a function of land use are provided in Strecker et al (2005) and presented in Table 2-7. The area of land required for a BMP is typically reported as a percentage of the total contributing area. Strecker et al (2005) found values of those percentages for various BMPs reported in the literature (Table 2-8).

Table 2-7: Land cost estimates as function of land use

Land Use	Land Cost ($/acre)
Unimproved Land	$25,000 – 50,000
Residential	$75,000 – 200,000
Commercial	$100,000 – 300,000
High Density	$500,000 – 3,000,000

Source: Strecker et al (2005)

Table 2-8: Ratios of land required/contributing area for structural BMPs

BMP	Min %	Max %
Retention (Wet) Pond	1	5
Infiltration Basin	2	3
Wetland	1.5	6.5
Sand Filter	0	3
Porous Landscape Detention	2	7

Source: Strecker et al (2005)

2.6. Operation and Maintenance Costs

Operation and maintenance (O&M) costs are attributed to activities that ensure and verify that structural BMPs remain effective (USEPA 2004). It is acknowledged that accurately estimating O&M costs for BMPs is difficult due to the intrinsic variability and uncertainty of stormwater events, however it is also recognized that these costs are significant and cannot be neglected. A variety of activities are required for BMP O&M such as inspections, lawn mowing, debris and litter removal, sediment removal, inlet/outlet cleaning, etc. Typically, annual O&M cost estimates have been reported as a percentage of the construction costs (Strecker et al 2005). USEPA (2004) summarizes the findings of Wiegand et al (1986), Schueler (1987), SWRPC (1991), Brown and Schueler (1997), and the Watershed Management Institute (WMI) (1997) in this manner.

In addition, Landphair et al's (2000) cost findings can also be summarized as such[1]. However other methods of reporting maintenance costs have also been used. The USDOT (2002b) qualifies maintenance costs using "low", "moderate", or "high" designations. Wossink and Hunt (2003) developed parametric equations relating 20 years of O&M costs to the BMP drainage area and Lampe et al (2005) developed spreadsheets to generate "bottom-up" cost estimates based on the input values for the requirements of labor, time, equipment and materials and the frequency of maintenance. Table 2-9 summarizes maintenance cost estimates reported in the literature and Table 2-10 is a spreadsheet-based input table developed by Lampe et al (2005) for estimating the maintenance costs for extended detention basins. Some of the maintenance cost estimates provided in the literature are based on cost information (bid tabs, labor reports, etc.) provided by property managers, stormwater utilities and/or stormwater maintenance personnel; while other estimates were developed using unit cost estimating guides such as RS Means. Lampe et al's (2005) table method for producing cost estimates allows for the use of both data sources and also can be modified by a user to fit their maintenance program.

2.7. Administrative Costs

Administrative costs account of the additional costs of operating a stormwater management program, including the costs of maintenance planning and oversight, regulatory reporting, compliance inspections, etc. A review of the literature did not

---

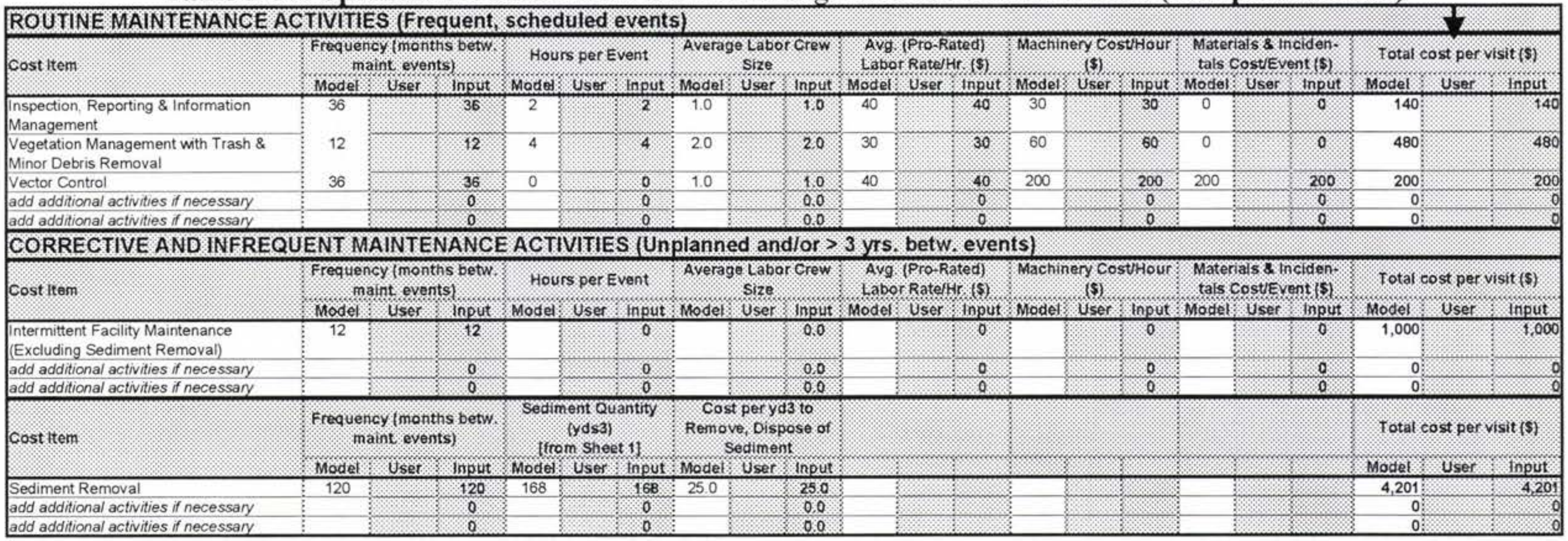
[1] Landphair et al estimated construction and maintenance costs for using three different construction methods. The reported range reflects the differences in those construction methods (and costs) only.

provide any reported estimates for administrative costs in the context of a stormwater management program, however Urbonas (2008) suggested a rough estimate as 12% of the annual O&M costs.

Table 2-9: Summary of maintenance costs reported

BMP	USDOT (2002)	Wossink and Hunt (2003)	Landphair et al (2000)	USEPA (1999)	USEPA (2004)
Constructed Wetland Basin	Moderate	$4,502x^{0.153}$	-	-	2-6%
Constructed Wetland Channel	Moderate	-	-	-	-
Extended Detention Basin	Low	-	0.5-2%	-	<1%
Hydrodynamic Separator	Moderate	-	-	<$1,000/yr	-
Inlet Inserts	Moderate-High	-	-	-	-
Media Filter Vault	High	-	-	-	-
Porous Landscape Detention	Low	$3,437x^{0.152}$	11%	-	-
Retention (Wet) Pond	Low	$9,202x^{0.269}$	1.5-4.5%	-	3-6%
Sand Filter Basin	Moderate	-	0.5-4%	-	1-10%
Sand Filter Vault	Moderate	$10,556x^{0.534}$	2.5-9.5%	-	11-13%
Sediment/Oil/Grease Separator	High	-	-	-	-
Vault with Capture Volume	High	-	-	-	-
Permeable Pavement	Moderate	-	39%	-	-

Table 2-10: Spreadsheet based table for estimating BMP maintenance costs (Lampe et al 2005)



ROUTINE MAINTENANCE ACTIVITIES (Frequent, scheduled events)

Cost Item	Frequency (months betw. maint. events)			Hours per Event			Average Labor Crew Size			Avg. (Pro-Rated) Labor Rate/Hr. ($)			Machinery Cost/Hour ($)			Materials & Incidentals Cost/Event ($)			Total cost per visit ($)		
	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input
Inspection, Reporting & Information Management	36		36	2		2	1.0		1.0	40		40	30		30	0		0	140		140
Vegetation Management with Trash & Minor Debris Removal	12		12	4		4	2.0		2.0	30		30	60		60	0		0	480		480
Vector Control	36		36	0		0	1.0		1.0	40		40	200		200	200		200	200		200
add additional activities if necessary			0			0			0.0			0			0			0	0		0
add additional activities if necessary			0			0			0.0			0			0			0	0		0

CORRECTIVE AND INFREQUENT MAINTENANCE ACTIVITIES (Unplanned and/or > 3 yrs. betw. events)

Cost Item	Frequency (months betw. maint. events)			Hours per Event			Average Labor Crew Size			Avg. (Pro-Rated) Labor Rate/Hr. ($)			Machinery Cost/Hour ($)			Materials & Incidentals Cost/Event ($)			Total cost per visit ($)		
	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input
Intermittent Facility Maintenance (Excluding Sediment Removal)	12		12			0			0.0			0			0			0	1,000		1,000
add additional activities if necessary			0			0			0.0			0			0			0	0		0
add additional activities if necessary			0			0			0.0			0			0			0	0		0

Cost Item	Frequency (months betw. maint. events)			Sediment Quantity (yds3) [from Sheet 1]			Cost per yd3 to Remove, Dispose of Sediment												Total cost per visit ($)		
	Model	User	Input	Model	User	Input	Model	User	Input										Model	User	Input
Sediment Removal	120		120	168		168	25.0		25.0										4,201		4,201
add additional activities if necessary			0			0			0.0										0		0
add additional activities if necessary			0			0			0.0										0		0

2.8. Rehabilitation/Replacement Costs

All constructed facilities are given (or assumed) to have a design life, which is the amount of time over which the facility is expected to function as designed before major rehabilitation or replacement activities are needed. The rehabilitation and replacement costs in this model represent the costs associated with those activities that occur after the design life of the BMP has been exceeded. There is little published information on these costs, which may be partially attributable to the fact that most BMPs have not yet reached their design life. However, USDOT (2002b) reports a range of expected design life values for most structural BMPs (Table 2-11). Similar to construction and land costs, these costs vary from site to site.

Table 2-11: Expected design life for BMPs (from USDOT 2008)

BMP	Design Life (years)
Constructed Wetland Basin	20-50
Constructed Wetland Channel	20-50
Extended Detention Basin	20-50
Hydrodynamic Separator	50-100
Inlet Inserts	10-20
Media Filter Vault	5-20
Permeable Pavements	15-20
Porous Landscape Detention	5-20
Retention (Wet) Pond	20-50
Sand Filter Basin	5-10[1]
Sand Filter Vault	5-20
Sediment/Oil/Grease Separator	50-100
Vault with Capture Volume	50-100

Notes:

[1] – time required before deep tilling of basin is required

2.9. Salvage Value

Strecker et al (2005), in a similar work to estimate life cycle costs of BMPs, suggested that estimating the future salvage value is too difficult and therefore were assumed to be zero. It is also reasonable to think that BMPs will actually have no salvage value, assuming that they will remain in place in perpetuity. Therefore, in this model, salvage value is assumed to be zero.

2.10. Measuring BMP Effectiveness

Most BMP studies to date have focused on measuring pollutant removal using inlet/outlet monitoring and reporting the findings either using the Efficiency Ratio Method or the Summation of Loads Method. In response to finding that these methods provided misleading BMP performance results, Strecker et al (2001) developed a protocol for evaluating BMP effectivnesss by determining the following;

1. How much stormwater runoff and BMP discharge is reduced by evapotranspiration (ET), infiltration, source controls, etc.
2. How much stormwater runoff is treated by the BMP and how much bypasses (i.e. capture efficiency)?
3. What is the effluent quality of the BMP discharge and the bypassed flows?

This method accounts for all runoff and pollutant load generated from the watershed, in contrast to previous methods that accounted solely for the runoff that passes through the BMP inlet and outlet.

3. MODEL METHODOLOGY

This section documents the methods used to compute BMP effectiveness and life cycle costs.

3.1. Precipitation Data

The model requires two precipitation parameter inputs, mean annual precipitation depth and the 2-Year, 1-Hour total rainfall depth. Default values for these parameters are programmed into the model based on location within the Denver region (Table 3-1). The mean annual precipitation for the Denver, Colorado region is 15.8 inches, as reported on the National Weather Service website (NWS 2008). The 2-Year, 1-Hour rainfall depths for locations near Denver, Colorado region are shown in Figure 3-1 (UDFCD 2004).

Table 3-1 : Default model precipitation values for selected locations in Front Range of Colorado

Location	Mean Annual Precipitation (in)	2-Year, 1-Hour (in)
Arvada	15.8	0.95
Aurora	15.8	1.00
Boulder	15.8	0.87
Denver Metro	15.8	0.95
Lakewood	15.8	0.99
Longmont	15.8	1.02
Parker	15.8	0.97
Westminster	15.8	0.98

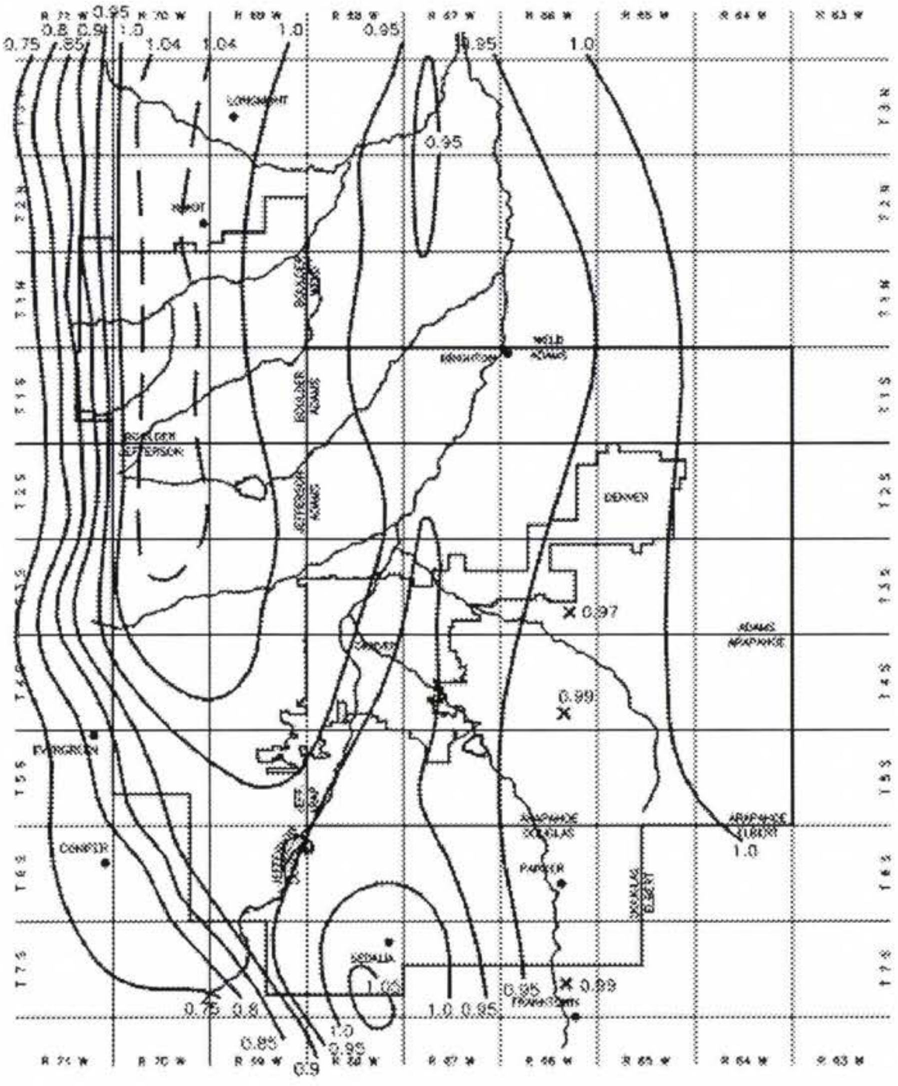


Figure 3-1: Map showing 2-Year, 1-Hour rainfall depths for locations near Denver, CO (UDFCD 2004).

3.2. Watershed Imperviousness

Watershed imperviousness is a commonly used metric for describing the extent of development in an urban area. The model uses "total" and "effective" imperviousness values in its computations and each is described in the following sections. Effective imperviousness is a function of the total imperviousness and the level of source controls applied to the watershed, and empirical equations used to estimate BMP size and rainfall-runoff relationships were developed as a function of the effective imperviousness.

3.2.1. Land Use Total Imperviousness

Total imperviousness is the percentage of a subcatchment (development, watershed, etc.) that is covered by impermeable surfaces (roads, roofs, parking lots, etc.) that do not allow precipitation to infiltrate into the soil. Typical values of total imperviousness as a function of land use are suggested in the USDCM (UDFCD 2004) and summarized in Table 3-2.

Table 3-2 : Default values of total imperviousness for each land use type (UDFCD 2004).

Land Use Type	Percent Imperviousness
Commercial	95
Industrial – Light	80
Industrial – Heavy	90
Residential – Single Family (1,000 sf)	28[1]
Residential – Single Family (2,000 sf)	39[1]
Residential – Single Family (3,000 sf)	51[1]
Residential – Single Family (4,000 sf)	62[1]
Residential – Single Family (5,000 sf)	72[1]
Residential – Multi-Unit (detached)	60
Residential – Large Lot (>1/2 acre)	27[1]
Residential – Apartments	80
Parks, Cemeteries	5
Institutional	50
Paved Area	100
Undeveloped	2

Notes:

[1] - Average values taken from Figures RO 3-5 in USDCM, Vol. 1

3.2.2. Source Controls

Source controls, also sometimes referred to as low impact development (LID) techniques, refer to the use of grass buffers, grass swales, porous pavements and other features to minimize directly-connected impervious areas (MDCIA), thus reducing effective imperviousness. The model allows the user to choose from one of four levels of source control; "Level 0", "Level 1", "Level 2" and "PP". Each option is described below. The affects of implementing source controls on effective imperviousness are described in the following section.

Level 0 – Level 0 source control generally refers to traditional development with roof downspouts and driveways draining directly to curb and gutter systems.

Level 1 – The primary intent of Level 1 MDCIA is to direct the runoff from impervious surfaces to flow over grass-covered areas and porous pavement, and to increase overland travel time so as to encourage the removal of the heavier suspended solids before runoff leaves the site, enters a curb and gutter, or enters another stormwater collection system. Thus, at Level 1, as many of the impervious surfaces as possible are made to drain over grass buffer strips before reaching a stormwater conveyance system (UDFCD 2004). Level 1 source controls are less effective in areas with high total imperviousness because there is not adequate space available to implement grass swales and buffer strips.

Level 2 - As an adjunct to Level 1, this level replaces solid street curb and gutter systems with no curb or slotted curbing and low-velocity grass-lined swales and pervious street shoulders. Conveyance systems and storm sewer inlets will still be needed to collect runoff at downstream intersections and crossings where stormwater flow rates exceed the capacity of the swales. Small culverts will be needed at street crossings and at individual driveways until inlets are provided to convey the flow to a storm sewer (UDFCD 2004). Level 2 source controls are less effective in areas with high total imperviousness because there is not adequate space available to implement grass swales and buffer strips.

PP – "PP" refers to the use of porous pavement (or a variation thereof) as a source control, particularly in areas of high total imperviousness such as shopping centers where Level 1 and Level 2 source controls less effective.

3.2.3. Land Use Effective Imperviousness

Effective imperviousness is the percentage of a watershed that is impervious and drains runoff directly to the paved or piped stormwater collection system. It is a function of the total imperviousness and any source controls applied to the watershed, and is used to compute the size of storage BMPs and the runoff coefficient used to estimate runoff volume and peak flow rates. Empirical methods for estimating effective imperviousness have been developed by UDFCD and are described below according to the level of source controls applied.

None – When no source controls are implemented, the effective imperviousness is equal to the total imperviousness.

Level 1 & Level 2 – Level 1 and Level 2 source controls reduce the effective imperviousness by an amount that is dependant on the total imperviousness of the watershed. The model uses UDFCD's methods for reducing effective imperviousness, as illustrated in Figure 3-2.

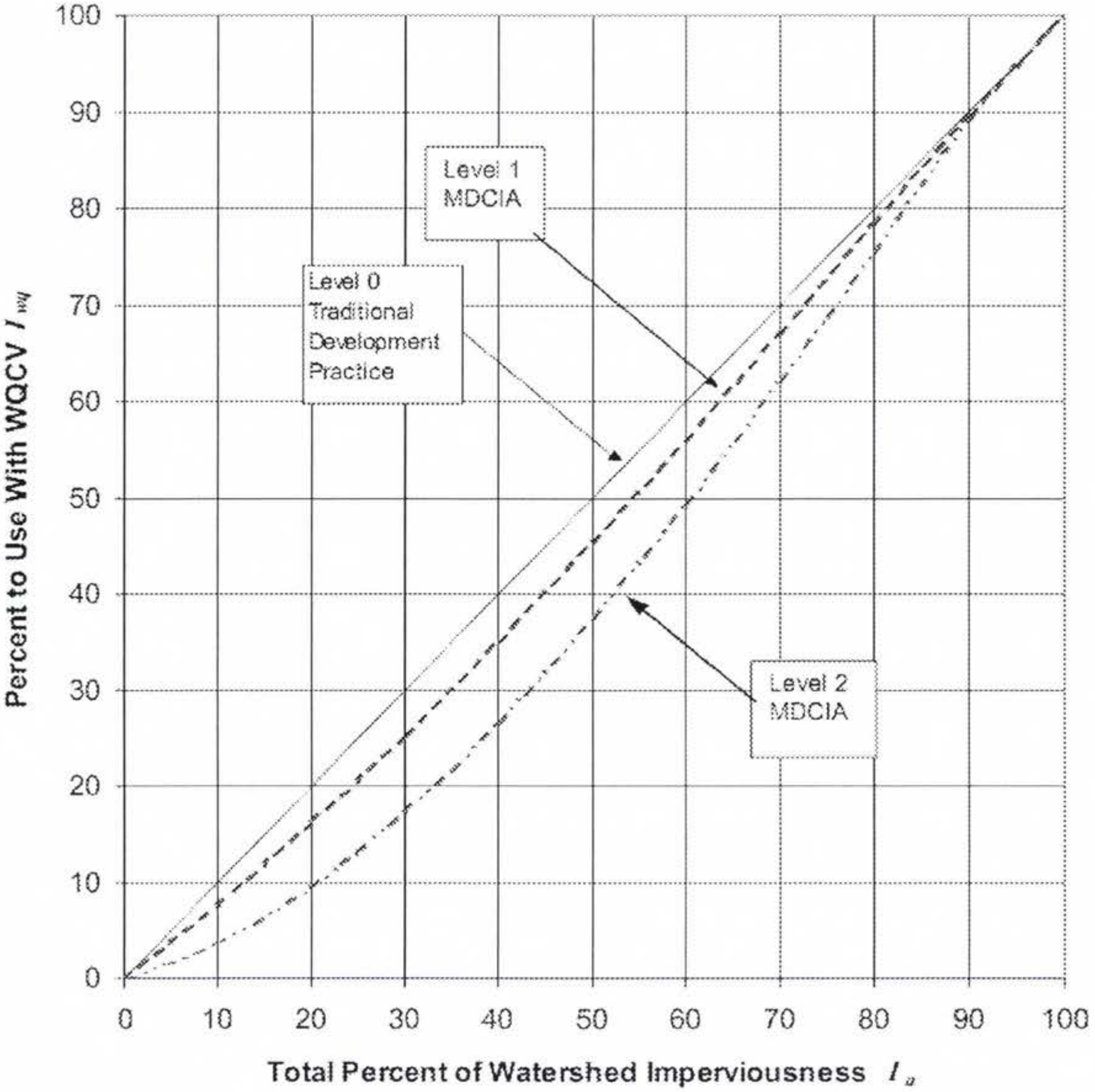


Figure 3-2: Effective imperviousness adjustments for Level 1 and Level 2 MDCIA (UDFCD 2004).

For programming purposes, the plots in Figure 3-2 were converted to the regression equations (3-1), (3-2) and (3-3), which are imbedded within the model macros.

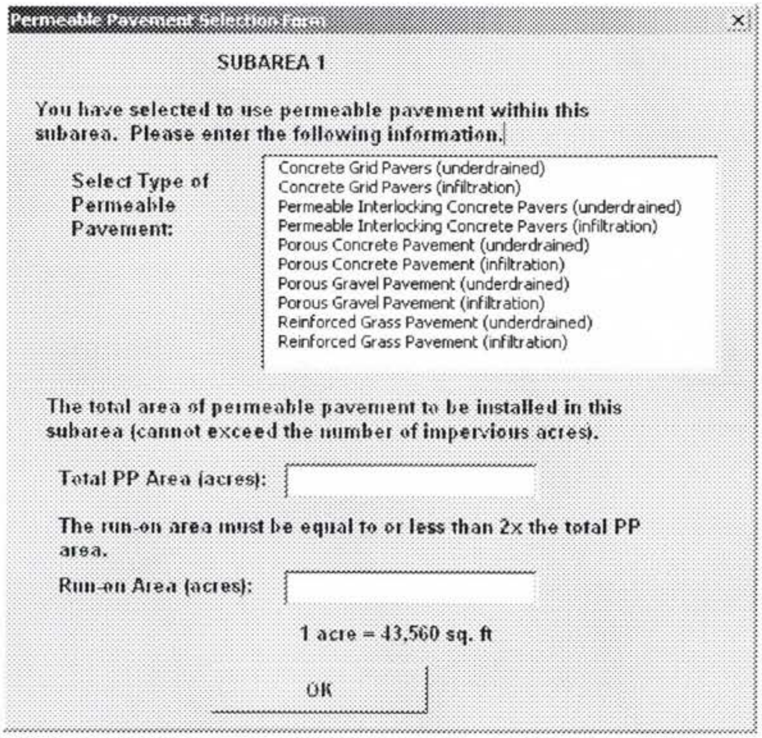
Level 0
$$EI = TI \tag{3-1}$$

Level 1
$$EI = 0.2156TI^2 + 0.8005TI \tag{3-2}$$

Level 2 $$EI = -0.5014TI^3 + 1.2301TI^2 + 0.2764TI \qquad \textbf{(3-3)}$$

Where EI = Effective imperviousness and TI = Total imperviousness.

<u>PP</u> – "PP" refers to the use of permeable pavement as a source control. PP is most effective in areas of high total imperviousness where Level 1 and Level 2 source controls less effective. When "PP" is selected as source control in the model a form appears on the screen (Figure 3-3) within which the user selects the type of permeable pavement to be implemented, its total surface area and the area of impervious surface that runs onto the permeable pavement (i.e. run-on area). The user can select from 5 types of permeable pavement; permeable interlocking concrete pavers (PICP) (aka cobblestone block pavement), concrete grid pavement (CGP) (aka modular block pavement), reinforced grass pavement (RGP), porous gravel pavement (PGP) and porous concrete pavement



SUBAREA 1

You have selected to use permeable pavement within this subarea. Please enter the following information.

Select Type of Permeable Pavement:

- Concrete Grid Pavers (underdrained)
- Concrete Grid Pavers (infiltration)
- Permeable Interlocking Concrete Pavers (underdrained)
- Permeable Interlocking Concrete Pavers (infiltration)
- Porous Concrete Pavement (underdrained)
- Porous Concrete Pavement (infiltration)
- Porous Gravel Pavement (underdrained)
- Porous Gravel Pavement (infiltration)
- Reinforced Grass Pavement (underdrained)
- Reinforced Grass Pavement (infiltration)

The total area of permeable pavement to be installed in this subarea (cannot exceed the number of impervious acres).

Total PP Area (acres):

The run-on area must be equal to or less than 2x the total PP area.

Run-on Area (acres):

1 acre = 43,560 sq. ft

Figure 3-3: Permeable pavement selection user form

(PCP), each with or without underdrains. The effective imperviousness of PP suggested by UDFCD (2004) are shown graphically in Figure 3-4.

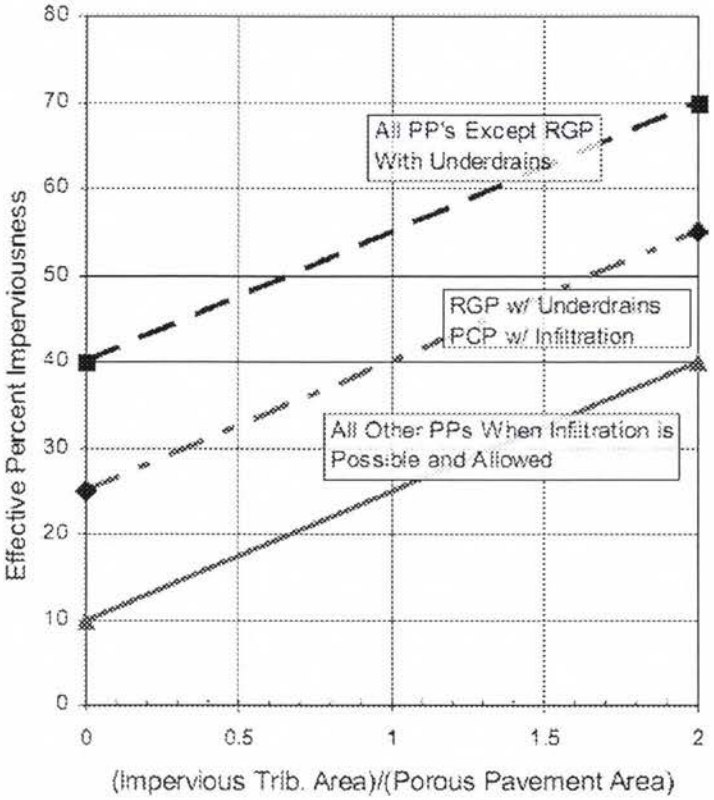


Figure 3-4: Effective imperviousness adjustments for using permeable pavements.

3.3. Runoff Coefficients

UDFCD has developed empirical equations for estimating watershed runoff coefficients as a function of the imperviousness of the watershed. The UDFCD equations are used in the model and are provided below (UDFCD 2004).

$$C_A = K_A + \left(1.31i^3 - 1.44i^2 + 1.135i - 0.12\right) \text{ for } C_A>0 \text{ otherwise } C_A=0 \qquad \textbf{(3-4)}$$

$$C_{CD} = K_{CD} + \left(0.858i^3 - 0.786i^2 + 0.774i + 0.04\right) \qquad \textbf{(3-5)}$$

$$C_B = (C_A + C_{CD})/2 \tag{3-6}$$

Where i = watershed imperviousness, C_A = runoff coefficient for NRCS Type A soils, C_B = runoff coefficient for NRCS Type B soils, C_{CD} = runoff coefficient for NRCS Type C & D soils, K_A = correction factor for Type A soils (Table 3-3) and K_{CD} = correction factor for Type C & D soils (Table 3-3).

Table 3-3 : Table of correction factors for calculating runoff coefficients

Soil Type	**Storm Return Period**	
	2–Year	**5-Year**
A	0	-0.08i + 0.09
C & D	0	-0.10i + 0.11

The model uses a 2-year return storm period (correction factors = 0) for generating runoff and the 5-year correction factors are used to calculate the time of concentration for the Rational Method.

3.4. BMP Size

The size of a BMP refers to the quantity of its design storage volume, its design flowrate, or its surface area. "Volume-based" BMPs are designed to capture and treat a specified volume of runoff and "flow-based" BMPs are designed to convey and treat a specified peak flowrate of runoff. "Area-based" BMPs, such as permeable pavements, are designed to reduce an area's imperviousness. Table 3-4 lists the BMPs and their design classification. The methods for computing BMP size are described in the following sections.

3.4.1. Volume-Based BMPs

UDFCD has developed design criteria for sizing volume-based structural BMPs so that the runoff from approximately 80% of the annual precipitation events is captured and effectively treated for water quality purposes. The water quality capture volume (WQCV) refers to a specific depth of precipitation that should be captured by the BMP, and is a function of the contributing area effective imperviousness and the required drawdown time of the BMP. Multiplying the WQCV by the contributing area gives the recommended storage volume for capturing and treating 80% of annual precipitation events. The procedures used for computing the WQCV are as follows. **Note**: The WQCV computed for each BMP does not account for additional storage that may be required for flood control. Equation (3-7) is UDFCD's empirical equation for estimating the WQCV of a BMP.

Table 3-4: BMP design classification

BMP	Design Classification
Constructed Wetland Basin	Volume-based
Constructed Wetland Channel	Flow-based
Extended Detention Basin	Volume-based
Hydrodynamic Separator	Flow-based
Inlet Inserts	Flow-based
Media Filter Vault	Volume-based
Permeable Pavements	Area-based
Porous Landscape Detention	Volume-based
Retention (Wet) Pond	Volume-based
Sand Filter Basin	Volume-based
Sand Filter Vault	Volume-based
Sediment/Oil/Grease Separator	Flow-based
Vault w/ Capture Volume	Volume-based

$$WQCV = a*(0.91EI^3 - 1.19EI^2 + 0.78EI) \tag{3-7}$$

Where $WQCV$ = water quality capture volume (watershed-inches), a = coefficient based on suggested drawdown time for the BMP, and EI = effective imperviousness of the watershed (%).

UDFCD also has procedures for designing the storage volume of EDBs and RPs to capture and treat the excess urban runoff volume (EURV) for both water quality and flow control purposes. The EURV is the additional runoff that is generated when undeveloped land is urbanized and is dependent on the imperviousness and soil type of the watershed. Equations (3-7), (3-9), and (3-10) are used to compute the EURV for soil types A, B and C/D, respectively.

$$EURV_A = 1.1 * (2.0491EI - 0.1113) \quad \textbf{(3-8)}$$

$$EURV_B = 1.1 * (1.2846EI - 0.0461) \quad \textbf{(3-9)}$$

$$EURV_{C/D} = 1.1 * (1.1381EI - 0.0339) \quad \textbf{(3-10)}$$

Where $EURV$ = excess urban runoff volume (watershed-inches) and EI = effective imperviousness of the watershed (%).

The design volume of BMPs are then computed using Equation (3-11) for volume measured in acre-feet (AF) or Equation (3-12) for volume measured in cubic feet (ft^3).

$$DesignVolume(AF) = StorageVolume / 12 * CA * ASF \quad \textbf{(3-11)}$$

$$DesignVolume(ft^3) = StorageVolume / 12 * CA * ASF * 43{,}560 \quad \textbf{(3-12)}$$

Where CA = contributing area (acres), ASF = additional storage factor and $StorageVolume$ = WQCV or EURV (watershed-inches). Drawdown time ("a") and additional storage factor ("ASF") values for each volume-based BMP in the model are presented in Table 3-5. The drawdown time coefficients are values recommended by UDFCD (2004). The ASF values were determined as described below:

Table 3-5: Volume-based BMP design factors (UDFCD 2004)

BMP	Drawdown Time Coefficient, *a*	Additional Storage Factor, *ASF*
Extended Detention Basin	1.0	1.2
Retention (Wet) Pond - WQCV	0.8	2.6
Retention (Wet) Pond – EURV	0.8	1.5
Sand Filter Basin	1.0	1.0
Vault w/ Capture Volume	0.8	1.1
Sand Filter Vault	0.8	1.0
Media Filter Vault	0.8	1.0
Constructed Wetland Basin	0.9	1.75
Porous Landscape Detention	0.8	1.0

Extended Detention Basin – additional 20% storage is needed for sediment accumulation

Retention Pond (WQCV) – additional 160% storage is needed for the permanent pool and sediment accumulation.

Retention Pond (EURV) – additional 50% storage is needed for permanent pool and sediment accumulation.

Constructed Wetland Basin – additional 75% storage is needed for permanent pool and sediment accumulation.

Vault with Capture Volume – additional 10% storage is needed for sediment accumulation.

3.4.2. Flow-Based BMPs

UDFCD recommends sizing flow-based BMPs to convey the 2-year peak flow rate. The peak flow rate is computed from the Rational Method, using UDFCD methods for estimating time of concentration and design rainfall intensity. UDFCD has additional design criteria for constructed wetland channels (CWC) that must be met after the design flow rate is determined.

Peak flow rates are estimated from the Rational Method, Equation (3-13):

$$Q = CIA \tag{3-13}$$

Where Q = peak flow rate (cfs), C = runoff coefficient for contributing area, I = rainfall intensity (in/hr), A = contributing area (acres).

The rainfall intensity is computed using Equation (3-14), derived by UDFCD and applicable to the Front Range region of Colorado.

$$I = \frac{28.5P_1}{(10 + Tc)^{0.786}} \tag{3-14}$$

Where P_1 = 2-Year, 1-hour point rainfall depth (inches) and Tc = time of concentration (minutes).

The time of concentration is the sum of the travel times for initial (overland) flow, Ti, and channelized flow, Tt.

$$Tc = Ti + Tt \tag{3-15}$$

For locations within the Front Range region of Colorado, the travel time for initial (overland) flow, Ti, is the lesser of the two values computed in Equations (3-16) and (3-17).

$$Ti = \frac{0.395(1.1 - C_5)\sqrt{L_{OF}}}{S^{0.33}} \tag{3-16}$$

$$Ti = \frac{L_{OF}}{180} + 10 \tag{3-17}$$

Where C_5 = runoff coefficient for 5-year frequency, S = watershed slope (ft/ft) and L_{OF} = overland flow length (ft).

Travel time for channelized flow is computed with Equation (3-18)

$$Tt = \frac{L_{CF}}{V} \tag{3-18}$$

Where L_{CF} = channelized flow length (ft) and V = average velocity (ft/s) computed using Equation (3-19).

$$V = C_v S^{0.5} \tag{3-19}$$

Where C_v = conveyance coefficient[2] and S = watershed slope (ft/ft).

To minimize the number of required user inputs, the overland and channelized flow lengths are automatically computed by the model, assuming a square, v-shaped draining watershed, as shown in Figure 3-5. These assumed lengths are considered reasonable for planning-level studies.

Overland and channelized flow lengths are computed using Equations (3-20) and (3-21), respectively.

$$L_{OF} = 0.5 * \sqrt{CA_{BMP} * 43560} \tag{3-20}$$

---

[2] The conveyance coefficient is assumed to be 20, the value used for paved areas and shallow paved swales which are expected in urban watersheds.

$$L_{CF} = \sqrt{CA_{BMP} * 43560} \tag{3-21}$$

Where L_{OF} = overland flow length (ft) (maximum of 300 ft), L_{CF} = channelized flow length (ft) and CA_{BMP} = contributing area to the BMP (acres).

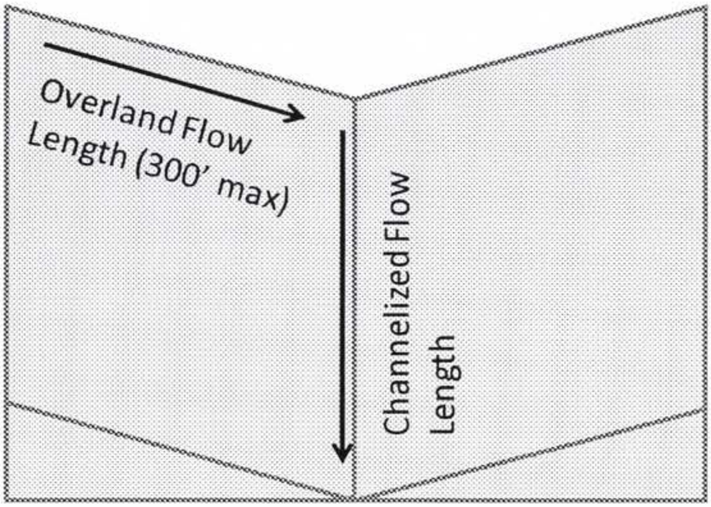


Figure 3-5: Diagram showing overland and channelized flow lengths assuming v-shaped watershed

3.5. Construction Costs

Construction costs are represented in the form of a parametric equation (3-22) where costs are expressed as a function of the BMP size, a base cost and an exponent term that reflects economies of scale typically realized with construction projects.

$$ConCost = C + XU^{\alpha} \tag{3-22}$$

Where $ConCost$ = total construction cost, C = base cost, X = unit cost, U = size of the BMP (ft^2, ft^3, AF, cfs, acres) and α = economies of scale factor.

The size of the BMP is the storage volume for volume-based BMPs, design flow rate for flow-based BMPs and surface area for area-based BMPs. This method of computing construction costs was chosen because it achieves the model objectives of being able to evaluate multiple BMP sizes within one scenario, is able to reflect economies of scale and is simple enough for users to adjust the cost equation to fit their needs.

3.5.1. Construction Cost Equation Selection and Modification

The construction costs obtained from the literature serve as the basis for the construction cost equations used in the model. Some reported costs could be applied "as is" to the model with the only modifications being cost adjustments for time and location (discussed in Sections 3.12 and 3.13), however in other cases the reported costs required modification to fit the model parametric equation format. Also, in cases where more than one cost equation was reported in the literature for the same BMP, a decision to select one over another was required. This section discusses the method(s) used to modify and/or select costs from the literature for use in the model.

Selecting from More than One Reported Cost

Several BMPs have more than one cost equation reported in the literature. In these cases, a decision to choose one over the other(s) was made considering the factors listed below:

- How long ago the cost estimate was prepared. Brown and Schueler (1997) found that cost estimates had changed significantly from 1986 to 1997 and suggested that the older cost estimates were no longer valid due to changes in design criteria over time.

- How reliable and/or comprehensive the results appeared. How many individual BMPs were evaluated to develop a cost equation, what the R^2-value was for the equation or how detailed the engineer's estimates were.
- How well the existing results fit the model's parametric equation method of costs being a function of storage volume or flowrate. Having to modify equations that report costs as a function of say, watershed area, would require additional assumptions that could introduce more uncertainty into the equations.

Typically, "competing" costs evaluated well on some factors but not others, therefore the selection was ultimately based on engineering judgment considering all of the factors and costs together.

Modifying Reported Costs for Model Use

Some modifications were necessary when the reported costs were not provided in the form of a parametric equation. In cases where costs were reported for more than two sizes of a BMP, the costs were plotted against the corresponding sizes and a best-fit line (based on linear or power equation R^2-value) was fit to the data using Microsoft Excel. The equation of the best fit line was then taken as the parametric cost equation.

Some BMPs only have cost ranges reported. When costs were reported as a range of unit costs (for example, \$5-10 per ft^2 or \$2,000-5,000 per acre), the cost ranges were converted to parametric equations using the following procedures:

1. Reasonable minimum and maximum BMP sizes were determined. This value may either be reported in the literature or assumed based on experience.

2. The highest unit cost was assumed to apply to the minimum size BMP and lowest unit cost to the maximum size BMP. This assumption is consistent with economies of scale that are typically observed with construction projects.
3. The total costs (BMP size multiplied by unit cost) were plotted against the corresponding BMP sizes and a best-fit power curve was fit to the two data points using Microsoft Excel. The equation of the best fit line was then taken as the parametric cost equation.

Parametric cost equations were developed for hydrodynamic separators, permeable pavements, sediment/oil/grease separators and vaults with capture volume.

Hydrodynamic Separator

Six cost data points were available from USEPA (1999), 2 data points each for 3 different types of proprietary devices. Those points are presented in Table 3-6 and plotted in Figure 3-6. The best-fit line through the data points was linear (R^2-value = 0.96), suggesting that the construction costs of hydrodynamic separators do not exhibit economies of scale.

Table 3-6: Cost data points used for developing a parametric cost equation for hydrodynamic separators (USEPA 1999)

Device	Size (cfs)	Unit Cost ($/cfs)	Total Cost (1999$)
Device #1 – Minimum	3	$7,200	$21,600
Device #1 – Maximum	62	$2,300	$142,600
Device #2 - Minimum	0.75	$13,300	$10,000
Device #2 – Maximum	13	$2,700	$35,100
Device #3 - Minimum	1.6	$6,250	$10,000
Device #3 – Maximum	25	$1,600	$40,000

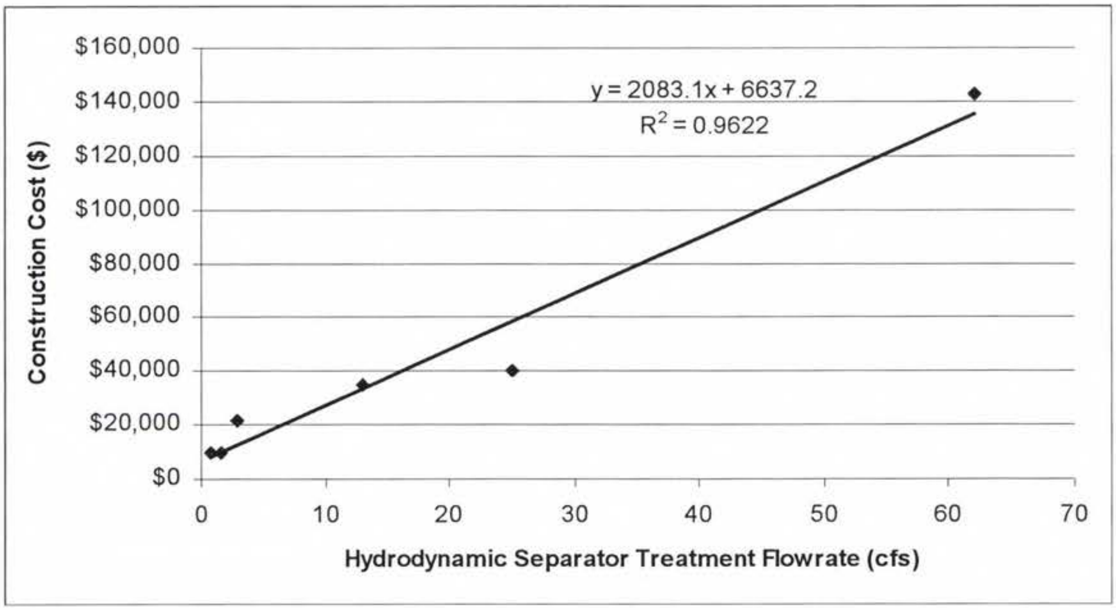


Figure 3-6: Cost curve generated for hydrodynamic separators

Permeable Pavement

It was assumed that the minimum and maximum size of permeable pavements is 0.1 and 2 acres, respectively, and that the reported construction cost ranges by the LID Center (2001) apply over this range. Table 3-7 shows the cost and size data points plotted in Figure 3-7 for each of the 5 types of permeable pavements.

Vault with Capture Volume

Cost and storage volume information was reported in USEPA (2001) for six projects located throughout the US. The data points are presented in Table 3-8 and plotted in Figure 3-8. The best-fit line through the data points was linear (R^2-value = 0.97), suggesting that the construction costs of vaults with capture volume do not exhibit economies of scale.

Table 3-7: Cost data points used for developing parametric cost equations for permeable pavements

Permeable Pavement Type	Size (ft^2)	Unit Cost ($\$/ft^2$)	Total Cost (2001\$)
Concrete Grid Pavers – Minimum	4,356	\$10.00	\$43,560
Concrete Grid Pavers – Maximum	87,120	\$5.00	\$435,600
Permeable Interlocking Concrete Pavers - Minimum	4,356	\$10.00	\$43,560
Permeable Interlocking Concrete Pavers – Maximum	87,120	\$5.00	\$435,600
Reinforced Grass Pavement - Minimum	4,356	\$5.75	\$25,047
Reinforced Grass Pavement – Maximum	87,120	\$1.50	\$130,680
Porous Gravel Pavement - Minimum	4,356	\$5.75	\$25,047
Porous Gravel Pavement – Maximum	87,120	\$1.50	\$130,680
Porous Concrete Pavement - Minimum	4,356	\$6.50	\$28,314
Porous Concrete Pavement – Maximum	87,120	\$2.00	\$174,240

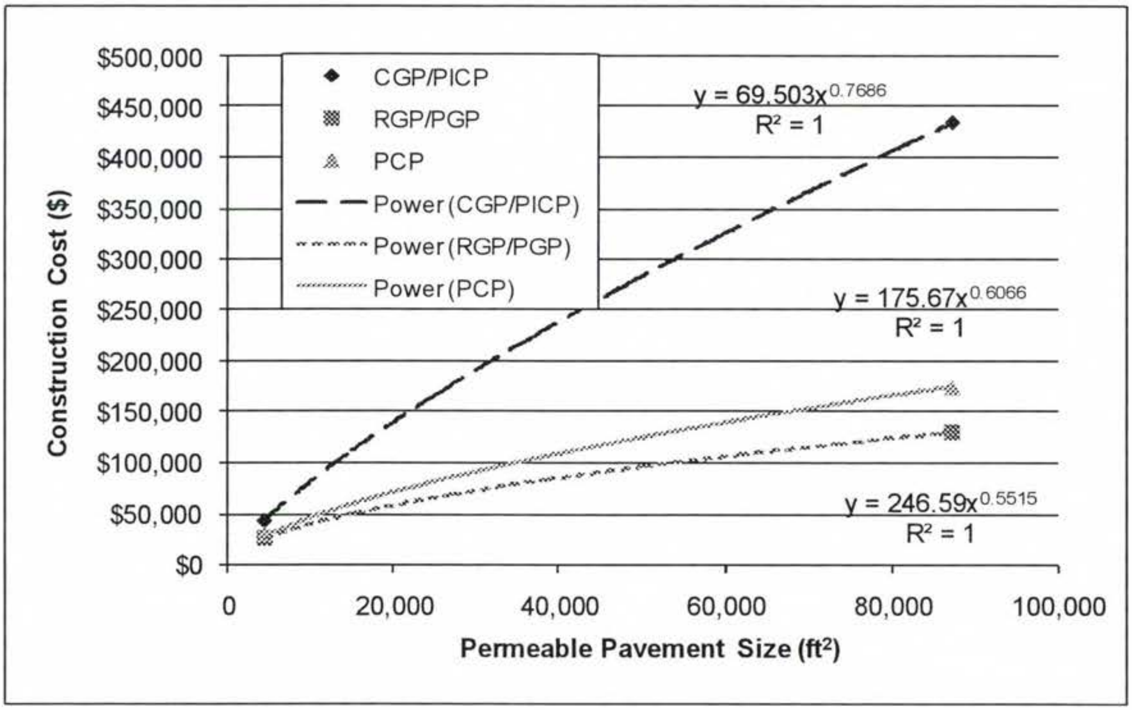


Figure 3-7: Cost curves generated for permeable pavements

Table 3-8: Data points used for developing parametric cost equations for vaults with capture volume

Type	Size (ft^2)	Construction Cost
Corrugated Steel Pipe	868,380	$6,750,000
Aluminum	251,336	$900,000
High Density Polyethylene	50,126	$187,500
High Density Polyethylene	2859.3	$21,143
Concrete	16026.2	$200,250
Concrete	3741.8	$63,750

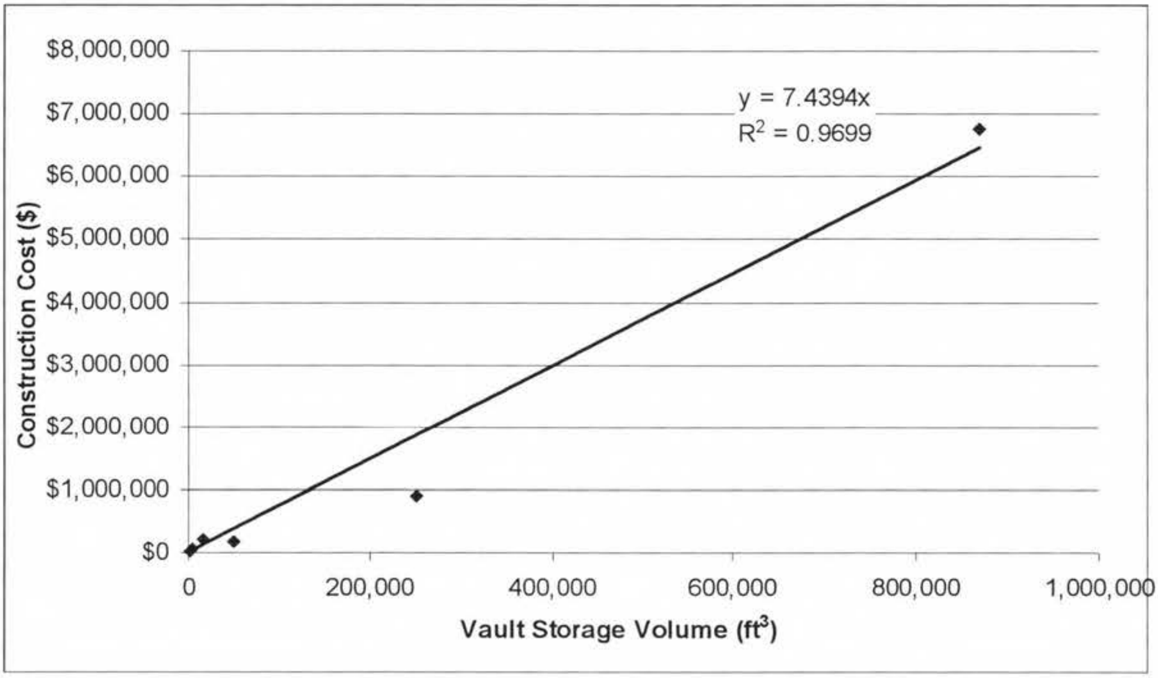


Figure 3-8: Cost curve generated for vaults with capture volume

Sand Filter Vault

Wossink and Hunt (2003) developed a parametric cost equation for SFVs, relating the construction cost to the size of the watershed area. Their equation was modified to relate costs to the size of the BMP using the following procedures and assumptions.

1. Estimate the values of watershed area and costs from the plot used by Wossink and Hunt (2003) to develop the cost curve they reported. Those

values are presented in Table 3-9. (Their study did not present the actual values used, just the plot of values).

2. Assume that the reported watershed areas were 100% impervious, as sand filters usually drain highly impervious areas such as parking lots.
3. Compute the WQCV using Equations (3-7) and (3-12), as recommended by UDFCD.
4. Plot reported costs against the computed WQCV and generate a cost curve by applying a best-fit trendline (Table 3-10 and Figure 3-9).

The best-fit trendline (R^2-value = 0.95) is linear, suggesting that sand filter vaults do not show economies of scale.

Table 3-9: Estimated watershed areas and costs used by Wossink and Hunt (2003) for developing a sand filter cost equation

Watershed Area (acres)	Construction Costs (2003$)
0.5	$40,000
1	$40,000
1	$60,000
1	$65,000
1.1	$40,000
1.2	$65,000
2	$25,000
2	$125,000
5	$215,000
9	$465,000

Note: This table includes only 10 data points, whereas the authors report 12 data points were used to generate the cost equation. The two missing data points could not be discerned from the plot.

BMPs without Construction Costs Reported in the Literature

Three BMPs (SOGs, MFVs and CWCs) did not have cost estimates reported in the literature; however it is possible to apply cost estimates reported for BMPs with similar design and functionality to these BMPs.

Table 3-10: Data points used for developing parametric cost equation for sand filter vaults

WQCV (ft^3)	Construction Costs (2003$)
726	$40,000
1452	$40,000
1452	$60,000
1452	$65,000
1597	$40,000
1742	$65,000
2904	$25,000
2904	$125,000
7260	$215,000
13068	$465,000

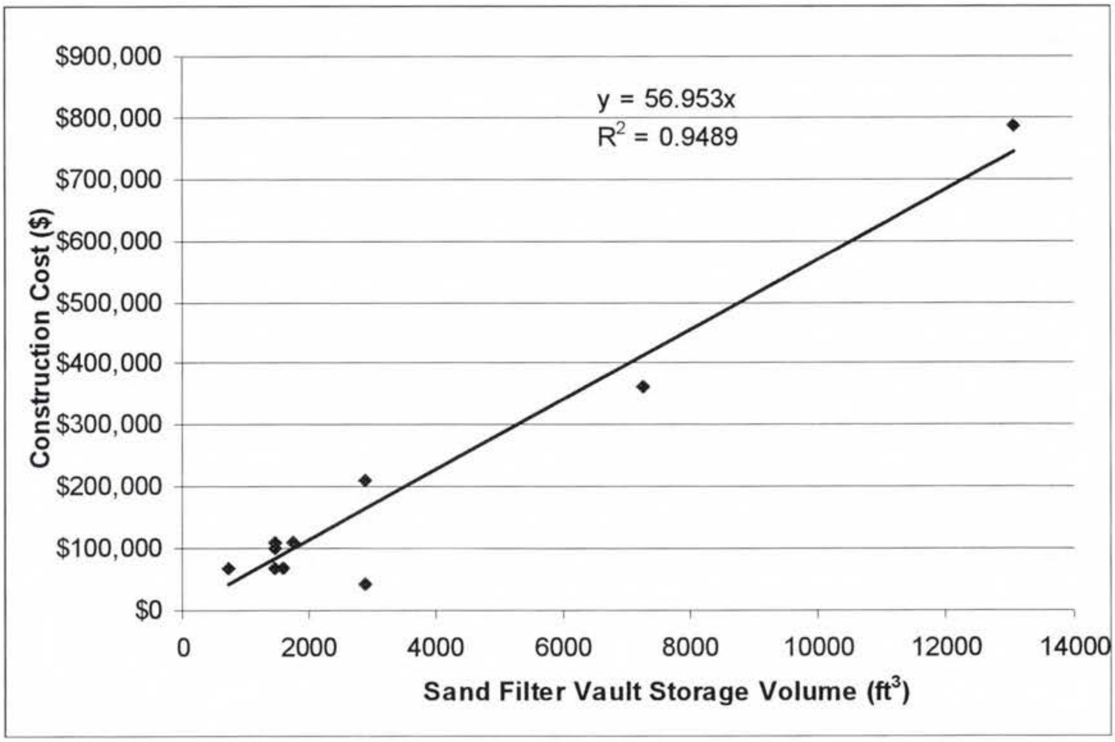


Figure 3-9: Cost curve generated for sand filter vaults

Sediment/Oil/Grease Separator

Sediment/oil/grease separators are similar to hydrodynamic separators, in that both devices are generally manufactured offsite, have concrete structures with internal, metallic components and require excavation for installation. Given these similarities and the fact that no SOG costs were reported in the literature, it is assumed that the construction costs of SOGs will be similar to HSs.

Media Filter Vaults

Media filter vaults are similar in design and construction as sand filter vaults, with the most significant difference being the filtering material. Assuming the cost difference between the sand and media filtering material is negligible compared to the other construction costs, than the cost equation reported for a sand filter vault is also applicable to media filter vaults.

Constructed Wetland Channel

The cost equation reported for constructed wetland basins can be applied to constructed wetland channels assuming that a CWC is an elongated, linear wetland cell and that the majority of the construction costs of stormwater wetlands are related to excavation and wetland plantings. To do so, a relationship between the design flowrate of a CWC and the total volume of the channel must be developed.

The volume of a CWC, computed using Equation (3-23), is the product of the cross-sectional area of the channel (normal to flow) and the length of the channel. UDFCD provides guidance for sizing the cross-sectional area of the channel; however the length of the channel can vary from site to site and is not a function of the design flowrate. The methods and assumptions for each component are discussed separately below.

$$V = A * L \tag{3-23}$$

Where V = total volume (ft^3), A = cross-sectional area of channel (ft^2) and L = length of channel (ft).

Channel Cross-Sectional Area

The channel cross-section is determined using Manning's Equation for a trapezoidal channel. To minimize the number of required user-inputs, all the characteristics of the channel, except for bottom width, have been assumed according to UDFCD recommendations. The model then solves for bottom width and cross-sectional area, using Equations (3-24)-(3-26). Key assumptions used to develop the equations are described below and are based on UDFCD recommended values.

- The bottom width must be a minimum of 8 feet.
- The runoff velocity at full-flow is assumed to be 2 feet per second.
- The Manning's coefficient is assumed to be 0.08.
- The slope of the channel is assumed to be 0.001.
- The depth of runoff at full-flow is assumed to be 3 feet.
- Side slopes are assumed to be 5:1 (horizontal:vertical).

$$Q = \frac{1.49}{n} A R^{2/3} S^{0.5} \tag{3-24}$$

$$A = 3b + 45 \tag{3-25}$$

$$R = \frac{(0.5878b + 8.8255)}{(0.1959b + 6)} \tag{3-26}$$

Where Q = peak flow rate (cfs), A = channel cross sectional area (ft^2), R = channel hydraulic radius (ft), S = channel slope (ft/ft) and b = channel bottom width (ft).

Sizing Channel Length(L)

Channel length is equal to the square root of the area draining to the channel, Equation (3-27). This assumes that the contributing area is square and the channel bisects the area as in a classic "V-shaped" watershed model.

$$L = \sqrt{CA_{BMP} * 43{,}560} \qquad \textbf{(3-27)}$$

Where L = channel length (ft) and CA_{BMP} = contributing area to the BMP (acres).

3.5.2. Construction Cost Equations Used in Model

Table 3-11 summarizes the default equations used to compute BMP construction cost estimates in the model. The costs are adjusted to May 2008, nationally-averaged costs using the Engineering News Record (ENR) Construction Cost Index (CCI) value of 8,141 (ENR 2008). The procedures for adjusting costs using this index are documented in Sections 3.12 and 3.13.

Table 3-11: Summary of construction cost equations used in the model

BMP	Cost Equation (2008$)	Source	Notes
Constructed Wetland Basin	$\$41.5(V)^{0.705}$	Brown and Schueler (1997) and USEPA (2008)	
Constructed Wetland Channel	$\$41.5(V)^{0.705}$	Brown and Schueler (1997) and USEPA (2008)	Assumed similar to CWB costs
Extended Detention Basin	$\$14.8(V)^{0.78}$	Brown and Schueler (1997)	
Hydrodynamic Separator	$2,800(F)+ $8,918	USEPA (1999)	Adapted from range of reported costs
Inlet Inserts	$100(E)	AdsorbantsOnline (2009) Bowhead Env. & Safety (2009)	Average of reported range of costs for disposable-type filters
Media Filter Vault	$56.95(V)	Wossink and Hunt (2003)	Adapted from cost equation reported for sand filter vault
Porous Landscape Detention	$\$10.3(V)^{0.99}$	Wossink and Hunt (2003)	
Retention (Wet) Pond	$\$15.4(V)^{0.75}$	Brown and Schueler (1997)	
Sand Filter Basin	$\$30.3(V)^{0.69}$	Young et al (1996) reported in USEPA (2004)	
Sand Filter Vault	$56.95(V)	Wossink and Hunt (2003)	Adapted from cost equation reported for sand filter vault
Sediment/Oil/Grease Separator	$2,800(F)+ $8,918	USEPA (1999)	Assumed similar costs to hydrodynamic separators
Vault with Capture Volume	$7.44(V)	USEPA (2001)	Adapted from range of reported costs
Concrete Grid Pavers (Modular Blocks)	$\$89.3(SA)^{0.77}$	The LID Center (2009)	Adapted from range of reported costs

BMP	Cost Equation (2008$)	Source	Notes
Permeable Interlocking Concrete Pavers (Cobblestone Blocks)	$\$89.3(SA)^{0.77}$	The LID Center (2009)	Adapted from range of reported costs
Porous Concrete Pavement	$\$317(SA)^{0.61}$	The LID Center (2009)	Adapted from range of reported costs
Porous Gravel Pavement	$\$226(SA)^{0.55}$	The LID Center (2009)	Adapted from range of reported costs
Reinforced Grass Pavement	$\$226(SA)^{0.55}$	The LID Center (2009)	Adapted from range of reported costs

Notes:
E = each
F = design flowrate (cfs)
SA = surface area (ft^2)
V = storage volume (ft^3)

3.6. Land Costs

Land costs are a function of the land required for the BMP and the cost of the land on which the BMP will be constructed. For storage BMPs, the land required can be computed using the impervious area of the subcatchment and a derived coefficient referred to as the "land consumption factor" (LCFCTR), with land costs then being computed using Equation (3-28).

$$LandCost = LC * IA * LCFCTR \tag{3-28}$$

Where $LandCost$ = cost of land required for the BMP, LC = cost of land based on land use (\$/acre), IA = impervious area contributing to the BMP (acres) and $LCFCTR$ = factor relating the land required for the BMP to the impervious area contributing to it (%).

Permeable pavements and BMPs located underground do not have land costs associated with them.

The land required for constructed wetland channels is equal to the surface area of the channel, which is the product of the channel top width and length. Land costs for CWCs are computed using Equation (3-29).

$$LandCost = LC * Tw * L \tag{3-29}$$

Where $LandCost$ = cost of land required for the BMP, LC = cost of land based on land use (\$/acre), L = channel length (ft) and Tw = channel top width (ft).

The channel length is determined using Equation (3-27). The channel top width is equal to the bottom width of the channel plus 30 feet, assuming a 3 foot channel depth and 5:1 side slopes.

3.6.1. Cost of Land Based on Land Use

The cost of land is a function of the land use. The default land cost values used in the model are the average of the range of land costs reported in the literature for similar land uses (Table 3-12).

Table 3-12: Unit Land Costs Based on Land Use

Land Use	Unit Land Cost ($/acre)
Commercial	$200,000
Industrial – Light	$200,000
Industrial – Heavy	$200,000
Residential – Single Family	$130,000
Residential – Multi-Unit (detached)	$1,750,000
Residential – Large Lot (>1/2 acre)	$130,000
Residential – Apartments	$1,750,000
Parks, Cemeteries	$35,000
Institutional	$130,000
Paved Area	$1,750,000
Undeveloped	$35,000

3.6.2. Land Required for BMPs (LCFCTR)

Estimates of the area of land required for BMPs has been reported in the literature as a percentage of the watershed area. Despite having these values available, we decided to develop our own estimates using UDFCD BMP design recommendations to determine the surface area of BMPs as a function of their storage volume. Recognizing that storage volume is dependant on the impervious area contributing to the BMP, the area of land consumed by the BMP can then be related to the impervious area draining to that BMP. The following sections describe the methods and assumptions used to develop this relationship for each BMP that requires land.

<u>Constructed Wetland Basin</u>

UDFCD design criteria suggest that CWBs be designed with approximately 2,859 ft^3 of storage per impervious acre of contributing area. This volume accounts for the WQCV, sediment accumulation and the permanent pool. Assuming an average depth of 2 feet, the surface area required for a CWB is approximately 1,430 ft^2 per impervious acre. Also assuming that an area equal to 100% of the CWB surface area should be set aside for maintenance access and other considerations, the total land required for a CWB is approximately 2,859 ft^2 per impervious acre of contributing area, or 6.5%.

Constructed Wetland Channel

The LCFCTR used for CWCs is 100% because the land required for the BMP is computed directly from the surface area of the BMP, not indirectly as a function of the impervious area. The value of 100% implies the land required for the BMP is equal to the surface area of the BMP.

Extended Detention Basin -WQCV

UDFCD design criteria suggest that EDBs designed to capture the WQCV contain approximately 2,178 ft^3 of storage per impervious acre of contributing area. This volume accounts for the WQCV plus an additional 20% for sediment accumulation. Assuming an average EDB depth of 2 feet, the surface area required for an EDB is approximately 1,090 ft^2 per impervious acre. Also assuming that an area equal to 100% of the EDB surface area should be set aside for maintenance access and other considerations, the total land required for an EDB is approximately 2,178 ft^2 per impervious acre of contributing area, or 5%.

Extended Detention Basin –EURV

UDFCD design criteria suggest that EDBs designed to capture the EURV contain approximately 5,445ft^3 of storage per impervious acre of contributing area, assuming soil types C and D (most common in the Front Range region). This volume accounts for the EURV plus an additional 20% for sediment accumulation. Assuming an average EDB depth of 2 feet, the surface area required for an EDB is approximately 2,722 ft^2 per impervious acre. Also assuming that an area equal to 100% of the EDB surface area should be set aside for maintenance access and other considerations, the total land required for an EDB is approximately 5,445 ft^2 per impervious acre of contributing area, or 12.5%.

Porous Landscape Detention

UDFCD design criteria suggest that PLDs be designed to capture approximately 1,452 ft^3 of runoff per impervious acre of contributing area. This volume accounts for the WQCV only. Assuming that the WQCV can "pond" to a depth of 1 foot on the surface of the PLD, the surface area required for an SFB is approximately 1,452 ft^2 per impervious acre, or 3.33%.

Retention Pond -WQCV

UDFCD design criteria suggest that RPs (designed to capture the WQCV) be designed with approximately 3,775 ft^3 of storage per impervious acre of contributing area. This volume accounts for the WQCV plus an additional 160% for sediment accumulation and the permanent pool. Assuming an average depth of 4 feet, the surface area required for an RP is approximately 944 ft^2 per impervious acre. Also assuming that an area equal to 100% of the RP surface area should be set aside for maintenance access and other considerations, the total land required for an RP is approximately 1,888 ft^2 per impervious acre of contributing area, or 4.33%.

Retention Pond –EURV

UDFCD design criteria suggest that RPs (designed to capture the EURV) be designed with approximately 6,086 ft^3 of storage per impervious acre of contributing area assuming soil types C and D (most common in the Front Range region). This volume accounts for the EURV plus an additional 50% for sediment accumulation and the permanent pool. Assuming an average depth of 4 feet, the surface area required for an RP is approximately 1,522 ft^2 per impervious acre. Also assuming that an area equal to 100% of the RP surface area should be set aside for maintenance access and other considerations, the total land required for an RP is approximately 3,044 ft^2 per impervious acre of contributing area, or 7.8%.

Sand Filter Basin

UDFCD design criteria suggest that SFBs be designed with approximately 1,815 ft^3 of storage per impervious acre of contributing area. This volume accounts for the WQCV only. Assuming an average depth of 3 feet, the surface area required for an SFB is approximately 605 ft^2 per impervious acre. Also assuming that an area equal to 100% of the SFB surface area should be set aside for maintenance access and other considerations, the total land required for an SFB is approximately 1,210 ft^2 per impervious acre of contributing area, or 2.78%.

Sand/Media Filter Vaults

UDFCD does not provide design criteria for these BMPs, therefore the average value (1.5%) of the reported land requirements (0-3%) will be used in the model.

Underground BMPs

Underground BMPs do not consume any land and the LCFCTRs are set equal to 0%.

Table 3-13 summarizes the LCFCTR values used in the model.

Table 3-13: LCFCTR values used for computing BMP land costs

BMP	LCFCTR
Constructed Wetland Basin	6.5%
Constructed Wetland Channel	100%
Extended Detention Basin-EURV	12.5%
Extended Detention Basin-WQCV	5%
Hydrodynamic Separator	0%
Inlet Inserts	0%
Media Filter Vault	1.5%
Permeable Pavements	0%
Porous Landscape Detention	3.3%
Retention (Wet) Pond-EURV	7.8%
Retention (Wet) Pond-WQCV	4.3%
Sand Filter Basin	2.8%
Sand Filter Vault	1.5%
Sediment/Oil/Grease Separator	0%
Vault w/ Capture Volume	0%

3.7. Contingency, Engineering and Administration Costs

The additional costs attributable to contingencies, engineering, permitting, erosion control, administration, etc. are assumed to be 40% of the construction costs, as recommended for Denver-area projects by Urbonas (2008).

3.8. Capital Cost Calculations

Capital costs include construction costs, land costs and additional costs attributed to contingencies, engineering, administration etc., and are computed using Equation (3-30):

$$CCost = (1 + CEA) * (C + XU^{\alpha}) + LandCost \qquad \textbf{(3-30)}$$

Where $CCost$ = capital cost for an individual BMP, CEA = factor accounting for contingencies/engineering/administration (%), C = base cost ($), X = unit cost ($ per unit), U = number of units of BMP Size (AF, ft^3, ft^2, acre, cfs), α = economy of scale factor and $LandCost$ = land costs ($).

The default values of each variable, for each BMP type, are presented in Table 3-14.

3.9. Maintenance Cost Calculations

As with capital costs, it was preferred to develop cost equations that related annual maintenance costs to the size of the BMP. Annual maintenance costs for a single BMP typically reflect the costs of performing a wide variety of activities. Those activities can generally be divided into two components; those with costs that vary according to the size of the BMP (referred to herein as "variable" maintenance activities) and those that do not (herein referred to as "constant" maintenance activities). Equation (3-31) was developed for estimating annual maintenance costs as a function of multiple maintenance activities in both components.

Table 3-14: Default values of capital cost parameters used in the model

BMP	CEA (%)	C($)	X($/unit)	Units	α	LCFCTR(%)
Constructed Wetland Basin	40	$0	$41.5	ft^3	0.71	6.5%
Constructed Wetland Channel	40	$0	$41.5	ft^3	0.71	100%
Extended Detention Basin (WQCV)	40	$0	$14.8	ft^3	0.78	5%
Extended Detention Basin (EURV	40	$0	$14.8	ft^3	0.78	12.5%
Hydrodynamic Separator	40	$0	$12,994	cfs	0.56	0%
Inlet Inserts	40	$0	$100	each	1	0%
Media Filter Vault	40	$0	$57.0	ft^3	1	1.5%
Porous Landscape Detention	40	$0	$10.3	ft^3	0.99	3.3%
Retention (Wet) Pond (WQCV)	40	$0	$15.4	ft^3	0.75	4.3%
Retention (Wet) Pond (EURV)	40	$0	$15.4	ft^3	0.75	7.8%
Sand Filter Basin	40	$0	$30.3	ft^3	0.69	2.8%
Sand Filter Vault	40	$0	$57.0	ft^3	1	1.5%
Sediment/Oil/Grease Separator	40	$0	$12,994	cfs	0.56	0%
Vault with Capture Volume	40	$0	$7.44	ft^3	1	0%
Concrete Grid Pavers	40	$0	$89.3	ft^3	0.77	0%
Permeable Interlocking Concrete Pavers	40	$0	$89.3	ft^3	0.77	0%
Porous Concrete Pavement	40	$0	$317	ft^3	0.61	0%
Porous Gravel Pavement	40	$0	$226	ft^3	0.55	0%
Reinforced Grass Pavement	40	$0	$226	ft^3	0.55	0%

$$MCost = C_C + C_V * BMPSize \qquad \textbf{(3-31)}$$

Where $BMPSize$ = number of units of BMP Size (AF, ft^3, ft^2, acre, cfs), $MCost$ = annual maintenance costs for BMP, C_C = total annual cost for "constant" maintenance activities and C_V = total annual unit cost for "variable" maintenance activities.

Table 3-15 shows the maintenance cost equations developed for each BMP. The methods and assumptions used to develop the cost equations are explained in Appendix A.

Table 3-15: Annual maintenance cost equations

BMP	C_C($)	C_V($/unit)	Units
Constructed Wetland Basin	$0	$1,956	AF
Constructed Wetland Channel	$0	$960	Acre
Extended Detention Basin (WQCV)	$1,849	$2,782	AF
Extended Detention Basin (EURV	$1,849	$2,782	AF
Hydrodynamic Separator	$0	$749	cfs
Inlet Inserts	$4,514	$0	each
Media Filter Vault	$0	$1.86	CF
Porous Landscape Detention	$0	$0.62	CF
Retention (Wet) Pond (WQCV)	$1,521	$1,598	AF
Retention (Wet) Pond (EURV)	$1,521	$1,598	AF
Sand Filter Basin	$0	$1,096	AF
Sand Filter Vault	$0	$1.86	CF
Sediment/Oil/Grease Separator	$0	$832	cfs
Vault with Capture Volume	$0	$0.66	CF
Concrete Grid Pavers	$0	$125	Acre
Permeable Interlocking Concrete Pavers	$0	$125	Acre
Porous Concrete Pavement	$0	$125	Acre
Porous Gravel Pavement	$0	$5,647	Acre
Reinforced Grass Pavement	$0	$4,040	Acre

3.10. Rehabilitation/Replacement Cost Calculations

Rehabilitation/replacement costs are computed as percentage of the original construction costs of the BMP using Equation (3-32);

$$RCost = R * ConCost \qquad \textbf{(3-32)}$$

Where *RCost* = rehabilitation/replacement costs for an individual BMP, *R* = percentage of construction costs and *ConCost* = construction costs of BMP.

3.10.1. Reoccurrence Interval of Rehabilitation/Replacement Costs

Rehabilitation and replacement costs reoccur at time intervals equal to the expected design life of each BMP. With a few exceptions (described below), the design life assumed in the model is based on the average of a range of values of expected design lives reported by USDOT (2002).

Inlet Inserts

The estimated design life for inlet inserts reported in USDOT (2002) is not considered applicable to the type of inlet inserts represented in this model. In this model, inlet inserts are assumed to be disposable-type inserts that are replaced whenever they become filled with debris and sediment and not when their material lives are exceeded. Therefore, replacement costs are a function of the frequency of maintenance, which is an input to the model's maintenance tables.

Hydrodynamic Separators and Sediment/Oil/Grease Separators

The design life for "manufactured systems" reported in USDOT (2002) is assumed to represent those structures that are primary constructed with precast concrete. However, the HSs and SOGs in this model are assumed to be representative of the more recent proprietary models that include relatively sophisticated hydraulic controls and screens constructed of steel or some other metallic material. These materials do not last as long as concrete, therefore a design life of 25 years is assumed in this model.

3.10.2. Rehabilitation/Replacement Costs as a Percentage of Construction Costs

There was no information reported in the literature for rehabilitation and replacement costs of BMPs, therefore estimates of costs as a percentage of the original construction costs were made using best engineering judgment. The assumptions made to do so are explained in the following paragraphs.

Large, Aboveground BMPs with Extensive Infrastructure

The BMPs that fall under this category include constructed wetland basins, constructed wetland channels, extended detention basins and retention ponds. The majority of construction costs can be attributed to excavation and installation of infrastructure such as berms, wingwalls, grade controls, outlet structures, etc. Once the design lives of these BMPs are exceeded, it is assumed that most of the installed infrastructure will require rehabilitation and/or replacement. Replacing these items is assumed to cost approximately 80% of the original construction costs. The 20% savings from the original construction costs is assumed to come from not requiring extensive re-excavation. Note that these costs do not include the costs of sediment removal, which usually occurs more frequently, and is included as a maintenance cost in this model.

"Filtering" BMPs

"Filtering" BMPs include porous landscape detention, sand filter basins and sand and media filter vaults. Most of the construction costs of these BMPs can be attributed to excavation and installation of the filtering media. Once the design life of these BMPs is exceeded, it is assumed that the filtering media would need to be removed and replaced at a cost equal to the original construction cost. This assumes that removal of the filtering media would require a similar effort as the original excavation and installation of new media would be similar to the original media installation effort.

Belowground BMPs

The BMPs that fall under this category are hydrodynamic separators, sediment/oil/grease separators, and vaults with capture volume. Much of the original construction costs can be attributed to excavation, device procurement and installation. Once the design life of these BMPs is exceeded, it is assumed that they must be completely removed and new devices installed, at a cost of approximately 120% of the original construction costs. The additional 20% of costs is assumed to account for additional effort needed to remove and dispose of the existing device. The costs of excavation, procurement and installation of the new device are assumed to be similar to the original costs.

Inlet Inserts

This BMP is assumed to be a disposable-type insert that is replaced whenever it becomes full with debris and sediment. Being that replacing this BMP is more of a maintenance issue than a design life issue; the costs for replacement are included in the maintenance cost table.

Permeable Pavements

The construction costs of permeable pavements can mostly be attributed to grading of the site and installation of the subbase and pavement material. At the end of the design life, it is assumed that replacement of the pavement would include demolition/removal and replacement of the pavement material at a cost of approximately 80% of the original construction costs.

Table 3-16 presents the percentage value and cost reoccurrence interval for each BMP.

Table 3-16: Rehabilitation/replacement cost percentages and frequency estimates

BMP	Frequency (years)	Cost (as % of construction costs)
Constructed Wetland Basin	35	80%
Constructed Wetland Channel	35	80%
Extended Detention Basin (WQCV)	35	80%
Extended Detention Basin (EURV	35	80%
Hydrodynamic Separator	25	120%
Inlet Inserts	0	0%
Media Filter Vault	12	100%
Porous Landscape Detention	12	100%
Retention (Wet) Pond (WQCV)	35	80%
Retention (Wet) Pond (EURV)	35	80%
Sand Filter Basin	8	100%
Sand Filter Vault	12	100%
Sediment/Oil/Grease Separator	25	120%
Vault with Capture Volume	75	120%
Concrete Grid Pavers	18	80%
Permeable Interlocking Concrete Pavers	18	80%
Porous Concrete Pavement	18	80%
Porous Gravel Pavement	18	80%
Reinforced Grass Pavement	18	80%

3.11. Administrative Cost Calculations

Administrative costs are calculated using the following equation (3-33);

$$ACost = I + D * MCost \quad \textbf{(3-33)}$$

Where $ACost$ = annual administrative costs for an individual BMP, I = annual compliance inspection costs, D = percentage (of annual maintenance costs) and $MCost$ = annual maintenance costs.

Annual compliance inspection costs were estimated to be approximately \$19 per BMP per year (see Appendix A for details). The percentage of annual maintenance costs is assumed to be 12%.

3.12. Cost Adjustments for Time

Cost data reported in the literature were adjusted for inflation to May 2008 dollars using Equation (3-34) with the 20-city average value of the ENR CCI (ENR 2008). Table 3-17 presents average annual 20-city ENR CCI values from 1986 to 2008.

$$Cost(present) = Cost(base\ year) \bullet \frac{ENRCCI(base\ year)}{ENRCCI(present)} \tag{3-34}$$

Table 3-17: Engineering News Record 20-City construction cost index for 1986-2008 (ENR 2008)

Year	20-City ENR CCI	Year	20-City ENR CCI
1986	4295	1998	5920
1987	4406	1999	6059
1988	4519	2000	6221
1989	4615	2001	6334
1990	4732	2002	6538
1991	4835	2003	6695
1992	4985	2004	7115
1993	5210	2005	7446
1994	5408	2006	7888
1995	5471	2007	8089
1996	5620	May 2008	8141
1997	5826		

3.13. Cost Adjustments for Location

Cost data can also be adjusted for location to account for regional differences in construction costs (materials, labor, etc.). Along with the 20-city nationally-averaged index, ENR also publishes regional indices for 20 cities in the United States. These indices adjust costs from the 20-city nationally-averaged costs using Equation (3-35). Table 3-18 presents the regional index and factor for each city for May 2008.

$$Cost(regional) = Cost(national) \bullet \frac{ENRCCI(regional)}{ENRCCI(national)} \quad \textbf{(3-35)}$$

Table 3-18: Engineering News Record regional cost indices for May 2008 (ENR 2008)

City	Regional CCI	Regional Factor (Regional/National)
20-City average	8141	-
Atlanta	5290	0.65
Baltimore	5537	0.68
Birmingham	5535	0.68
Boston	10004	1.23
Chicago	11176	1.37
Cincinnati	7602	0.93
Cleveland	8555	1.05
Dallas	5005	0.61
Denver	5782	0.71
Detroit	9071	1.11
Kansas City	9303	1.14
Los Angeles	9224	1.13
Minneapolis	9620	1.18
New Orleans	4549	0.56
New York	12482	1.53
Philadelphia	9874	1.21
Pittsburgh	7617	0.94
St. Louis	8769	1.08
San Francisco	9174	1.13
Seattle	8642	1.06

3.14. Net Present Value Cost Calculations

Net present value costs are computed using the Equations (3-36) and (3-37) (Newnan 1996).

$$TCn = \left(\sum CCosts + RCosts + MCosts + ACosts\right) \bullet (1 + IR)^{n} \qquad \textbf{(3-36)}$$

Where TCn = total annual costs ($) in year "n", $CCosts$ = capital costs ($) in current dollars (i.e. year "0"), $RCosts$ = rehabilitation/replacement costs ($) in current dollars (i.e. year "0"), $MCosts$ = maintenance costs ($) in current dollars (i.e. year "0"), $ACosts$ = administrative costs ($) in current dollars (i.e. year "0"), IR = average inflation rate (%) over planning horizon of project and n = year of evaluation.

$$NPV = \left(\sum_{n}^{1} TCn \bullet (1 + ROR)^{-n} \right) \qquad \textbf{(3-37)}$$

Where NPV = net present value of all costs and ROR = average rate of return (%) over planning horizon of project.

3.14.1. Inflation Rate

The inflation rate describes how the costs for maintenance, administration, and rehabilitation/replacements will increase in the future. The average long-term inflation rate for these activities was estimated by evaluating the annual change in the 20-city average ENR CCI. Over the past 50 years, the 20-city average ENR CCI has increased from 759 in 1958 to 8141 in May 2008 (ENR 2008). During that time, the average annual increase in ENR CCI was 4.6%.

3.14.2. Planning Horizon

The planning horizon of a project defines the time over which the net present value of the project costs will be evaluated. A planning horizon of 50 years is recommended by

UDFCD and other water resource organizations, recognizing the longevity of such projects and the difficulty in financing their construction (Urbonas 2008).

3.14.3. Rate of Return

The rate of return (ROR) describes how monies that are set aside (invested) in the present day will appreciate in the future. The future worth of these investments can then be used to pay for future costs such as maintenance and administration. There was no information in the literature documenting typical ROR values for municipalities and/or stormwater management agencies, therefore an estimate of 5% was assumed.

3.15. BMP Effectiveness Calculations

This model evaluates the effectiveness of BMPs using three different measures:

1. The reduction in annual runoff volume discharged to the receiving waters
2. The reduction in annual pollutant loading to the receiving waters, and
3. The percentage of annual runoff that is captured by BMPs that can be designed to control discharge (i.e. attenuate peak flows)

As explained in the following sections, measures 1 and 2 are computed in accordance with recommendations provided by Strecker et al (2001) for evaluating the BMP effectiveness.

3.15.1. Reduction in Annual Runoff Volume to Receiving Waters

The percent reduction of annual runoff volume discharged to the receiving water is computed using Equation (3-38).

$$RunoffReduction = \frac{WatershedRunoff - TotalDischarge}{WatershedRunoff} * 100 \tag{3-38}$$

Where *WatershedRunoff* = total runoff generated from the watershed (ft^3) and *TotalDischarge* = total volume discharged to receiving water (ft^3)

Runoff Generated from the Watershed

Numerous methods exist for quantifying runoff volume from a watershed. Continuous simulation models such as the Stormwater Management Model (SWMM) (Rossman 2008) and the Hydrologic Simulation Program-Fortran (HSPF) (Bicknell et al 1997) are popular models for estimating event-based runoff from urban areas, however their complexity and large data input requirements make them relatively user-intensive. Other methods such as the National Resources Conservation Service (NRCS) Rainfall Excess Method (Soil Conservation Service, 1975) or The Simple Method (Schueler, 1987) require less data inputs and fewer computations, yet still provide acceptable estimates of runoff volume from a watershed. For this model, a modified version of The Simple Method is used because it only requires annual rainfall depth as an input, whereas the NRCS Method requires daily rainfall depth as an input. Landphair et al (2000) and Weiss et al (2002) also used The Simple Method is similar BMP evaluation studies.

The Simple Method computes annual runoff depth using Equation (3-39);

$$RunoffDepth = P * Pj * RC \tag{3-39}$$

Where *RunoffDepth* = annual runoff depth (inches), P = annual precipitation (inches), Pj = fraction of annual storms producing runoff (0.9) and RC = runoff coefficient for watershed.

In this model, it is assumed that 90% of the annual precipitation produces runoff. Schueler (1987) provides an empirical equation for determining the runoff coefficient as a function of the watershed percent imperviousness, however UDFCD's method for estimating runoff coefficients (Section 3.3) is used in the model.

Multiplying the runoff depth computed above by the watershed area (acres) gives the total annual runoff volume generated (Equation (3-40)).

$$WatershedRunoff = \frac{RunoffDepth}{12} * WatershedArea * 43{,}560 \tag{3-40}$$

Total Discharge to the Receiving Water

The total discharge to the receiving water is the sum of the volume of runoff that bypasses the BMP directly into the receiving water (BMP Bypass Volume), and the volume that is discharged from the BMP (BMP discharge), both of which are a function of the effective runoff.

$$TotalDischarge = BMPBypassVolume + BMPDischarge \tag{3-41}$$

The effective runoff is the volume of runoff that reaches the inlet to the BMP and is less than the watershed runoff if source controls are used. It is computed using the same methods as watershed runoff, however as explained in Section 3.2.2, source controls reduce the effective imperviousness of the watershed, which consequently results in a smaller volume of runoff computed using Equation (3-39).

The BMP Bypass Volume is a percentage (λ) of the effective runoff that either fully bypasses the BMP (in the case of an off-line BMP) or is not adequately treated by the BMP because of lack of capacity. For flow-based BMPs and those designed for the

WQCV, λ is assumed to be 15% based on the assumption that the WQCV will adequately treat approximately 85% of the annual runoff. For BMPs designed to capture the EURV, λ is approximately 2% (Urbonas 2008), reflecting the ability of larger storage to capture a greater percentage of runoff.

$$BMPBypassVolume = EffectiveRunoff * \lambda \tag{3-42}$$

The BMP discharge volume is the percentage (1-λ) of effective runoff that does not bypass the BMP, minus the percentage (θ) lost within the BMP due to infiltration and/or ET.

$$BMPDischarge = EffectiveRunoff * (1 - \lambda) * (1 - \theta) \tag{3-43}$$

Strecker et al (2005) reported values for the ratio of measured inflow/measured outflow for several BMPs using data contained in the International BMP Database (Table 3-19). In addition, UDFCD (unpublished data) has estimated the same ratios for other BMPs, also shown in Table 3-19.

Table 3-19: Ratio of measured outflow/measured inflow for various BMPs

BMP Type	Outflow/Inflow
Detention Basins$^{(1)}$	0.70
Biofilters$^{(1)}$	0.62
Media Filters$^{(1)}$	1.00
Hydrodynamic Separators$^{(1)}$	1.00
Wetland Basins$^{(1)}$	0.95
Retention Ponds$^{(1)}$	0.93
Wetland Channels$^{(1)}$	1.00
Sand Filter w/ underdrain$^{(2)}$	≤0.6
Porous Landscape Detention w/ underdrain$^{(2)}$	≤0.4

Sources:
(1) - Strecker et al (2004)
(2) - UDFCD (unpublished data)

Assuming that values less than one are the result of losses due to infiltration and ET, those ratios were used to assign θ values for each of the BMPs used in the model (Table 3-20).

3.15.2. Reduction in Annual Pollutant Loading to Receiving Waters

The percent reduction of annual pollutant loading discharged to the receiving water is computed using Equation (3-44);

$$PollutantReduction = \frac{WatershedLoad - DischargeLoad}{WatershedLoad} * 100 \quad \textbf{(3-44)}$$

Where $WatershedLoad$ = annual pollutant load generated from the watershed (lb) and $DischargeLoad$ = annual pollutant load discharged to the receiving water (lb)

Table 3-20: Percent volume losses within BMPs due to ET and infiltration

BMP	θ - value
Extended Detention Basin	30%
Retention (Wet) Pond	7%
Constructed Wetland Basin	5%
Constructed Wetland Channel	0%
Sand Filter Vault	0%
Media Filter Vault	0%
Sediment/Oil/Grease Separator	0%
Porous Landscape Detention (underdrained)	60%
Porous Landscape Detention (infiltration)	100%
Vault with Capture Volume	0%
Hydrodynamic Separator	0%
Sand Filter Basin (underdrained)	40%
Sand Filter Basin (infiltration)	100%
Inlet Inserts	0%

The annual load of a pollutant can be computed using Equation (3-45);

$$Load = V * C * 6.24e^{-5} \quad \textbf{(3-45)}$$

Where *Load* = annual pollutant loading (lb), *V* = annual volume of runoff (ft^3), *C* = average annual concentration of pollutant (mg/L) and 6.24e^{-5} = unit conversion factor.

Concentrations of pollutants in stormwater can vary over several orders of magnitude during a single storm event (Strecker et al 2005), therefore a parameter called Event Mean Concentration (EMC), is used to represent the flow-weighted average concentration of a pollutant during a storm event (Geosyntec Consultants et al 2002). EMCs are computed using Equation (3-46);

$$EMC = \frac{M}{V} \tag{3-46}$$

Where *EMC* = event mean concentration, *M* = total mass of pollutant over the entire storm event and *V* = total volume of runoff over the entire storm event.

If EMCs are computed for many individual storms, then the average or median of the population of EMCs may reasonably represent the expected concentration of a pollutant over a long period of time (i.e. annually).

Pollutant Load Generated from the Watershed

When estimating pollutant loads in urban stormwater, it is common to assume that certain land uses will produce certain concentrations of pollutants in runoff. This model follows that assumption and computes watershed pollutant loads according to Equation (3-47).

$$WatershedLoad = WatershedRunoff * LandUseEMC * 6.24e^{-5} \tag{3-47}$$

Where *WatershedRunoff* = annual runoff generated from the watershed (ft^3), *LandUseEMC* = average EMC of a pollutant for a specific land use (mg/L) and 6.24e^{-5} = unit conversion factor.

Table 3-21 presents the default land use EMCs used in the model. These values are derived from UDFCD reported values and information provided by Maestre et al (2005), as documented in Appendix B.

Table 3-21: Land use average EMCs in stormwater runoff for Denver, CO (UDFCD 2004)

Constituent	Units	Industrial	Commercial	Residential	Undeveloped
Total Suspended Solids	mg/L	399	225	240	400
Total Nitrogen	mg/L	2.7	3.3	3.4	3.4
TKN	mg/L	1.8	2.3	2.7	2.9
Nitrate + Nitrite	mg/L	0.91	0.96	0.65	0.50
Total Phosphorus	mg/L	0.43	0.42	0.65	0.40
Dissolved Phosphorus	mg/L	0.20	0.15	0.22	0.10
Copper, Total	µg/L	84	43	29	40
Copper, Dissolved[1]	µg/L	32	19	17	23
Lead, Total	µg/L	130	59	53	100
Lead, Dissolved[1]	µg/L	26	16	13	25
Zinc, Total	µg/L	520	240	180	100
Zinc, Dissolved[1]	µg/L	292	95	78	43

[1] - Estimated based on total/dissolved ratios reported in Maestre et al (2005)

Pollutant Load Discharged to the Receiving Water

The total pollutant load discharged to the receiving water is the sum of both the load discharged from the BMP after effective treatment (BMPLoad) and the load of runoff that bypasses or is not effectively treated by the BMP (BypassLoad), as shown in Equation (3-48).

$$DischargeLoad = BMPLoad + BypassLoad \tag{3-48}$$

The BMPLoad is computed using Equation (3-49);

$$BMPLoad = BMPDischarge * EffluentEMC * 6.24e^{-5} \tag{3-49}$$

Where $BMPDischarge$ = annual volume of discharge from BMP (ft^3), $EffluentEMC$ = median EMC of a pollutant for a specific BMP (mg/L) and $6.24e^{-5}$ = unit conversion factor.

Geosyntec Consultants and Wright Water Engineers (2008) have reported median values of effluent EMCs from a variety of structural BMPs, computed using data contained within the International Stormwater BMP Database. The model uses those reported values for the expected effluent quality from each BMP (Table 3-22), with some modifications and assumptions which are described in Appendix B.

The BypassLoad is computed using Equation (3-50) assuming that the pollutant concentrations are equal to the concentrations in the watershed runoff.

$$BypassLoad = BMPBypassVolume * LandUseEMC * 6.24e^{-5} \tag{3-50}$$

Where $BMPBypassVolume$ = annual volume of runoff that bypasses the BMP (ft^3), Equation (3-42), $LandUseEMC$ = average EMC of a pollutant for a specific land use (mg/L) and $6.24e^{-5}$ = unit conversion factor.

3.15.3. Percent of Annual Runoff Receiving Peak Flow Reduction

Peak flow reduction is another important BMP evaluation metric because it reflects how. Some BMPs have the ability to provide peak flow reduction while others do not, however quantifying the measure requires design details such as outlet orifice sizes and storage depth-volume relationships that are usually not known at the planning level. Instead planners will probably be more interested in whether or not the selected BMP(s) can

Table 3-22: BMP Effluent EMCs used in the model

BMP	Total Suspended Solids (mg/L)	Total Phosphorus (mg/L)	Total Nitrogen (mg/L)	Total Kjeldahl Nitrogen (mg/L)	Total Zince (mg/L)	Dissolved Zinc (mg/L)	Total Lead (mg/L)	Dissolved Lead (mg/L)	Total Copper (mg/L)	Dissolved Copper (mg/L)
Constructed Wetland Basin	17.77	0.14	1.15	1.05	0.03071	0.01791	0.00326	0.00087	0.00423	0.00736
Constructed Wetland Channel	37.25	0.37	1.91	1.35	0.03071	0.01790	0.00875	0.00087	0.00423	0.00736
Extended Detention Basin	31.04	0.19	2.72	1.89	0.06020	0.02584	0.01577	0.00206	0.01210	0.00737
Hydrodynamic Separator	49.96	0.28	1.48	0.94	0.07212	0.05480	0.00428	0.00195	0.01180	0.02350
Inlet Inserts	38.00	0.12	0.70	1.90	0.09867	0.06867	0.00663	0.00077	0.01370	0.00872
Media Filter Vault	15.86	0.14	0.76	1.55	0.03763	0.05125	0.00376	0.00118	0.01025	0.00900
Porous Landscape Detention	23.92	0.34	0.78	1.51	0.03983	0.02540	0.00670	0.00196	0.01066	0.00840
Retention (Wet) Pond	13.37	0.12	1.43	1.09	0.02935	0.03286	0.00532	0.00248	0.00636	0.00473
Sand Filter Basin	15.86	0.14	0.76	1.55	0.03763	0.05125	0.00376	0.00118	0.01025	0.00900
Sand Filter Vault	15.86	0.14	0.76	1.55	0.03763	0.05125	0.00376	0.00118	0.01025	0.00900
Sediment/Oil/Grease Separator	41.80	1.27	2.07	1.48	0.14025	0.19175	0.01220	0.00227	0.01278	0.01365
Vault with Capture Volume	31.04	0.19	2.72	1.89	0.06020	0.02584	0.01577	0.00206	0.01210	0.00737

Source: International BMP Database (Geosyntec Consultants and Wright Water Engineers 2008 and 2009) provide peak flow reduction. In the model, each BMP is categorized as either being able to control runoff peak flow ("Yes"), or not ("No") (Table 3-23). This metric then refers to the percent of annual runoff generated from the watershed that is captured by BMPs that can provide peak flow reduction. If mitigating for runoff peak flows is a priority for a stormwater planner, then higher values for this metric will be desired.

Table 3-23: Summary of BMPs that provide peak flow attenuation

BMP	Peak Flow Attenuation
Constructed Wetland Basin	Yes
Constructed Wetland Channel	Yes
Extended Detention Basin (WQCV)	Yes
Extended Detention Basin (EURV	Yes
Hydrodynamic Separator	No
Inlet Inserts	No
Media Filter Vault	No
Porous Landscape Detention	Yes
Retention (Wet) Pond (WQCV)	Yes
Retention (Wet) Pond (EURV)	Yes
Sand Filter Basin	Yes
Sand Filter Vault	No
Sediment/Oil/Grease Separator	No
Vault with Capture Volume	Yes

4. USING THE MODEL

4.1. Model Structure

The model was developed using multiple worksheets within a single Excel workbook. A brief description of each worksheet is included on the "Information" worksheet that is automatically loaded each time the model is opened. The worksheet tabs are color-coded according to their intended use, as described in Table 4-1.

Table 4-1 : Explanation of worksheet tab colors

Worksheet Tab Color	Worksheet Purpose
Blue	These worksheets contain cells that require the user to input information
Purple	These worksheets contain cells that have default parameter values already defined (i.e. cost curves, EMCs, etc.), but can be edited by the user if necessary.
Green	These worksheets are "Read-Only" worksheets. Editing these worksheets may adversely affect model processes.

The model requires many input parameter values, some of which must be defined by the user and others that are computed automatically by the model. Each parameter is categorized and color-coded (similar to worksheet tabs) as described in Table 4-2.

4.2. Getting Started

This section describes the step-by-step process for setting up and evaluating the results of the model. These steps are the minimum steps necessary for "getting started", i.e. to operate the model using default values for costs and BMP effectiveness. More advanced options exist for changing the default values that are used by the model and the steps for doing so are described in Section 4.4. Before getting started, *ensure that macros are enabled in Microsoft Excel.*

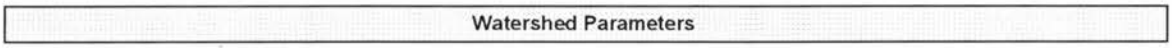
Table 4-2 : Explanation of cell and column colors

Cell/Column Color	Category	Purpose
Blue	User-Defined	The user must enter a value, make a selection from a drop-down box, or use the default value already entered (if available).
Green	Model-Defined	These cells/columns are "read-only" and are populated automatically by the model. Editing these cells and/or columns may adversely affect model processes.

4.2.1. Entering Required Inputs

All of the required inputs to the model are entered on the "InputParameters" worksheet under one of the following headings:


Project-Specific Precipitation and Cost Parameters

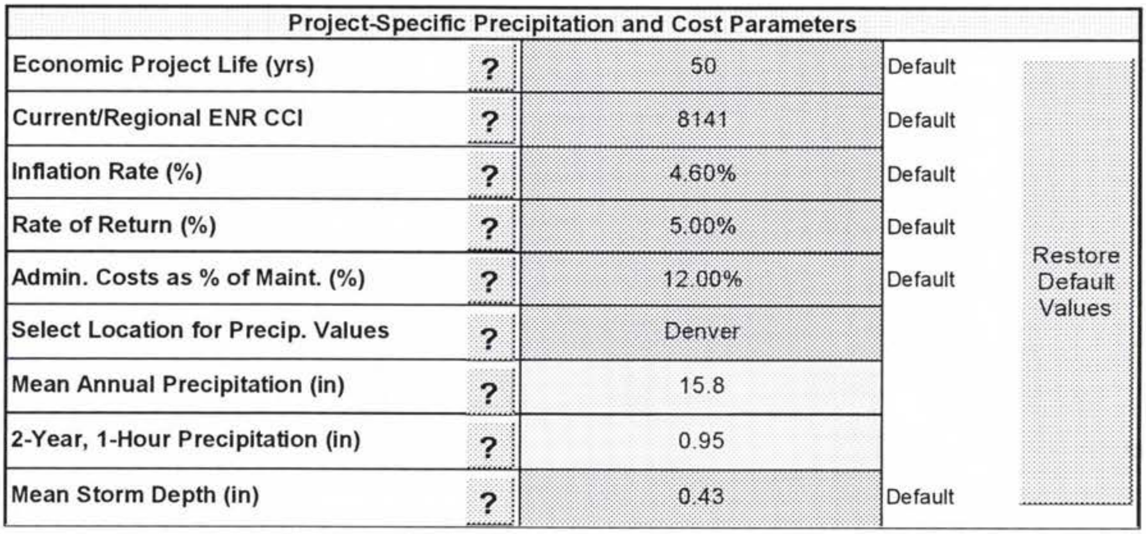

Watershed Parameters


○ Select Regional-Control BMP


⊙ Select Site-Control BMP

4.2.2. Project-Specific Cost and Precipitation Parameters

The model requires several parameters for project-specific precipitation and life cycle cost calculations. The model default values (shown in Figure 4-1) are generally applicable to the Denver, Colorado region, however because some of these values are likely to vary from project to project it is recommended that the user review and verify the applicability of the default values before using them. Descriptions of each required parameter are provided in Section 3 of this thesis.



Project-Specific Precipitation and Cost Parameters

Economic Project Life (yrs)	?	50	Default
Current/Regional ENR CCI	?	8141	Default
Inflation Rate (%)	?	4.60%	Default
Rate of Return (%)	?	5.00%	Default
Admin. Costs as % of Maint. (%)	?	12.00%	Default
Select Location for Precip. Values	?	Denver	
Mean Annual Precipitation (in)	?	15.8	
2-Year, 1-Hour Precipitation (in)	?	0.95	
Mean Storm Depth (in)	?	0.43	Default

Figure 4-1: Default model values for precipitation and life cycle cost calculations

4.2.3. Watershed Parameters

This section describes the procedures for inputting watershed parameters into the model.

Delineating Subcatchments

First, the user must identify the total number of subcatchments located within the area (or watershed) of interest. The steps for doing so are described below. Note that the total number of subcatchments cannot exceed 40 in one workbook.

As the spreadsheet layout suggests, each subcatchment can only have one value for contributing area, land use, total imperviousness, source controls, effective imperviousness, soil type, runoff coefficient, BMP type, and BMP density (i.e. number of impervious acres contributing per BMP). The following protocol is recommended for determining the number of subcatchments needed within a watershed:

1. Determine the number of land uses in the watershed. Assign a subcatchment to each land use and calculate a contributing area.
2. For each subcatchment, is there more than one type of source control being implemented? If yes, then divide the subcatchment(s) up by source control.
3. For each subcatchment, is there more than one type of soil present? If yes, than divide the subcatchment(s) up by soil type.
4. For each subcatchment, is there more than one type of BMP being applied? If yes, then divide the subcatchment(s) up by BMP type.
5. For each subcatchment, will each individual BMP within that subcatchment capture runoff from a (relatively) equal area? (In other words, if more than one BMP is to be implemented within the same subcatchment, does each BMP have an equal number of impervious acres draining to it?). If not, than divide the subcatchment into additional subcatchments, so that the appropriate number of impervious acres draining to each BMP can be input.
6. For each subcatchment, is the slope relatively uniform? If not, then divide the subcatchment(s) into additional subcatchments and calculate the slope for each. Also recalculate the contributing area of all subcatchments.

Entering Subcatchment Parameters

Once the total number of subcatchments (each with its own unique combination of watershed parameters) is determined, then the watershed parameters may be entered as described in the following steps. Input of the watershed parameters follows a left-to-right progression from column to column for each subcatchment, starting with Column C.

For each subcatchment:

1. Enter a subcatchment ID in Column C (this is optional…the model will still run if left blank).
2. Enter a contributing area in total acres in Column D.
3. Select a land use type from the dropdown list in Column E.
4. Enter a value for total imperviousness in Column F, OR, click on the "Enter Default Imperviousness Values" button to have the model automatically fill in the values based on UDFCD recommended values. When all values are updated, the button will turn from red to green.
5. Select an appropriate source control method from the dropdown list in Column G to apply to the subcatchment. If "PP" is selected from the dropdown list, then a pop-up form will appear with information needed for evaluating the use of permeable pavement in the subcatchment. (For more information on applying/selecting source controls, see Section 3.2.2).
6. Enter a value for effective imperviousness in Column H, OR, click on the "Calculate Effective Imperviousness" button to have the model automatically compute the values based on UDFCD protocols. When all values are updated, the button will turn from red to green. (For more information on how effective imperviousness is computed, see Section 3.2.3).

7. Select the dominant NRCS soil type for the subcatchment from the dropdown list in Column I.
8. Enter the average slope of the subcatchment as a percentage in Column J. The slope should be relatively uniform throughout watershed for better results.
9. Enter a value for effective runoff coefficient in Column K, OR, click on the "Calculate Runoff Coefficients" button to compute the value based on UDFCD protocols. When all values are updated, the button will turn red to green.

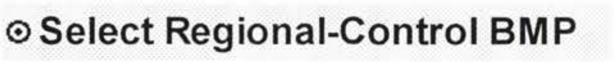
4.2.4. BMP Parameters

The section describes how to apply BMPs to the subcatchments. The first step is to determine whether to apply a single regional-control BMP or multiple site-control BMPs. The regional control BMP will treat runoff from all of the subcatchments combined, whereas site-control BMPs are applied at the subcatchment level only.

Regional-Control BMPs

To apply a regional-control BMP, follow these steps.

1. Select the regional-control BMP button



2. Select the BMP to be applied from the dropdown list in Cell O24.

3. Input a land cost value into Cell T24 for the location where the regional BMP will be installed. For applicable land costs for different land use types, reference the table on the "LandCosts" worksheet.
4. Click on the "Calculate BMP Sizes" button to compute the size of the BMP required. The button will turn green when all values are updated.

Site-Control BMPs

To apply a site-control BMP, follow these steps.

1. Select the site-control BMP button.

⊙ Select Site-Control BMP

2. Select the BMP to be applied to each subcatchment in Column O.
3. Enter the number of impervious acres that will runoff to each individual BMP located within the subcatchment. The value entered should be within the ranges presented in Table 4-3 for best results. If the number of impervious acres draining to each BMP is less than the total number of impervious acres in the subcatchment, then more than one BMP will be applied, each with the same number of impervious acres contributing. Inappropriately applying very large or very small impervious areas to certain BMPs may result in unrealistic results. An error message will pop up if this value is entered outside of these ranges.

4. Click on the "Calculate BMP Sizes" button to determine the size of the BMPs required for each subcatchment. The button will turn green when all values are updated.

Table 4-3 : Range of impervious acres applicable for each BMP

BMPs	Impervious Acres to each BMP	
	Minimum	**Maximum**
Constructed Wetland Basin	2	n/a
Constructed Wetland Channel	2	n/a
Extended Detention Basin - WQCV	2	n/a
Extended Detention Basin - EURV	2	n/a
(U) Inlet Inserts	0.1	0.25
Porous Landscape Detention – Infiltration	0.1	5
Porous Landscape Detention – Underdrain	0.1	5
Retention Pond – WQCV	2	n/a
Retention Pond – EURV	2	n/a
Sand Filter Basin – Infiltration	0.5	5
Sand Filter Basin - Underdrain	0.5	5
Media Filter Vault	0.1	5
Sand Filter Vault	0.1	5
(U) Hydrodynamic Separator	0.1	5
(U) Sediment/Oil/Grease Separator	0.1	2
(U) Vault w/ Capture Volume	0.1	5

Notes:

n/a - indicates BMP can be designed to treat an unlimited area

4.3. Generating and Interpreting Model Results

To generate model outputs, select the "Report" worksheet and click on the "Update Summary Report" button  to generate/update summary results. Model results are output into several different worksheets, each of which is described in the following sections.

4.3.1. "Report" Worksheet

The "Report" tab of the spreadsheet summarizes the costs and effectiveness of the selected BMP scenario in tabular and chart forms.

Summary of Water Quality Table

The water quality results summary table is presented as Table 4-4.

Table 4-4: Summary of Water Quality Results table

Constituent	Watershed Pollutant Load (lb/yr)	Discharged Pollutant Load (lb/yr)	Pollutant Reduction (%)	Cost per Unit Removed ($/lb)
Total Suspended Solids	95852.90	51600.01	46%	$14.39
Total Phosphorus	178.93	164.87	8%	$45,318.08
Total Nitrogen	1405.84	988.36	30%	$1,525.83
Total Kjeldahl Nitrogen	979.83	801.23	18%	$3,566.66
Total Zinc	102.24	62.69	39%	$16,103.33
Dissolved Zinc	40.25	33.69	16%	$97,071.51
Total Lead	25.13	13.36	47%	$54,111.23
Dissolved Lead	6.98	3.55	49%	$185,389.63
Total Copper	18.32	10.89	41%	$85,738.82
Dissolved Copper	8.14	6.33	22%	$351,429.15

The values displayed under the heading **"Watershed Pollutant Load"** are the sum of annual pollutant loads generated from all subcatchments. It is presumed that these would be the pollutant loadings to the receiving waters if no BMPs or source controls were in place.

The values displayed under the heading "**Discharged Pollutant Load**" are the total annual pollutant loads entering the receiving water from all subcatchments, with the selected source controls and BMP(s) in place. These values account for pollutant reductions due to infiltration and treatment of runoff within the source controls and BMPs.

The values displayed under the heading **"Pollutant Reduction"** are the annual percent reduction of each pollutant that is achieved with the selected source controls and BMP(s) in place.

The values displayed under the heading **"Cost per Unit Removed"** are the total life cycle costs for removing one unit of pollutant during the planning horizon of the project.

The **"Summary of Watershed and Discharged Pollutant Loads"** chart (Figure 4-2) graphically presents the values in the summary table.

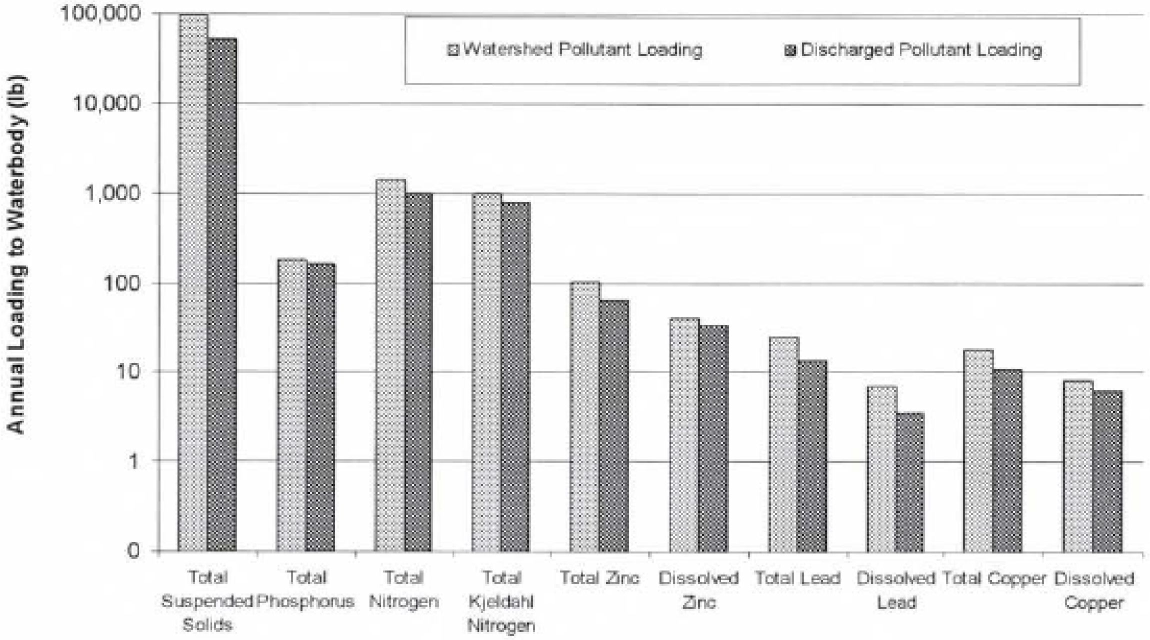
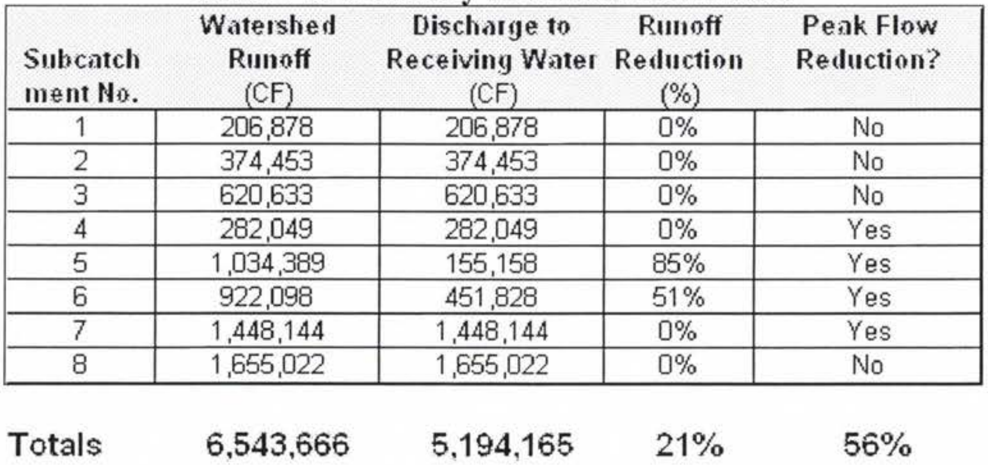


Figure 4-2: Summary of pollutant load reporting chart

Summary of Runoff Table

The Runoff summary table is presented as Table 4-5. The values displayed under the heading **"Watershed Runoff"** are the total annual runoff volumes generated from each subcatchment, if no source controls or BMP(s) were in place. These volumes are a function of the precipitation and runoff coefficient computed using the total imperviousness. If a regional BMP is being used than only one row of values will appear representing the total runoff volume from all subcatchments together. The values displayed under the heading **"Discharge to Receiving Water"** are the total annual runoff volumes entering the receiving water from each subcatchment, with the selected source controls and BMPs in place. These values account for runoff reduction due to losses such as infiltration and evaporation that occur within the selected source controls and BMP(s). If a regional BMP is being used than only one row of values will appear representing the total discharge volume from the regional BMP.

Table 4-5: Summary of Runoff results table



Subcatchment No.	Watershed Runoff (CF)	Discharge to Receiving Water (CF)	Runoff Reduction (%)	Peak Flow Reduction?
1	206,878	206,878	0%	No
2	374,453	374,453	0%	No
3	620,633	620,633	0%	No
4	282,049	282,049	0%	Yes
5	1,034,389	155,158	85%	Yes
6	922,098	451,828	51%	Yes
7	1,448,144	1,448,144	0%	Yes
8	1,655,022	1,655,022	0%	No
Totals	**6,543,666**	**5,194,165**	**21%**	**56%**

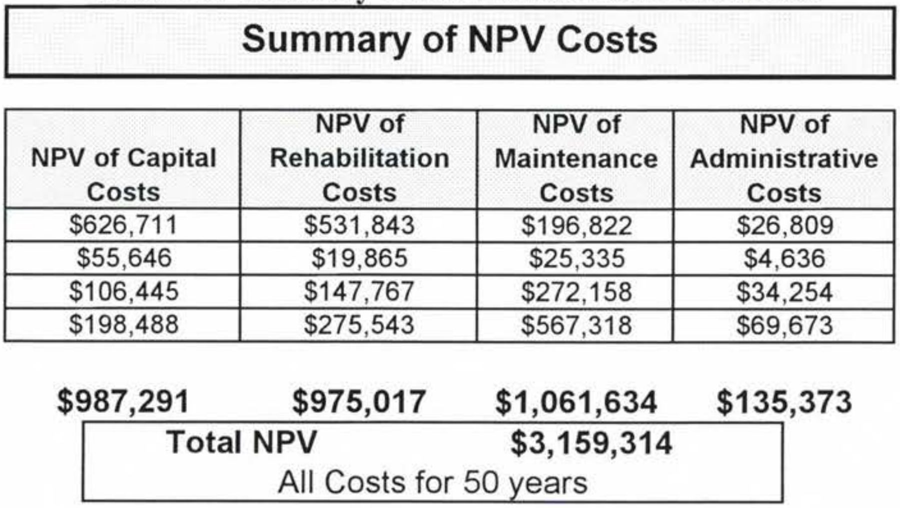
The values under the heading **"Runoff Reduction"** are the annual percent reduction of runoff volume from each subcatchment that is achieved with the selected source controls and BMP(s) in place.

The values under the heading **"Peak Flow Reduction"** display whether or not the BMP selected for the subcatchment is able to reduce peak flows through the use of flow controls. The "Totals" value is the percentage of total runoff volume that is being captured by BMPs that reduce peak flow. This value allows the user to understand qualitatively how effective the selected BMP scenario is for attenuating peak flows.

Summary of Costs

The Cost summary table with example data is presented as Table 4-6.

Table 4-6: Summary of Net Present Value Cost table



Summary of NPV Costs

NPV of Capital Costs	NPV of Rehabilitation Costs	NPV of Maintenance Costs	NPV of Administrative Costs
$626,711	$531,843	$196,822	$26,809
$55,646	$19,865	$25,335	$4,636
$106,445	$147,767	$272,158	$34,254
$198,488	$275,543	$567,318	$69,673
$987,291	**$975,017**	**$1,061,634**	**$135,373**

Total NPV **$3,159,314**
All Costs for 50 years

The values displayed in each cell are the net present value of the costs associated with the selected source controls and BMPs for each subcatchment. If a regional BMP is being used than only one row of values will appear representing the total costs for the regional BMP and any source controls applied. All costs are summed and reported as the "Total NPV" value.

The **"Annual Cost Summary"** chart (Figure 4-3) graphically displays the annual costs for capital, rehabilitation, maintenance, and administration of all BMPs for the defined planning horizon. Capital and rehabilitation costs are displayed as vertical bars and reference the left vertical axis. Maintenance and administrative costs are displayed as dark red and yellow area charts, respectively; and reference the right vertical axis.

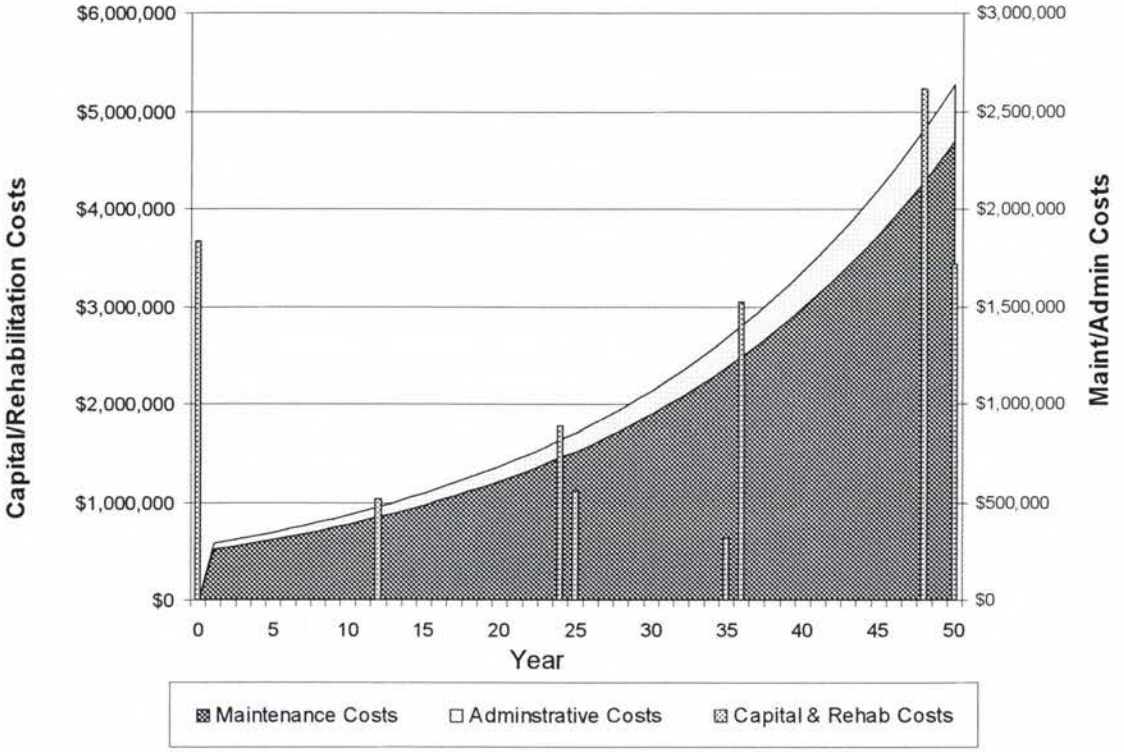


Figure 4-3: Annual Cost Summary Chart

4.3.2. "NPVCosts" Worksheet

The "NPVCosts" worksheet presents a breakdown of all annual costs over the defined planning horizon of the project. This worksheet is "Read-Only" and any modifications to it may adversely affect model computations. The equations used to calculate each value are described in Section 3.14.

4.3.3. "CapitalCosts" Worksheet

The "CapitalCosts" worksheet summarizes the capital and rehabilitation costs of the BMPs selected for each subcatchment. This worksheet is "Read-Only" and any modifications to it may adversely affect model computations.

4.3.4. "OMCosts" Worksheet

The "OMCosts" worksheet summarizes the maintenance and administrative costs of the BMPs selected for each subcatchment. This worksheet is "Read-Only" and any modifications to it may adversely affect model computations.

4.3.5. "SourceControlCosts" Worksheet

The "SourceControlCosts" worksheet summarizes the capital, maintenance and administrative costs of the source controls selected for each subcatchment. This worksheet is "Read-Only" and any modifications to it may adversely affect model computations.

4.3.6. "RunoffEMCs" Worksheet

The "RunoffEMCs" worksheet summarizes the annual pollutant loads (lbs per year) generated from each subcatchment. These loads are what would enter the receiving water(s) if no source controls or BMPs were implemented. This worksheet is "Read-Only" and any modifications to it may adversely affect model computations.

4.3.7. "EffluentEMCs" Worksheet

The "EffluentEMCs" worksheet summarizes the annual pollutant loads (lbs per year) for each subcatchment that would enter the receiving water(s) using the selected source controls and BMP(s). This worksheet is "Read-Only" and any modifications to it may adversely affect model computations.

4.3.8. "Runoff" Worksheet

The "Runoff" worksheet summarizes the annual runoff volumes that are generated from the contributing area, reduced through various source control and BMP processes (evaporation, infiltration, etc.), and released to the receiving water(s) for each subcatchment. It also shows which subcatchments have BMPs in place that will attenuate peak flows. This worksheet is "Read-Only" and any modifications to it may adversely affect model computations.

4.4. Advanced Options

This section describes how to modify or override the model's default values in order to more accurately represent a specific project. *The default values included in the model are considered scientifically defensible and based on best available information at the time of model release, and therefore should only be modified or replaced with values are also based on sound science.*

4.4.1. Modifying Runoff Mitigation Values

The "RunoffMitigation" worksheet contains information used to evaluate the effectiveness of BMPs at mitigating increased runoff volumes generated from urbanization. Each BMP has two values associated with it. The first value under the "BMP Runoff Volume Reduction" heading represents the percentage of total runoff volume that is "lost" (i.e. not discharged through the BMP outlet) within the BMP, generally due to infiltration and ET processes. The second value indicates whether or not the BMP is capable of reducing peak runoff flows through losses and/or storage. The default values used in the model are explained and justified in Section 3.15 of this thesis.

4.4.2. Modifying Water Quality Values

The "WaterQuality" worksheet contains information used in computing pollutant loads with and without BMPs. The worksheet includes two tables of information, one containing "BMP Effluent Event Mean Concentrations" and another containing "Land Use Event Mean Concentrations". The default values of Land Use EMCs (Table 3-21) and BMP Effluent EMCs (Table 3-22) and were derived from Table SQ-5 in the USDCM (UDFCD 2004) and the June 2008 version of the Analysis of Treatment Performance Report (Geosyntec Consultants & Wright Water Engineers 2008), respectively, using methods and assumptions described in Appendix B.

The user may edit these values if needed, however it is not recommended unless they are being replaced by values reported in an updated version of the reports cited above. Any updated versions of those reports should be available at www.udfcd.org or www.bmpdatabase.org.

4.4.3. Modifying Land Cost Values

The values in the table on the "LandCost" worksheet are the unit land costs ($ per acre) used by the model to compute total land costs for BMP implementation. The values are average values of the ranges reported in Strecker et al (2005) and shown in Table 2-7. The user may edit the values in the table with values more representative of the project location if necessary.

4.4.4. Modifying BMP Cost Values

The default cost parameters for each BMP are located on separate worksheets, each named with an abbreviation of the BMP that is shown on the "Information" tab. For all of the cost worksheets, the user can input a value into any blue-shaded cell and that input value will override any default value included in the model. Other options are described below.

4.4.5. Editing Capital Cost Parameters

The capital cost input table is presented in Figure 4-4 and the procedures for editing capital cost parameters are described below.

Selecting Option 1 or Option 2

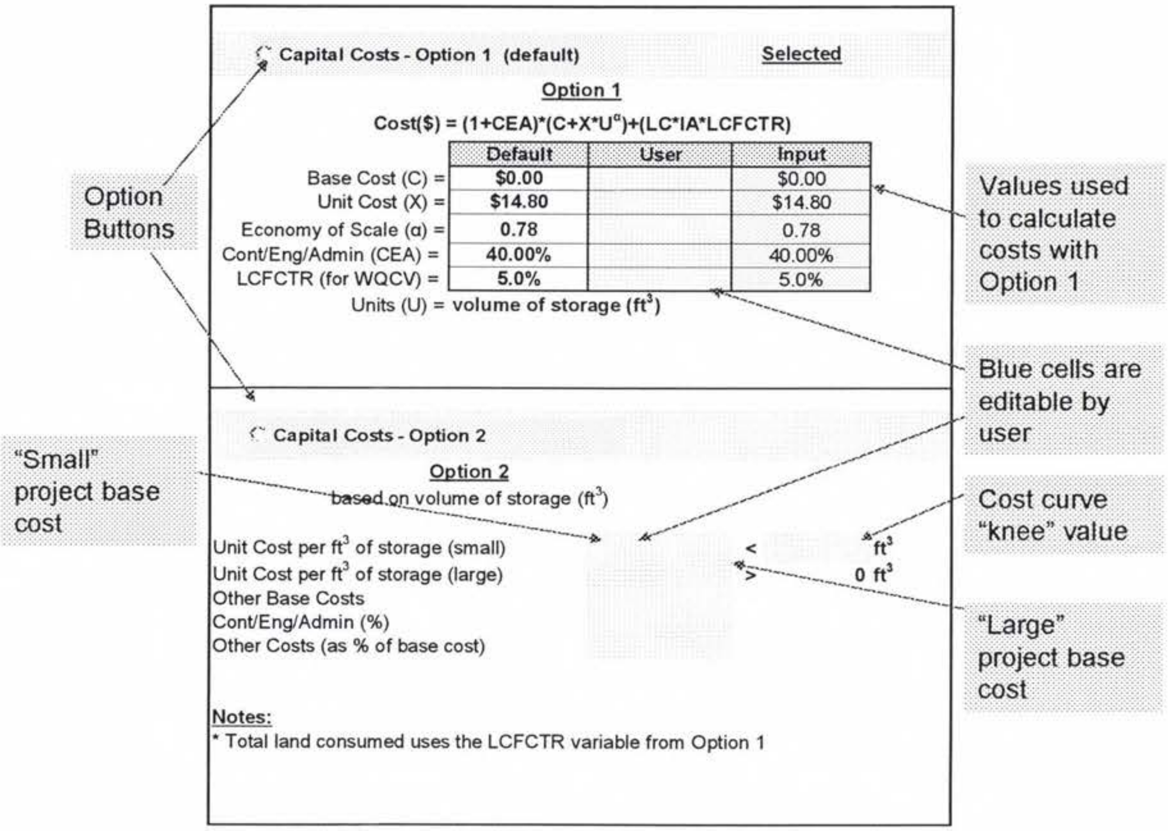
First, select the option to use by clicking on the appropriate selection button shown below. To compute capital costs, the user has the option of using a non-linear parametric equation (Option 1) or using a cost-curve generating option (Option 2). Option 1 is the default option.

● Capital Costs - Option 1 (default)

○ Capital Costs - Option 2

Option 1 Editing

If Option 1 is selected, the user may override any of the default values by entering a value in the blue-shaded cell to the right of the default value cell. After doing so, the "Input" value will change from the default value to the user-defined value. The "Input" value is the value used in the model computations.



○ Capital Costs - Option 1 (default) Selected

Option 1

Cost(\$) = (1+CEA)*(C+X*U^α)+(LC*IA*LCFCTR)

	Default	User	Input
Base Cost (C) =	$0.00		$0.00
Unit Cost (X) =	$14.80		$14.80
Economy of Scale (α) =	0.78		0.78
Cont/Eng/Admin (CEA) =	40.00%		40.00%
LCFCTR (for WQCV) =	5.0%		5.0%

Units (U) = volume of storage (ft^3)

○ Capital Costs - Option 2

Option 2

based on volume of storage (ft^3)

Unit Cost per ft^3 of storage (small) < ft^3
Unit Cost per ft^3 of storage (large) > 0 ft^3
Other Base Costs
Cont/Eng/Admin (%)
Other Costs (as % of base cost)

Notes:
* Total land consumed uses the LCFCTR variable from Option 1

Figure 4-4: Capital cost input table

Option 2 Editing

If Option 2 is selected, the user must enter a value into each of the blue-shaded cells. This option generates two linear cost functions which intersect at the value input into cell "F27", otherwise known as the "knee" in the curve. These two functions together generate a cost curve, with higher unit costs for a BMP smaller than the "knee" value and lower unit costs for a BMP larger than the "knee" value.

With both options, the user can view the cost curve (Figure 4-5) that is generated in the chart located below the capital cost data entry cells. This allows the user to efficiently determine the construction costs of a variety of BMP sizes.

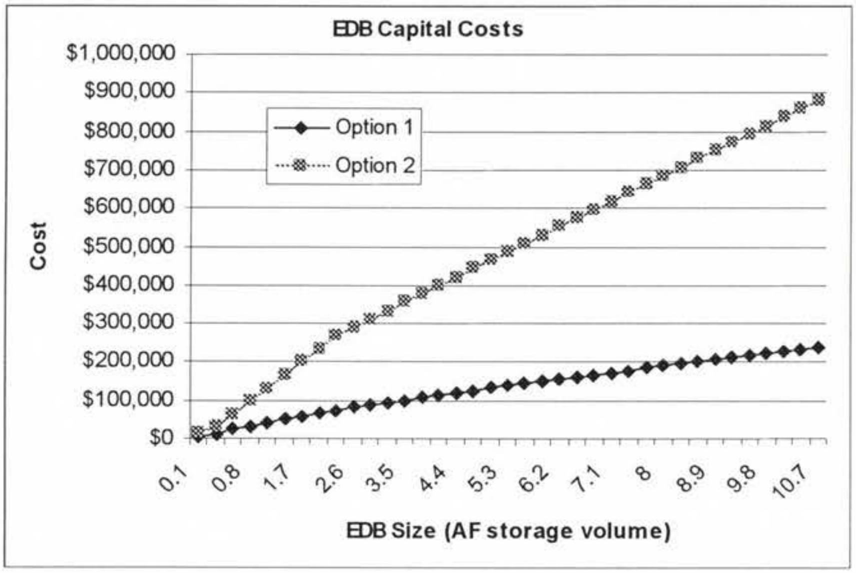


Figure 4-5: Chart showing example cost curves generated using the capital cost input tables

4.4.6. Editing Maintenance Cost Parameters

The procedures for editing maintenance cost parameters on the maintenance cost table (Table 4-7) are explained below.

Selecting Cost Estimating Option

The user has two options for estimating annual maintenance costs. Option 1 (the default option) is to develop bottom-up cost estimates using the information contained within the maintenance activity cost table. Option 2 is to compute annual maintenance costs as a simple percentage of the construction costs. To use and/or edit Option 1, continue with the following directions.

Selecting Option 1 – Using Maintenance Cost Table

To estimate costs using the maintenance table, make sure that cell "M37" is blank. The computational macros for this option only run when "M37" is blank.

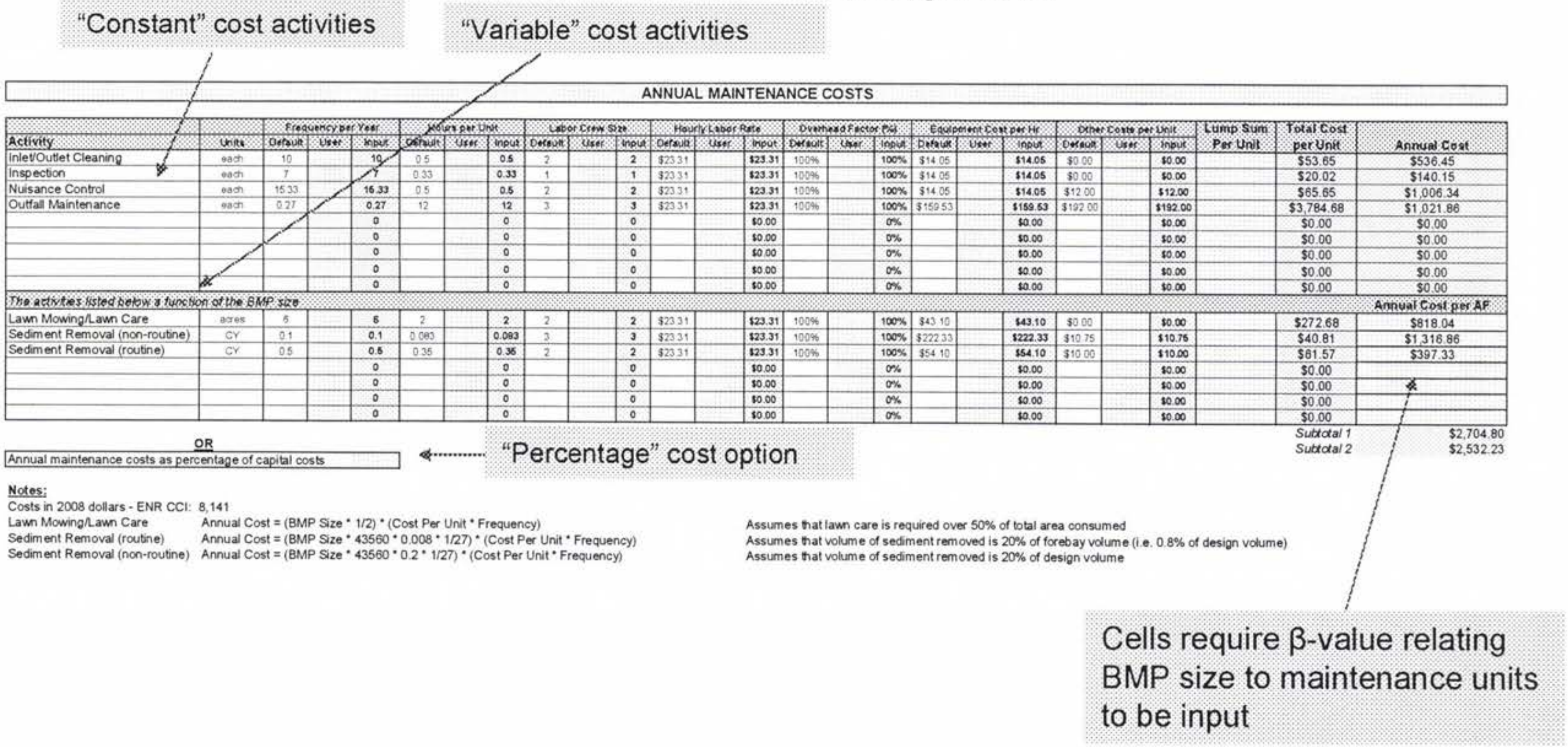
Override Default Values in the Maintenance Cost Table

To override a default value from an existing activity in the maintenance cost table, input a value into the blue-shaded "user" cell to the right of the "default" cell. The "input" cell value will change from the default value to the user-defined value. The "input" value is the value used by the model.

Deleting an Activity from the Maintenance Cost Table

To remove a maintenance activity from the maintenance table, simply delete all values in the row of that activity. You will not be able to delete the equations in the green-shaded cells as those cells are protected. To ensure that all data from deleted correctly, the value in Column AH of that row should equal $0.00.

Table 4-7: Maintenance cost input tables



"Constant" cost activities

"Variable" cost activities

ANNUAL MAINTENANCE COSTS

Activity	Units	Frequency per Year			Hours per Unit			Labor Crew Size			Hourly Labor Rate			Overhead Factor (%)			Equipment Cost per Hr			Other Costs per Unit			Lump Sum Per Unit	Total Cost per Unit	Annual Cost
		Default	User	Input	Default	User	Input	Default	User	Input	Default	User	Input	Default	User	Input	Default	User	Input	Default	User	Input			
Inlet/Outlet Cleaning	each	10		10	0.5		0.5	2		2	$23.31		$23.31	100%		100%	$14.05		$14.05	$0.00		$0.00		$53.65	$536.45
Inspection	each	7		7	0.33		0.33	1		1	$23.31		$23.31	100%		100%	$14.05		$14.05	$0.00		$0.00		$20.02	$140.15
Nuisance Control	each	15.33		16.33	0.5		0.5	2		2	$23.31		$23.31	100%		100%	$14.05		$14.05	$12.00		$12.00		$65.65	$1,006.34
Outfall Maintenance	each	0.27		0.27	12		12	3		3	$23.31		$23.31	100%		100%	$159.53		$159.53	$192.00		$192.00		$3,784.68	$1,021.86
				0			0			0			$0.00			0%			$0.00			$0.00		$0.00	$0.00
				0			0			0			$0.00			0%			$0.00			$0.00		$0.00	$0.00
				0			0			0			$0.00			0%			$0.00			$0.00		$0.00	$0.00
				0			0			0			$0.00			0%			$0.00			$0.00		$0.00	$0.00
				0			0			0			$0.00			0%			$0.00			$0.00		$0.00	$0.00
The activities listed below a function of the BMP size																									Annual Cost per AF
Lawn Mowing/Lawn Care	acres	6		6	2		2	2		2	$23.31		$23.31	100%		100%	$43.10		$43.10	$0.00		$0.00		$272.68	$818.04
Sediment Removal (non-routine)	CY	0.1		0.1	0.083		0.083	3		3	$23.31		$23.31	100%		100%	$222.33		$222.33	$10.75		$10.75		$40.81	$1,316.86
Sediment Removal (routine)	CY	0.5		0.5	0.35		0.35	2		2	$23.31		$23.31	100%		100%	$54.10		$54.10	$10.00		$10.00		$61.57	$397.33
				0			0			0			$0.00			0%			$0.00			$0.00		$0.00	
				0			0			0			$0.00			0%			$0.00			$0.00		$0.00	
				0			0			0			$0.00			0%			$0.00			$0.00		$0.00	
				0			0			0			$0.00			0%			$0.00			$0.00		$0.00	
																								Subtotal 1	$2,704.80
																								Subtotal 2	$2,532.23

OR

Annual maintenance costs as percentage of capital costs

"Percentage" cost option

Notes:

Costs in 2008 dollars - ENR CCI:	8,141	
Lawn Mowing/Lawn Care	Annual Cost = (BMP Size * 1/2) * (Cost Per Unit * Frequency)	Assumes that lawn care is required over 50% of total area consumed
Sediment Removal (routine)	Annual Cost = (BMP Size * 43560 * 0.008 * 1/27) * (Cost Per Unit * Frequency)	Assumes that volume of sediment removed is 20% of forebay volume (i.e. 0.8% of design volume)
Sediment Removal (non-routine)	Annual Cost = (BMP Size * 43560 * 0.2 * 1/27) * (Cost Per Unit * Frequency)	Assumes that volume of sediment removed is 20% of design volume

Cells require β-value relating BMP size to maintenance units to be input

Adding an Activity to the Maintenance Cost Table

The maintenance table contains entry cells for two types of activities. The first activity is one in which the annual costs will not vary significantly according to the size of the BMP. These activities must be added in rows 18-26. The second activity type is one in which the annual costs do vary significantly with the size of the BMP. These activities must be added in rows 28-34.

To add an activity to the maintenance table, simply fill in appropriate values for each cost component as is done with the default activities. The user should enter the values into the blue-shaded "user" cells (not the white "default" cells) to signify that the activity has been added by the user and is not a model default activity.

If the activity is added to rows 28-34, then one additional step must be completed. In column AH, the user must input a Microsoft Excel equation that will relate the size of the BMP to the number of units of maintenance that is required each year. The equation must be of the form:

=β*AG(row#)*M(row#)

Where,

β = the number of units of maintenance per unit of BMP size

row# = row number of the activity

An example of how to determine the β-value is shown below. The derivation of β values for default activities is described in Appendix A.

Example 1: An extended detention basin size (storage) is measured in AF and sediment removal costs are estimated in cubic yards (CY). Sediment removal occurs once 20% of the EDB storage is filled with sediment. We must find a β-value that relates the required volume of sediment removal (in CY) to the size of the EDB (in AF).

$$\beta = \frac{0.2AF(SedimentRemoval)}{1AF(BMPSize)} * \frac{1613CY}{1AF} = 323\frac{CY(SedimentRemoval)}{1AF(BMPSize)}$$

By unit conversion, we find a β-value of 323.

Option 2 – Using Percentage of Construction Costs

To compute annual maintenance costs as a percentage of the BMP construction costs, simple input the appropriate percentage value into cell "M37". This will override the values in the maintenance cost table (but the values will still be visible).

4.5. Importing Inputs from another Workbook

Users can transfer their inputs and user-defined values to new versions of the model using the "Import Data from Another Model" button found on the "InputParameters" page. All user-defined information will be imported from the older model to the new model, however the model must be re-run in order to generate results with the newly imported data.

5. APPLICATION OF THE MODEL AND FINDINGS

In this section, the model is applied to two theoretical stormwater management problems to demonstrate its abilities.

5.1. Application #1 - Comparing underground BMPs and aboveground BMPs

5.1.1. Introduction

Underground BMPs, such as hydrodynamic separators, are often implemented in high-density developments where the cost of land is (presumably) too expensive to dedicate to aboveground BMPs. However, given their limited treatment capacity compared to, say, an extended detention basin, many individual HS may be needed to treat the same area as one, large EDB. A logical question then becomes, at what land cost is it more cost effective to use one strategy over another?

5.1.2. Modeling Scenario

In this scenario, stormwater runoff from a theoretical 160-acre high-density (85% imperviousness) commercial development is evaluated using two different BMP strategies; the first using multiple HSs, each designed to capture runoff from 5 impervious acres and the second using a single, "regional" EDB. By evaluating each scenario using several different land costs, it is presumed that a "break-point" can be found at which is more cost effective to use a regional EDB when land costs are below the "break-point". This finding could be useful to a stormwater management planner.

Both scenarios are evaluated using default values for all parameters and precipitation data for Denver, Colorado. Soil types are assumed to be NRCS Type "C" and the average watershed slope is 2%.

5.1.3. Results

The total NPV costs for each scenario are presented in Table 5-1.

Table 5-1: Total net present value costs for two different BMP scenarios as a function of land costs

Land Cost ($/acre)	Hydrodynamic Separator NPV Costs	Extended Detention Basin NPV Costs
$25,000	$16,000,000	$1,900,000
$100,000	$16,000,000	$2,500,000
$1,000,000	$16,000,000	$9,300,000
$1,500,000	$16,000,000	$13,000,000
$2,000,000	$16,000,000	$17,000,000

As expected, the total costs for Scenario 1 do not change according to land costs because underground BMPs do not consume land. However, the total costs for Scenario 2 do increase as the cost of land increases. The results suggest that when land prices are less than about $2,000,000, that a regional extended detention basin is a more cost effective stormwater management strategy. However, this finding assumes that both scenarios will meet or exceed the water quality regulations and does not account for the fact that, in most cases, EDBs are more efficient is removing TSS over the long-term. The next application is more involved and demonstrates how the model can be used to optimize the selection of BMPs to meet water quality regulations at the minimum cost.

5.2. Application #2 – Large Scale Urban BMP Retrofit Evaluation

5.2.1. Introduction

Water quality regulations have led many municipalities to retrofit existing developments with BMPs. The costs of acquiring land in highly developed areas can be costly and, as demonstrated in Application #1, may preclude the use of traditional aboveground BMPs such as detention basins. In such cases, the use of underground BMPs and LID BMPs has gained popularity. LID BMPs such as porous landscape detention and sand filter vaults have the advantage of using very little land and can be implemented within agency-owned right-of-ways to minimize the land acquisition costs. This application demonstrates how the model can be used to determine which of these BMPs is most cost effective in meeting a specific water quality regulation.

5.2.2. Modeling Scenario

The area of interest is already developed with no BMPs currently in place. The stormwater agency must reduce TSS loading to the receiving water by 60%, however because the area is already developed the costs of acquiring land and demolishing existing structures precludes of the use of aboveground BMPs (see Application #1). The following information is available.

- The 55 acre area has a land use density similar to commercial land uses (95%) and has an average slope of 2%.
- Portions of existing right-of-ways (roadways, sidewalks, alleyways) could be used for long, narrow-type BMPs, such as PLDs or SFVs. There would be no

land costs associated with these areas because the city/agency already owns them.

- Soils in the area are NRCS Type D and are NOT adequate for infiltration-type BMPs (i.e. underdrains are required).

Although the watershed can be considered homogeneous, for this application it was subdivided into 11 subcatchments of 5 acres. This allows for applying BMPs to a certain percentage of the watershed while leaving other areas untreated in order to meet, but not exceed, the water quality regulations.

5.2.3. Scenario 1

For this scenario, the use of hydrodynamic separators is evaluated. Typically, the contributing area to each device should not exceed 5 impervious acres. Using an iterative process, it was found that implementing 10 hydrodynamic separators with treatment capacity of 10 cfs, each treating 5 acres (4.75 impervious acres), would reduce TSS loading approximately 61%. The 50-year NPV of all costs for this scenario is $5,200,000.

5.2.4. Scenario 2

For this scenario, the use of porous landscape detention (with underdrains) is evaluated. Generally, PLDs are designed to capture runoff from less than 5 impervious acres. Using an iterative process, it was found that approximately 8 PLDs, each capturing runoff from 5 acres (4.75 impervious acres), would reduce TSS loading by approximately 61%. The 50-year NPV of all costs for this scenario is $4,100,000. These costs neglect land costs, as it is assumed that the PLDs could be constructed within the right-of-ways.

5.2.5. Scenario 3

For this scenario, sand filter vaults are evaluated. To reduce TSS loading by 60%, 8 SFVs, each capturing runoff from 5 acres (4.75 impervious acres) would be required. The 50-year NPV of all costs for this scenario is $20,000,000. These costs neglect land costs, as it is assumed that the SFVs could be constructed within the right-of-ways.

5.2.6. Scenario 4

The last scenario evaluates the use of inlet inserts. Generally, inlet inserts are designed to capture runoff from 0.25 impervious acres or less. To reduce TSS loading by 60%, a total of 110 IIs would be required throughout the entire watershed at a 50-year NPV cost of $5,700,000.

5.2.7. Results

Table 5-2 summarizes the results of each of the 4 scenarios evaluated. Each scenario was optimized to reduce TSS loading by approximately 60% (19,000 lb/yr). Several important conclusions can be made from the results of this application. First, it shows how the model can be used to develop a cost-effective plan for achieving reductions in pollutant loadings to receiving waters. Second, it demonstrates the importance of including long-term maintenance and administrative costs when evaluating a cost effective BMP plan. One can see from the results that if BMPs were selected solely based on capital costs, that inlet inserts would appear considerably less costly than all other alternatives. However, because of their high maintenance requirements they actually appear to be the second most expensive solution for this application. Lastly, this evaluation took an experienced model user less than 1 hour to complete, which shows how the model will enable effective decisions to be made in an efficient manner.

Table 5-2: Summary table of results for Application #2

	Scenario			
	1	**2**	**3**	**4**
BMP	HS	PLD	SFV	II
Treated Area (acres)	50	40	40	55
Total NPV Costs	\$5,200,000	\$4,100,000	\$20,000,000	\$5,700,000
Capital Costs	\$530,000	\$690,000	\$4,100,000	\$29,000
Rehabilitation Costs	\$780,000	\$1,800,000	\$11,000,000	\$0
Maintenance Costs	\$3,500,000	\$1,500,000	\$4,400,000	\$4,900,000
Administrative Costs	\$430,000	\$180,000	\$530,000	\$760,000
Cost/lb TSS Removed	\$5.40	\$4.20	\$21.00	\$6.00

6. SUMMARY AND CONCLUSIONS

This model implements an improved approach for stormwater management planning where the cost effectiveness of structural BMPs is quantified using BMP whole life cycle costs and performance, while requiring only a minimal number of user inputs to describe the watershed and BMP(s) to be evaluated. To minimize the number of user inputs required algorithms were developed for; computing BMP size from watershed and precipitation parameters using methods recommended in the UDFCD Urban Storm Drainage Criteria Manual (UDFCD 2004), estimating whole life cycle costs as a function of BMP size using cost data collected from a variety of sources and estimating average annual pollutant loads and runoff volumes discharged to the receiving water(s). This model will enable stormwater managers and planners to help select the BMPs that will achieve the necessary reductions in annual pollutant loads and runoff volumes discharged to the receiving water(s) at the lowest unit cost. Other potential uses include planning for long-term maintenance costs of existing BMPs, evaluating how minimizing directly connected impervious areas will reduce WQCV requirements and the costs associated with it and providing cost information necessary to establish cost-sharing programs between developers and those entities responsible for BMP maintenance.

BMP size is computed using one of two methods, depending on if the BMP is storage-based or flow-based. For storage-based BMPs, empirical equations developed by UDFCD can be used to estimate the storage volume required to capture the WQCV or

EURV. For flow-based BMPs, the Rational Method can be used to compute a peak flow. All of these methods are applicable at both large and small scale, however the Rational Method should not be applied for subcatchments greater than 160 acres.

BMP whole life cycle costs include the costs of construction, permitting, design and engineering, land acquisition, routine and non-routine maintenance, administration and rehabilitation (after reaching the BMP design life). Each cost is computed as a function of the physical size or capacity of the BMP, which allows for multiple BMPs of various sizes to be modeled within the same scenario. Many of the more common BMPs had construction cost equations reported in the literature, although there were differences in the units in which the equations were developed. Some cost equations related costs to the physical size or capacity of the BMP while others reported costs as a function of the contributing area. The latter required some modifications to fit the model's cost equation format. Less common BMPs did not have cost equations available from the literature and equations had to be developed using either a few data points available from example projects, a range of unit costs reported, or cost information available from similar types of BMPs. In these cases, it was assumed that economies of scale (i.e. lower unit costs for larger BMPs) existed and power equations were fit to the data. However, it was surprising to find that some of the reported construction cost data did not reveal economies of scale. Linear trendlines fit to data from hydrodynamic separators, sand filter vaults and vaults with capture volume revealed higher R^2-values than a power function. In each of these cases one data point representing a large, expensive project seemed to be the cause for this; however no reasonable defense could be made to ignore those data points. Additionally, the best fit equations for sand filter vaults and vaults with capture volume required forcing the cost intercept to be zero in order to eliminate the negative cost intercept that resulted from the true best fit linear relationship. This procedure was necessary in order to eliminate the possibility of a negative construction cost for very small BMPs, however it may indicate that diseconomies of scale (i.e. higher unit costs for larger projects) exist for these types of BMPs.

Permitting, design and engineering costs were estimated as a percentage of the construction costs, as is common with planning phase cost estimates. For the Denver, CO area, this percentage was estimated at 40% by experienced professionals. Land acquisition costs were estimated using unit land costs (which vary according to land use) reported in the literature and a derived "land consumption" factor (LCFCTR) that relates the number of impervious acres draining to a BMP (a model input parameter) to the area of land it consumes. The LCFCTR was derived using BMP design criteria recommended by UDFCD.

Maintenance costs estimates were developed using information collected through interviews with stormwater utilities and maintenance personnel in the Denver, CO region, unit cost estimating guidebooks and recommendations provided by UDFCD. The data collected on maintenance frequency, hours required per activity, labor, equipment and materials costs allowed for the development of "bottom up" unit cost estimates for each maintenance activity (i.e. $ per cubic yard of sediment removal), which is an improvement over the commonly used method of estimating annual maintenance costs as a percentage of the original construction costs. This method also explicitly reveals which maintenance activities cost more than others, which could lead to maintenance policy or BMP design changes in order to reduce costs. In addition, derivation of a nondimensional "β" term that relates the number of units of maintenance required (i.e. cubic yards of sediment removal) to the size of the BMP (i.e. acre-feet of storage) allows for one maintenance activity unit cost to be applied to any size of BMP.

Most BMPs constructed in the US are still functioning adequately or have not been rehabilitated as needed; therefore there is little published data available to estimate BMP rehabilitation costs at this time. Assuming that BMP rehabilitation would require similar activities as original construction, rehabilitation costs were estimated as a percentage of the original construction costs with some modifications. These costs were assumed to occur at the end of the BMP design life, which was estimating using reported values from the literature.

The costs of administering a stormwater utility and/or maintenance program can be estimated as approximately 12% of the annual maintenance costs for Denver, CO.

Computing the whole life cycle costs of BMPs shows that the long-term maintenance, rehabilitation and administrative costs can be significant and may show that a BMP is much more expensive than it otherwise may appear based only on initial construction costs. Additionally, including land acquisition costs into the whole life cycle costs allows planners to determine when it is most cost effective to implement BMPs with little or no surficial "footprint". It is important to recognize that the cost estimates developed for the model contain a high level of uncertainty and should be considered "order-of-magnitude" estimates.

This model measures performance of the entire BMP system by accounting for the volume of runoff generated from the watershed, the volume of runoff that is adequately treated by the BMP, the runoff volume that bypasses the BMP, the volume of runoff lost through ET and infiltration within the BMP and the average EMCs of pollutants in each runoff component. This method ensures that the total volume of runoff and mass of pollutants is conserved and accounted for throughout the process from watershed generation to discharge to the receiving water, which encourages the use of infiltration and discourages the bypassing of BMP treatment in order to reduce pollutant loads and runoff volume discharged to the receiving waters. Also, unlike previous BMP performance measures that relied on the "percent removal" of a pollutant to determine the BMP effluent concentration, this model uses average effluent EMCs reported in the International BMP Database for the various BMPs included in the model. The information contained within the International BMP Database is derived from over 300 BMP studies conducted throughout the world and is recognized as being the source of the best BMP data currently available.

7. RECOMMENDATIONS FOR FUTURE WORK

This model is "first-of-its-kind" and was designed to be a "simple" model not only to open up the potential user base, but also because it is intended for use at the planning level where the details required for more sophisticated modeling are generally unavailable. As this model gains more use, there will likely be a push by users to improve its accuracy and sophistication. Given that stormwater and its impacts (both environmental and financial) are highly uncertain, a natural progression in model development would be to incorporate uncertainty so that the results are probabilistic, not deterministic. Uncertainties in precipitation, pollutant load generation and BMP efficiency have been studied and quantified and could be implemented without very much new research. Uncertainties in costs, however, have not been well studied and would require a quite extensive research project. Doing so could involve administering a large, national survey of BMP construction and maintenance costs. Any large cost collecting project should focus on reporting the BMP size with the costs, so that the algorithms developed for this model (relating cost to the BMP size) could be adapted to the new data. However, inherent in any reported maintenance cost is the uncertainty that exists from not knowing whether or not maintenance activities are being performed adequately to maintain BMP performance. For example, it may be known that hydrodynamic separators are cleaned out 4 times per year, but is that adequate? It may then be possible to link the probability of pollutant load generation to the probability of having to perform maintenance on a particular type of BMP.

Finally, future versions of the model could benefit from an optimization algorithm for the selection of BMPs to meet a specified water quality goal. This model relies on the user to select and apply BMPs using an iterative ("guess and check") process to meet a water quality goal, however it is possible that a genetic algorithm could be used to automate this process.

8. LITERATURE CITED

Adsorbants Online (2009). Storm Drain Filter Insert - Drain Guard. < http://www.absorbentsonline.com/draininserts.htm> (Accessed October 2009).

ASCE. (2006). "Life Cycle Cost Analysis – ASCE Policy Statement 451." <http://www.asce.org/pressroom/news/policy_details.cfm?hdlid=86> (Accessed June 9, 2009).

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Donigian, A.S., Jr., and Johanson, R.C. (1997). "Hydrological Simulation Program--Fortran, User's manual for version 11." *EPA/600/R-97/080* USEPA, National Exposure Research Laboratory, Athens, Ga.

Bowhead Environmental and Safety (2009). StreamGuard Oil, Grease and Sediment Catch Basin Insert. <http://www.shopbowhead.com/pc-120-54-streamguard-oil-grease-sediment-catch-basin-insert-10pack.aspx> (Accessed October 2009).

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

Engineering News Record. (2008). "Construction Cost Index History." <http://enr.construction.com/economics/historical_indices/default.asp>. (Accessed August 2008).

Front Range Agencies. (2008). Personal Communication.

Geosyntec Consultants and Wright Water Engineers. (2008). "Analysis of Treatment System Performance - International Stormwater Best Management Practices Database (1999-2008)." Prepared for Water Environment Research Foundation, American Society of Civil Engineers, US Environmental Protection Agency, Federal Highway Administration and American Public Works Association.

Geosyntec Consultants and Wright Water Engineers. (2009). "International Stormwater Best Management Practices Database." Prepared for Water Environment Research Foundation, American Society of Civil Engineers, US Environmental Protection Agency, Federal Highway Administration and American Public Works Association.

Geosyntec Consultants, Urban Drainage and Flood Control District and American Society of Civil Engineers. (2002). "Urban Stormwater BMP Performance

Monitoring." *EPA-821-B-02-001*. Prepared for USEPA Office of Water. Washington, D.C.

Interagency Catch Basin Insert Committee (ICDIC). (1995). "Evaluation of Commercially-Available Catch Basin Inserts for the Treatment of Stormwater Runoff from Developed Sites." King County, WA.

Lampe, L., Andrews, H., Barrett, M., Hollon, M., Jeffries, C., Kellagher, R., Martin, P., Woods-Ballard, B. (2005). "Post-Project Monitoring of BMPs/SUDs to Determine Performance and Whole-Life Costs – Phase 2". Water Environmental Research Foundation, 01-CTS-21T. Alexandria, VA.

Landphair, H.C., McFalls, J.A., Thompson, D. (2000). "Design Methods, Selection, and Cost-Effectiveness of Stormwater Quality Structures." Texas Department of Transportation, Report 1837-1. College Station, TX.

Low Impact Development Center. (2009). "LID Urban Design Models – Permeable Pavers Website." <http://www.lid-stormwater.net/permpaver_costs.htm> (Accessed February 2009).

Maestre, A., Pitt, R., and Center for Watershed Protection. (2005). "The National Stormwater Quality Database, Version 1.1. A Compilation and Analysis of NPDES Stormwater Monitoring Information." Prepared for USEPA, Office of Water. Washington D.C.

National Weather Service (2008). Climate Report Summary for Denver/Boulder, CO. <http://www.crh.noaa.gov/bou/include/showProduct.php?product=annsum08.txt> (Accessed July 2008).

Newnan, Donald, G. (1996). *Engineering Economic Analysis.* Engineering Press. San Jose. Sixth Edition.

Rossman, L. A. (2008). "Stormwater Management Model User's Manual – Version 5.0." *EPA/600/R-05/040*. USEPA, National Risk Management Research Laboratory, Cincinnati, OH.

Sample, D.J., Heaney, J.P., Wright, L.T., Fan, C., Lai, F., and Field, R. (2003). "Costs of Best Management Practices and Associated Land for Urban Stormwater Control." *Journal of Water Resources Planning and Management.*, 129(1), 59-68.

Schueler, T. (1987). "Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban Best Management Practices." Metropolitan Washington Council of Governments, Washington, D.C.

Soil Conservation Service. (1975). "Hydrology, Supplement A to Section 4". *National Engineering Handbook.* USDA-SCS. Washington, D.C.

Strecker, E.W., Quigley, M.M., Urbonas, B.R., Jones, J.E., Clary, J.K. (2001). "Determining Urban Storm Water BMP Effectiveness." *Journal of Water Resources Planning and Management*, 127(3), 144-149.

Strecker, E., Huber, W., Heaney, J., Bodine, D., Sansalone, J., Quigley, M., Leisenring, M., Pankani, D., and Thayumanavan, A. (2005). "Critical Assessment of Stormwater Treatment and Control Selection Issues." Water Environment Research Foundation, 02-SW-1. Alexandria, VA.

Southeast Wisconsin Regional Planning Committee (SEWRPC). (1991). "Costs of Urban Nonpoint Source Water Pollution Control Measures". Technical Report Number 31. Waukesha, WI.

USDOT. (2002a). "Stormwater Best Management Practices in an Ultra Urban Setting: Selection and Monitoring. Organic Media Filter Fact Sheet."
<http://www.fhwa.dot.gov/environment/ultraurb/3fs9.htm> (Accessed May 2009).

USDOT. (2002b). "Stormwater Best Management Practices in an Ultra Urban Setting: Selection and Monitoring. Final Selection Phase."
< http://www.fhwa.dot.gov/environment/ultraurb/uubmp6p4.htm#s651> (Accessed May 2009).

USEPA. (1999). "Stormwater Technology Fact Sheet – Hydrodynamic Separators." *EPA 832-F-99-017*. Office of Water, Washington, D.C.

USEPA. (2001). "Stormwater Technology Fact Sheet – On-Site Underground Retention/Detention." *EPA 832-F-01-005*. Office of Water, Washington, D.C.

USEPA. (2008). "EPA Stormwater Menu of BMPs - Stormwater Wetlands."
<http://cfpub.epa.gov/npdes/stormwater/menuofbmps/menu.cfm> (June 9, 2009)

USEPA. (2004). "The Use of Best Management Practices in Urban Watersheds." *EPA-600-R-04-184*, Office of Research and Development, Washington, D.C.

Urban Drainage and Flood Control District (UDFCD). (2004). *Urban Storm Drainage Criteria Manual, Volumes 1-3*. Denver, CO.

Urbonas, B.R. and Jones, J.E. (2001). "Summary of Emergent Urban Stormwater Themes." In *Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation*. ed. Ben R. Urbonas., Engineering Foundation Conference, Snowmass, CO. ASCE, Reston, VA., 1-8.

Urbonas, B. R. (2008). Personal Communication.

Watershed Management Institute (WMI). (1997). "Operation, Maintenance and Management of Stormwater Management Systems." Prepared for USEPA Office of Water, Washington, D.C.

Weigand, C., Schueler, T., Chittenden, W., and Jellick, D. (1986). "Cost of Urban Runoff Quality Controls." In *Urban Runoff Quality - Impact and Quality Enhancement Technology*. eds Ben R. Urbonas and Larry. A. Roesner., Engineering Foundation Conference, Henniker, NH. ASCE, New York, NY., 366-380.

Weiss, P.T., Gulliver, J.S., and Erickson, A.J. (2007). "Cost and Pollutant Removal of Storm-water Treatment Practices." *Journal of Water Resources Planning and Management*. 133(3) 218-229.

Wossink, A. and Hunt, B. (2003). "The Economics of Structural Stormwater BMPs in North Carolina." Report UNC-WRRI-2003-344, North Carolina State University, Raleigh, NC.

Young, G.K., Stein, S., Cole, P., Kammer, T., Graziano, F., and Bank, F. (1996). "Evaluation and Management of Highway Runoff. Water Quality Technical Report". Department of Environmental Programs, Metropolitan Washington Council of Governments, Washington, D.C.

Appendix A: Methods, Sources and Assumptions Used to Develop Maintenance Cost Estimates

A.1. Introduction

As with capital costs, it was preferred to develop cost equations that related annual maintenance costs to the size of the BMP. Annual maintenance costs for a single BMP typically reflect the costs of performing a wide variety of activities. Those activities can generally be divided into two components; those with costs that vary according to the size of the BMP ("variable" maintenance costs) and those that do not ("constant" maintenance costs). The following equation was developed for estimating annual maintenance costs as a function of multiple maintenance activities in both components.

$$MCost = \sum_{i=1}^{n}\left(F_i * A_i\right) + \sum_{j=1}^{m}\left(F_j * A_j * \beta_j\right) * BMPSize \qquad \textbf{(A-1)}$$

Where MCost = annual maintenance costs for an individual BMP, A = maintenance cost for one unit of activity, F = frequency of maintenance per year, β= coefficient specifying the number of maintenance units per unit of BMP size[1], BMPSize = number of units of BMP Size (AF, ft3, ft2, acre, cfs), i = indicates activities with "constant" maintenance costs, j = indicates activities with "variable" maintenance costs, n = number of "constant" maintenance activities for BMP and m = number of "variable" maintenance activities for BMP.

---

[1] For example, if it is determined that approximately 1 acre of lawn needs mowing for every 3 acre-feet of storage volume for RPs, then the coefficient value would be 0.33.

Substituting a single variable for the summation terms, Equation (1) can be rewritten as (2);

$$MCost = Cc + Cv * BMPSize \qquad \textbf{(A-2)}$$

Where Cc = total annual cost for "constant" maintenance activities and Cv = total annual unit cost for "variable" maintenance activities.

To use the equations above, it was necessary to determine the following information for each BMP:

1. What typical maintenance activities are required or recommended?
2. How often does maintenance occur?
3. How much does one unit of maintenance cost?
4. What is the relationship (β-value) between unit maintenance costs and BMP size for that activity?

A.2. Methodology

The methods, assumptions and data sources used to answer the four questions listed above are described in this section.

A.2.1. Necessary Maintenance Activities

Published lists of recommended BMP maintenance activities are readily available. In Chapter 3 of the Urban Storm Drainage Criteria Manual (USDCM) (UDFCD 2004), UDFCD provides maintenance recommendations for many of the BMPs included in this model. Other lists can be found on the EPA's stormwater fact sheets http://www.epa.gov/npdes/stormwater/menuofbmps).

Table A-1 lists the maintenance activities for each BMP that are included in the model.

Table A-1: Recommended maintenance activities

BMP	Activity	Frequency
All	Inspection	1
CGP	Sweeping/Vacuuming	2
CWB	Litter and Debris Removal	1
CWB	Sediment Removal (forebay)	0.5
CWB	Sediment Removal (basin)	0.05
CWC	Litter and Debris Removal	1
CWC	Vegetation/Woody Debris Removal	0.2
EDB	Inlet/Outlet Cleaning	6
EDB	Nuisance Control	12
EDB	Outlet Maintenance	0.25
EDB	Lawn Mowing/Lawn Care	6
EDB	Sediment Removal (forebay/micropool)	0.5
EDB	Sediment Removal (basin)	0.05
HS	Sediment Removal	4
HS	Traffic Control	4
II	Filter Replacement	4
MFV	Remove Media Filter Top Layer	1
PCP	Sweeping/Vacuuming	2
PGP	Gravel Finish Grading	12
PICP	Sweeping/Vacuuming	2
PLD	Annual Cleanup/Planting	1
RGB	Lawn Mowing/Lawn Care	15
RP	Nuisance Control	12
RP	Lawn Mowing/Lawn Care	6
RP	Sediment Removal (forebay/micropool)	0.5
RP	Sediment Removal (basin)	0.05
RP	Vegetation/Woody Debris Removal	0.33
SFB	Lawn Mowing/Lawn Care	6
SFB	Sediment Removal (forebay)	0.5
SFB	Scarify Top Sand Layer	1
SFV	Scarify Top Sand Layer	1
SOG	Sediment Removal	4
SOG	Traffic Control	4
VCV	Sediment Removal	0.2

A.2.2. Frequency of Maintenance

The frequency of maintenance describes how often maintenance is performed (reported in number of times per year) and varies according to the BMP for which it is being performed. If the activity was only performed once every several years, than the value would be less than 1. (For example: An activity performed once per five years would have a value of 0.2 times per year.). The frequencies in Table A-1 were obtained from interviews with stormwater maintenance personnel (Front Range Agencies 2008) and from UDFCD recommendations in the USDCM (UDFCD, 2004).

A.2.3. Maintenance Activity Unit Costs

The maintenance activity unit costs are the costs to perform one unit of maintenance (for example, the cost to remove 1 cubic foot of sediment from a BMP). These costs were developed using "bottom-up" or "unit-pricing" cost estimating procedures. Equation (A-3) is used to compute the maintenance unit cost for each activity.

$$\text{2008\$} \qquad A = E * CS * (LR + LR * OH) + E * EC + OC \qquad \text{(A-3)}$$

Where A = maintenance unit cost, E = efficiency of maintenance, CS = labor crew size, LR = hourly labor rate, OH = overhead factor, EC = equipment costs and OC = other costs.

Annual O&M unit cost estimates were prepared using information collected during interviews with seven stormwater utilities in the Denver, Colorado region and the RSMeans 2005 Site Work & Landscape Cost Data Guide (RSMeans, 2005). When sufficient cost information was provided from the stormwater utilities it was used in the cost calculations. However, at times the utilities could not provide any or all of the necessary information, so RS Means data was used to complement it.

A.2.4. Data Collection from Interviews with Stormwater Utilities

Personnel from seven stormwater utilities located near Denver, CO were interviewed to gather information and costs on BMP maintenance. The interviewee(s) was asked to estimate the average amount of resources (materials, equipment, personnel, etc.) and the average frequency of maintenance required for its BMPs, based on proactive maintenance[2]. In most cases, the interviewee(s) found it difficult to estimate "average" values, particularly for frequency of maintenance and maintenance efficiency (number of hours required), because they varied considerably from individual BMP to individual BMP. Nevertheless, the interviewee(s) usually provided a "best guess" at the values.

Several utilities reported cost information for extended detention basins, hydrodynamic separators and sediment/oil/grease separators; which are generally the most popular BMPs used in the area. Only one utility could provide costs for a single sand filter vault and porous concrete parking lot, another provided costs for a single constructed wetland channel, and another provided "average" costs for retention ponds based on multiple ponds located in its jurisdiction. The information collected during these interviews is summarized in Table A-2 and Table A-3.

---

[2] Keeping with project objectives which are to estimate the costs of proactive maintenance, not reactive.

A.2.5. Unit Cost Estimating Using RS Means

The RSMeans 2005 Site Work & Landscape Cost Data Guide (RSMeans, 2005) was used to complement the information gathered from the utility interviews. A summary of the unit costs used from RS Means is provided in

Table A-4 and Table A-5. All costs were adjusted from 2005 dollars to 2008 dollars using the ENR CCI, and then regionally adjusted to the Denver region using the RS Means region multiplier of 0.927.

A.2.6. Hourly Labor Rate

Average labor rates for stormwater maintenance personnel were collected from five agencies located near Denver, Colorado (Table A-3). The average labor rate between these was approximately $23.31 (in 2008 dollars).

A.2.7. Overhead Factor

It is assumed that overhead costs for maintenance personnel (insurance, vacation, retirement contribution, etc.) is approximately equal to the hourly labor rate, therefore this value is 100%.

A.2.8. Equipment Costs

Equipment costs are reported in Table A-3 and Table A-5 as hourly costs per piece of equipment. Generally, when more than one reported cost existed for the same equipment, the average of those costs was used in the model.

A.2.9. Other Costs

Other costs for materials, disposal, etc. are reported in Table A-3 and Table A-5 as unit costs. Generally, when more than one unit cost was reported for the same item, the average of those costs was used in the model.

Table A-2: Summary of maintenance activity information reported by Front Range Agencies

Activity	Units	Frequency	Hours per Unit	Crew	Equipment	Other Costs	Lump Sum Cost
Hydrodynamic Separator							
Sediment Removal	CY	4	0.5	3	Jet-Vac Truck	Sediment Disposal (wet)	-
Sediment Removal	CY	4	2	2	Jet-Vac Truck	Sediment Disposal (wet)	-
Sediment Removal	CY	4	1.5	2	Jet-Vac Truck	Sediment Disposal (wet)	-
Sediment Removal	CY	4	4	2	Jet-Vac Truck	Sediment Disposal (wet)	-
Sediment Removal	CY	4	2	2	Jet-Vac Truck	Sediment Disposal (wet)	-
Traffic Control	(a)	(a)	(a)	3(b)	Jet-Vac Truck	-	-
Traffic Control	(a)	(a)	(a)	3(b)	Jet-Vac Truck	-	-
Traffic Control	(a)	(a)	(a)	1	Pick-up Truck	-	-
Notes: – frequency and efficiency dependent on sediment removal – requires another street crew							
Extended Detention Basin							
Inlet/Outlet Cleaning	Each	6(c)	0.5	2	Pick-up Truck	-	-
Inlet/Outlet Cleaning	Each	6(c)	0.5	1	Pick-up Truck	-	-
Inspection	Each	6(c)	0.2	1	Pick-up Truck	-	-
Inspection	Each	6(c)	0.75	1	Pick-up Truck	-	-
Lawn Mowing/Care	Acre	3	2	2	Pick-up Truck Tractor w/ Mower	-	-
Nuisance Control	Each	24	0.8	1	Pick-up Truck	-	-
Nuisance Control	Each	12	0.25	2	Pick-up Truck	-	-
Nuisance Control	Each	10	0.5	1	Pick-up Truck	Mosquito/Algae Tablets ($35)	-
Outfall Maintenance (Rip-rap repair)	Each	0.2	12	3	Pick-up Truck (2) 3-CY Dumptrucks Skidsteer	6 CY Rip-Rap(d)	-
Outfall Maintenance	Each	0.33	-	-	-	-	$7,500

Activity	Units	Frequency	Hours per Unit	Crew	Equipment	Other Costs	Lump Sum Cost
(Rip-rap repair)							
Sediment Removal (routine)	CY	0.5	0.33	2	Small Dumptruck Skidsteer	Sediment Disposal	-
Sediment Removal (non-routine)	CY	0.1	0.08	4	Pick-up Truck Large Backhoe (2) Large Dumptrucks	Sediment Disposal	-
Notes: – after each major storm, assume 6 per year – assumed volume of riprap							
Constructed Wetland Channel							
Debris and Litter Removal	Each	4	1.5	2	Pick-up Truck	-	-
Porous Concrete							
Outlet Cleaning	Each	1	1	2	Jet-Vac Truck	-	-
Retention Pond							
Inspection	Each	6(e)	0.2	1	Pick-up Truck	-	-
Inspection	Each	6(e)	0.75	1	Pick-up Truck	-	-
Lawn Mowing/Care	Acre	3	2	2	Pick-up Truck Tractor w/ Mower	-	-
Tree Trimming	Each	0.33	2	5	Pick-up Truck	-	-
Nuisance Control	Each	10	1	1	Pick-up Truck	Mosquito/Algae Tablets ($70)	-
Notes: – after each major storm, assume 6 per year							
Sediment/Oil/Grease Separator							
Sediment Removal	CY	4	1	3	Jet-Vac Truck	Sediment Disposal (wet)	-
Sediment Removal	CY	4	1.33	2	Jet-Vac Truck	Sediment Disposal (wet)	-
Sediment Removal	CY	12	-	-	-	-	$277
Traffic Control	(f)	(f)	(f)	3(g)	Jet-Vac Truck	-	-

Activity	Units	Frequency	Hours per Unit	Crew	Equipment	Other Costs	Lump Sum Cost
Traffic Control	[f]	[f]	[f]	3[g]	Jet-Vac Truck	-	-
Traffic Control	[f]	[f]	[f]	1	Pick-up Truck	-	-
Notes: – frequency and efficiency dependent on sediment removal – requires another street crew							
				Sand Filter Vault			
Remove Top Sand Layer	CY	1	1.6	2	Skidsteer Dumptruck	Sediment Disposal	-

Table A-3: Summary of labor, equipment and materials costs reported by Front Range Agencies

Hourly Labor Rates	**Equipment Costs**		**Other Costs**	
	Equipment	**Hourly Cost**	**Material/Other**	**Unit Cost**
$20.33	Backhoe	$46.01	Sediment Disposal	$10/CY
$21.24	Backhoe	$62.00	Sediment Disposal	$10/CY
$24.00	Backhoe Trailer	$9.99	Sediment Disposal	$5/CY
$26.00	Dumptruck (tandem)	$54.73	Sediment Disposal (wet)	$100/CY
$25.00	Flatbed Truck	$10.02		
	Jet-Vac Truck	$44.02		
	Jet-Vac Truck	$83.00		
	Jet-Vac Truck	$101.00		
	Jet-Vac Truck	$200		
	Pick-up Truck	$10.29		
	Pick-up Truck	$10.00		
	Skidsteer	$14.96		

Table A-4: RS Means Cost Information for Maintenance Activities

Activity	Units	Hours per Unit	Crew	Equipment	Other Costs	RS Means #
Selective Clearing	Acre	32	1	Pick-up Truck Brush Saw	-	02230-200-0020
Scarify Subsoil	MSF	0.067	1	Skidsteer w/ Scarifier	-	02910-710-3050
Site Maintenance, Hand Pick-up	MSF	0.267	1	Pick-up Truck	-	02985-700-1130
Flower Bed Maintenance, Spring Prepare	MSF	4	1	Pick-up Truck	-	02985-700-1200
Flower Bed Maintenance, Fall Clean-up	MSF	8	1	Pick-up Truck	-	02985-700-0830
Finish Grading, Large Area	SY	0.008	2	Grader	-	02310-100-0100

Table A-5: RS Means Cost Information for Equipment and Materials

Equipment/Material	Units	Unit Cost	RS Means #
Dumptruck, Large (12-ton)	Hr	$55.18	01590-200-5250
Skidsteer, 1 CY	Hr	$34.81	01590-200-4890
Tractor w/ Rotary Mower	Hr	$28.99	02230-200-1080
Excavator, 1 CY	Hr	$99.68	01590-200-0150
Dumptruck, Small (1.5-ton)	Hr	$19.18	01590-200-5450
Brush Saw	Hr	$2.44	Crew Description A-1C
Street Sweeper	Hr	$78.29	01500-500-3400
Grader	Hr	$31.81	Crew Description B-11L
Rip-Rap (18" thickness)	SY	$15.79	02370-450-200

A.2.10. Efficiency of Maintenance

The efficiency of maintenance variable accounts for how much time each maintenance activity requires. More specifically, the actual value represents the number of hours required to complete one unit of maintenance. For example, if it requires approximately 30 minutes to mow 1 acre of grass, then $E = 0.5$. Generally, when more than one efficiency value was reported for the same activity, the average of those costs was used in the model.

A.2.11. Labor Crew Size

The labor crew size is the number of maintenance personnel needed to complete the maintenance activity. Generally, when more than crew size was reported for the same activity, the average of those values was used in the model.

A.2.12. Summary

Table A-6 shows the computed maintenance unit costs for each activity, alongside the estimated values of each variable as presented in the preceding sections.

Table A-6: Summary of Maintenance Unit Costs Developed for the UDFCD BMP Effectiveness and Cost Analysis Model

Activity	Units	Hours per Unit	Crew Size	Equipment Required	Equipment Cost/hr[1]	Other Materials	Other Costs	Cost per Unit[2]
Inspection	Each	0.33	1	Pickup Truck	$10.15	-	-	$19
Inlet/Outlet Cleaning	Each	0.5	2	Pickup Truck	$10.15	-	-	$52
Nuisance Control (EDB)	Each	0.5	1	Pickup Truck	$10.15	Product	$35	$63
Nuisance Control (RP)	Each	1	1	Pickup Truck	$10.15	Product	$70	$127
Outfall Maintenance	Each	12	3	Pickup Truck Large Dumptruck Skidsteer	$10.15 $55.18 $37.55	Rip-Rap	$200[3]	$3,113
Lawn Mowing/Lawn Care	Acre	2	2	Pickup Truck Tractor w/ Rotary Mower	$10.15 $31.27	-	-	$269
Sediment Removal – Non-Routine[4]	CY	0.08	4	Pickup Truck Large Excavator 2 Large Dumptrucks	$10.15 $99.68 $110.36	Sediment Disposal	$10	$43
Sediment Removal – Routine[5]	CY	0.33	2	Small Dumptruck Skidsteer	$19.18 $37.55	Sediment Disposal	$10	$59
Sediment Removal [6]	CY	1.2	2	Jet-Vac Truck	$110	Sediment Disposal	$100	$344
Traffic Control[7]	CY	1.2	2	Pickup Truck	$10.15	-	-	$124
Vegetation/Woody Debris Removal	Acre	16	2	Pickup Truck Brush Saw	$10.15 $2.62	-	-	$1,696
Scarify Top Sand Layer (SFB)	Acre	3	1	Skidsteer w/ Scarifiers	$37.55	-	-	$253
Remove Top Sand Layer (SFV)[8]	CY	2	2	Skidsteer Small Dumptruck	$37.55 $19.18	Sand Disposal	$10	$310

Activity	Units	Hours per Unit	Crew Size	Equipment Required	Equipment Cost/hr[1]	Other Materials	Other Costs	Cost per Unit[2]
Remove Top Media Layer (MFV) [10]	CY	2	2	Skidsteer Small Dumptruck	\$37.55 \$19.18	Sand Disposal	\$10	\$310
Litter & Debris Removal	Acre	6	2	Pickup Truck	\$10.15	-	-	\$620
Annual Cleanup	MSF	4	2	Pickup Truck	\$10.15	-	-	\$414
Annual Planting	MSF	2	2	Pickup Truck	\$10.15	-	-	\$207
Finish Grading	Acre	6	1	Grader	\$31.81	-	-	\$471
Pavement Sweeping	Acre	0.5	1	Street Sweeper/Vacuum	\$78.29	-	-	\$62
Inlet Filter Replacement	Each	0.5	1	Pick-up Truck	\$10.15	Filter Replacement	\$1,100	\$1,100

---

[1] Unless otherwise noted, hourly equipment costs include rental and operating costs, as reported in RSMeans 2005.

[2] Assumes labor rate of \$23.31 per hour and overhead costs equal to 100% of labor rate

[3] Assumes approximately 6 CY of rip-rap

[4] Applicable to large basin facilities such as extended detention basins, retention (wet) ponds, and constructed wetland basins

[5] Sediment removal from forebay for large basin facilities

[6] Applicable to underground structures such as hydrodynamic separators, sediment/oil/grease separators, etc.

[7] Required for sediment removal from underground structures, therefore the efforts are a function of the amount of sediment needing removal

[8] Costs apply for "Delaware-type" filters where access to the filter is available by removing inlet grates, allowing access for equipment

A.3. BMP Size/Unit Maintenance Cost Relationship (β-value)

Relationships between BMP size and unit maintenance costs were determined using BMP design recommendation and other assumptions. The reported β-value represents the number of maintenance units per unit of BMP size plus the appropriate unit conversions.

A.3.1. Concrete Grip Pavers

Pavement Sweeping/Vacuuming – Pavement sweeping and/or vacuuming occurs over the entire surface area of the installation. The β-value = 1

$$\text{Sweeping/Vacuuming (acres)} = \text{Surface Area (acres)} * 1\text{(acre/acre)} \qquad \textbf{(A-4)}$$

A.3.2. Constructed Wetland Basin

Sediment Removal (routine) – Routine sediment removal is assumed to be performed when the basin forebay has reached its sediment holding capacity (20% of the total forebay volume). The basin forebay volume should be about 10% of the total pond volume, therefore the amount of sediment removed from the forebay is equal to 2% of the total basin volume. The β-value = 32.27, including the unit conversion from AF to CY.

$$\text{Sediment Removed (CY)} = \text{Volume (AF)} * 32.27\text{ (CY/AF)} \qquad \textbf{(A-5)}$$

Sediment Removal (non-routine) – Non-routine sediment removal is assumed to be performed when 20% of the storage volume has accumulated sediment. The β-value = 322.67, including the unit conversion from AF to CY.

Sediment Removed (CY) = Volume (AF) * 322.67(CY/AF) **(A-6)**

Litter and Debris – The area requiring litter and debris removal is assumed to 50% of the total area consumed by the basin. Assuming 1 acre of land consumed per AF of storage volume, the β-value = 0.5

Litter and Debris Removal (acre) = Volume (AF) * 0.5 (acres/AF) **(A-7)**

A.3.3. Constructed Wetland Channel

The size of CWCs are reported as the design flowrate (cfs), however maintenance costs are computed as a function of the surface area of the channel.

Vegetation/Woody Debris Removal – The area requiring vegetation and woody debris removal is assumed to be the total area consumed by the channel. The β-value = 1

Vegetation/Woody Debris Removal (acre) = Area of Channel (acre) * 1(acres/acres) **(A-8)**

Litter and Debris – The area requiring litter and debris removal is assumed to be the total area consumed by the channel. The β-value = 1

Litter and Debris Removal (acre) = Area of Channel (acre) * 1(acres/acres) **(A-9)**

A.3.4. Extended Detention Basin

Sediment Removal (routine) – Routine sediment removal is assumed to be performed when the EDB forebay has reached its sediment holding capacity (20% of the total forebay volume). The EDB forebay volume should be about 5% of the total EDB volume, therefore the amount of sediment removed from the forebay is equal to 1% of the total EDB volume. The β-value = 16.13, including the unit conversion from AF to CY.

$$\text{Sediment Removed (CY)} = \text{Volume (AF)} * 16.13\text{(CY/AF)} \qquad \textbf{(A-10)}$$

Sediment Removal (non-routine) – Non-routine sediment removal is assumed to be performed when the EDB has reached its sediment holding capacity (20% of total EDB volume). The β-value = 322.67, including the unit conversion from AF to CY.

$$\text{Sediment Removed (CY)} = \text{Volume (AF)} * 322.67 \text{ (CY/AF)} \qquad \textbf{(A-11)}$$

Lawn Care/Lawn Mowing – Lawn care/mowing is assumed to be required over the entire area consumed by the EDB. Assuming 1 acre of land required per AF of storage volume, the β-value = 1.

$$\text{Lawn Care/Lawn Mowing (acre)} = \text{Volume (AF)} * 1 \text{ (acre/AF)} \qquad \textbf{(A-12)}$$

A.3.5. Hydrodynamic Separator

Sediment Removal – Sediment removal is assumed to be performed when the sediment holding capacity of the system is full. Each proprietary system has a unique relationship between sediment holding capacity and design flowrate, therefore a regression equation was developed using the relationships from three systems with information readily available[3]. The relationships and regression equation are presented in Figure A-1.

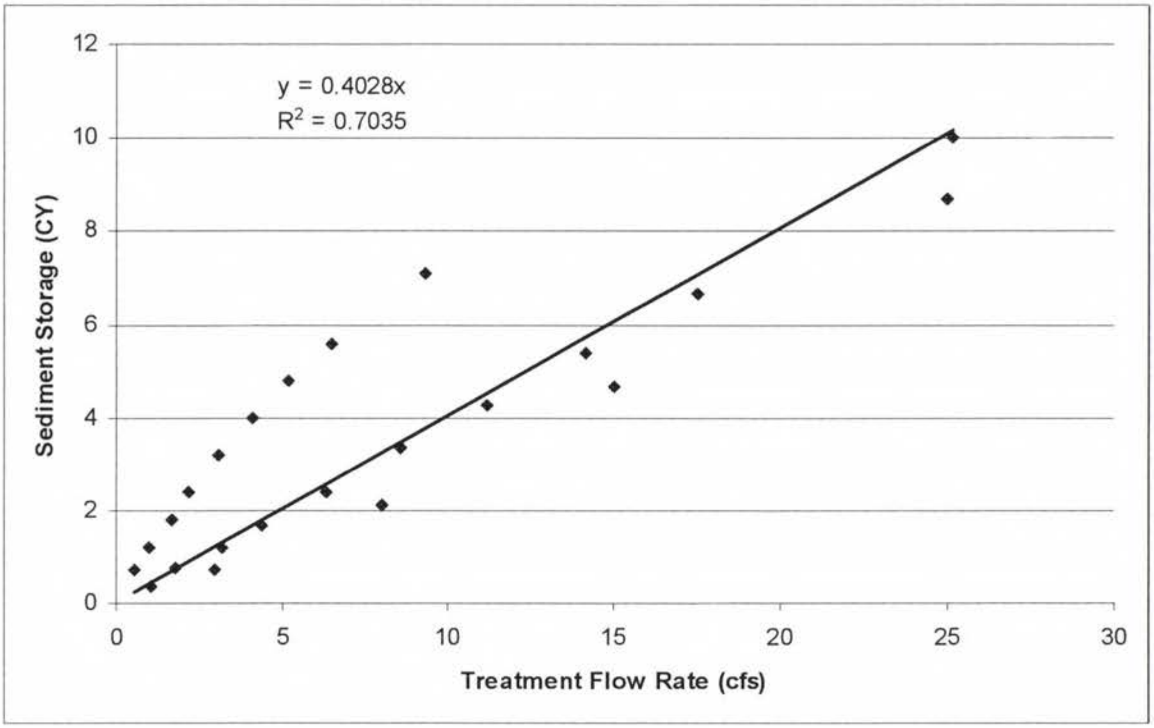


Figure A-1: Sediment storage and design flowrate relationships for hydrodynamic separators

The β-value for sediment removal in hydrodynamic separators is 0.4

Sediment Removed (CY) = Design Flowrate (cfs) * 0.4 (CY/cfs) **(A-13)**

---

[3] The systems used to establish the relationship were the Downstream Defender, Aqua-Swirl, and Vortechs; using information provided in product brochures.

Traffic Control – Traffic control is assumed to be required during sediment removal maintenance, therefore the same relationship described for sediment removal applies for traffic control. The β-value = 0.4

A.3.6. Media Filter Vault

Remove top media layer – Assuming that the top two inches are removed from the surface area of the vault, the surface area is approximately 33% of the total volume of media (i.e. the MFV is three feet deep), and the total volume of media is approximately 300% of the total volume of water storage (33% pore openings in media), the β-value = 0.006 including the unit conversion from CF to CY.

$$\text{Top Media Layer (CY)} = \text{Volume (CF)} * 0.006\ \text{(CY/CF)} \qquad \textbf{(A-14)}$$

A.3.7. Permeable Interlocking Concrete Pavers

Pavement Sweeping/Vacuuming – Pavement sweeping and/or vacuuming occurs over the entire surface area of the installation. The β-value = 1

$$\text{Sweeping/Vacuuming (acres)} = \text{Surface Area (acres)} * 1\text{(acre/acre)} \qquad \textbf{(A-15)}$$

A.3.8. Porous Concrete Pavement

Pavement Sweeping/Vacuuming – Pavement sweeping and/or vacuuming occurs over the entire surface area of the installation. The β-value = 1

$$\text{Sweeping/Vacuuming (acres)} = \text{Surface Area (acres)} * 1\text{(acre/acre)} \qquad \textbf{(A-16)}$$

A.3.9. Porous Gravel Pavement

Gravel Finish Grading - Grading occurs over the entire surface area of the installation. The β-value = 1

Gravel Grading (acres) = Surface Area (acres) * 1(acre/acre) **(A-17)**

A.3.10. Porous Landscape Detention

Annual Cleanup/Planting – The area requiring cleanup and planting is assumed to be the total surface area consumed by the BMP, which is the same as the storage volume of the PLD when assuming that water can pond up to 1 foot on top of the PLD. The β-value = 0.001.

Cleanup and Planting (MSF) = Volume(CF) * 0.001(MSF/CF) **(A-18)**

A.3.11. Reinforced Grass Pavement

Lawn Care/Lawn Mowing – Lawn care/mowing is assumed to be required over the entire surface area of the installation (β-value = 1).

Lawn Care/Lawn Mowing (acre) = Surface Area (acres)) * 1(acre/acre) **(A-19)**

A.3.12. Retention (Wet) Pond

Lawn Care/Lawn Mowing – Lawn care/mowing is assumed to be required over 50% of the area consumed by the BMP. Assuming 0.5 acres of land required per AF of storage volume, the β-value = 0.25.

Lawn Care/Lawn Mowing (acre) = Volume (AF) * 0.25(acres/AF) **(A-20)**

Sediment Removal (routine) – Routine sediment removal is assumed to be performed when the pond forebay has reached its sediment holding capacity (20% of the total forebay volume). The pond forebay volume should be about 5% of the total pond volume, therefore the amount of sediment removed from the forebay is equal to 1% of the total pond volume. The β-value = 16.13.

Sediment Removed (CY) = Volume (AF) * 16.13(CY/AF) **(A-21)**

Sediment Removal (non-routine) – Non-routine sediment removal is assumed to be performed when the pond has reached its sediment holding capacity (20% of total pond volume). The β-value = 322.67

Sediment Removed (CY) = Volume (AF) * 322.67(CY/AF) **(A-22)**

Vegetation/Woody Debris Removal – The area requiring vegetation and woody debris removal is assumed to 10% of the total area consumed by the pond. Assuming 0.5 acres of land required per 1 AF of storage volume, the β-value = 0.05.

Vegetation/Woody Debris Removal (acre) = Volume (AF) * 0.05(acres/AF) **(A-23)**

A.3.13. Sand Filter Basin

Lawn Care/Lawn Mowing – Lawn care/mowing is assumed to be required over 50% of the area consumed by the BMP. Assuming that 1 acre of land is required per 1.5 AF of storage volume, the β-value = 0.33.

Lawn Care/Lawn Mowing (acre) = Volume (AF) * 0.33 (acres/AF) **(A-24)**

Sediment Removal (routine) – Routine sediment removal is assumed to be performed when the basin forebay has reached its sediment holding capacity (20% of the total forebay volume). The forebay volume should be about 5% of the total basin volume, therefore the amount of sediment removed from the forebay is equal to 1% of the total pond volume. The β-value = 16.13.

Sediment Removed (CY) = Volume (AF) * 16.13(CY/AF) **(A-25)**

Scarify Top Sand Layer – Scarifying is required over the entire surface area of the sand filter, which is 1 ft^2 per CF of storage volume. The β-value = 0.33.

Scarifying Area (acre) = Volume (AF) * 0.33 (acres/AF) **(A-26)**

A.3.14. Sand Filter Vault

Remove top media layer – Assuming that the top two inches are removed from the surface area of the vault, the surface area is approximately 33% of the total volume of media (i.e. the SFV is three feet deep), and the total volume of media is approximately 300% of the total volume of water storage (33% pore openings in media), the β-value = 0.006 including the unit conversion from CF to CY.

Top Sand Layer (CY) = Volume (CF) *0.006(CY/CF) **(A-27)**

A.3.15. Sediment/Oil/Grease Separator

Sediment Removal – Sediment removal is assumed to be performed when the sediment holding capacity of the system is full. Each proprietary system has a unique relationship between sediment holding capacity and design flowrate, therefore a regression equation was developed using the relationships from three systems with information readily available[4]. The relationships and regression equation are presented in Figure A-2.

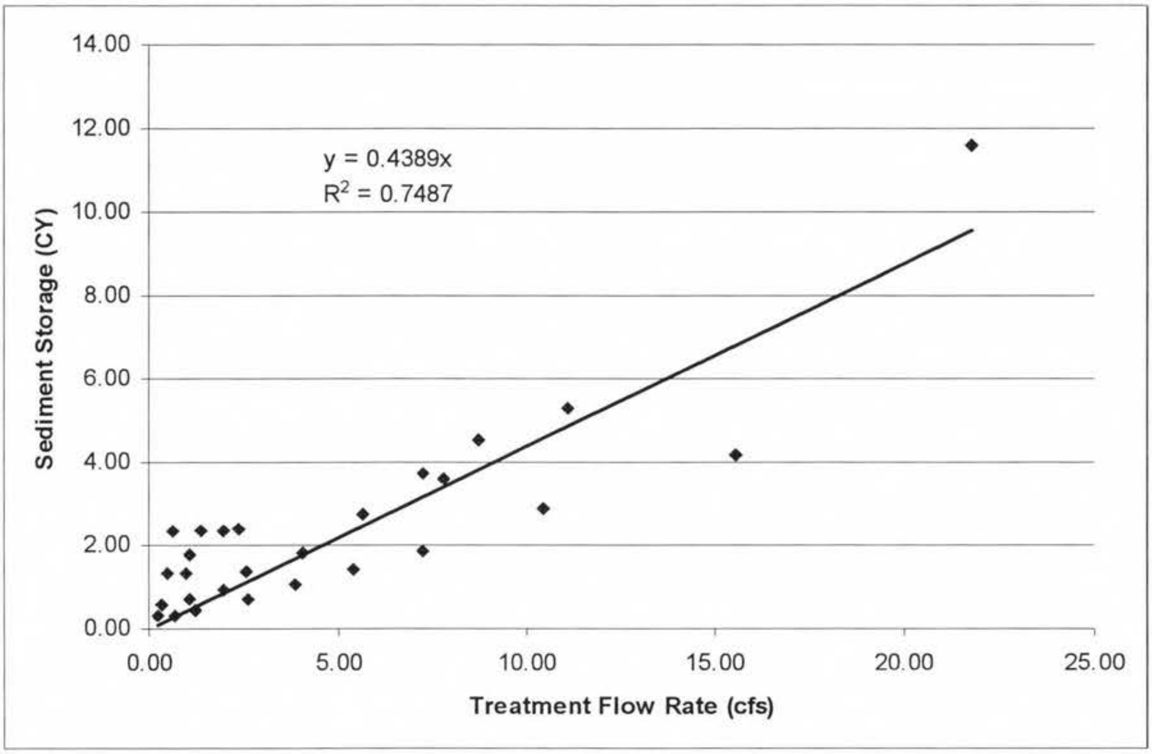


Figure A-2: Sediment storage and design flowrate relationships for sediment/oil/grease separators

The β-value for sediment removal in sediment/oil/grease separators is 0.44

Sediment Removed (CY) = Design Flowrate (cfs) * 0.44(CY/cfs) **(A-28)**

---

[4] The systems used to establish the relationship were the VortClarex, Stormceptor, Baysaver and V2B1; using information provided in product brochures.

Traffic Control – Traffic control is assumed to be required during sediment removal maintenance, therefore the same relationship described for sediment removal applies for traffic control. The β-value = 0.4

A.3.16. Vault with Capture Volume

Sediment Removal (routine) – Routine sediment removal is assumed to be performed when the vault has reached its sediment holding capacity (20% of the total volume). The β-value = 0.007 including the unit conversion from CF to CY.

$$\text{Sediment Removed (CY)} = \text{Volume (CF)} * 0.007\ \text{(CY/CF)} \qquad \textbf{(A-29)}$$

A.4. Maintenance Cost Equations

The maintenance cost equations developed for each BMP are described below. It should be noted that these cost equations are set as "default" values in the model, however the maintenance cost tables are user-editable and can be changed to fit any known maintenance costs.

A.4.1. Compliance Inspection

One activity that is common to all BMPs is inspection and the maintenance tables for each BMP include inspections. However in the model, inspections are considered administrative activities, not maintenance activities, therefore the costs of performing inspections are added to the annual administrative costs instead of the annual maintenance costs.

A.4.2. Concrete Grid/ Permeable Interlocking Concrete Block Pavers

Table A-7 summarizes the maintenance activities and their individual annual costs for cobblestone and modular block pavement. Equation (A-30) is used to compute total annual maintenance costs.

Table A-7: CGP/PICP maintenance activity costs

Activity	Type	Freq	A	β-value	Annual Cost*
-	-	-	-	-	-
				Total =	-
Sweeping/Vacuuming	Variable	2	$62	1	$125
				Total =	**$125**

Notes:

* – for unit-type activities, the annual cost is per acre of installation surface area

2008$ $$MCost = \$125 * BMPSize(acres) \qquad \textbf{(A-30)}$$

A.4.3. Constructed Wetland Basin

Table A-8 summarizes the maintenance activities and their individual annual costs for CWBs. Equation (A-31) is used to compute total annual maintenance costs.

Table A-8: CWB maintenance activity costs

Activity	Type	Freq	A	β-value	Annual Cost*
-	-	-	-	-	-
				Total =	-
Litter and Debris Removal	Unit	1	$620	0.5	$310
Sediment Removal (routine)	Unit	0.5	$60	32.27	$960
Sediment Removal (non-routine)	Unit	0.05	$43	322.67	$686
				Total =	**$1,956**

Notes:

* – for unit-type activities, the annual cost is per AF of storage volume

2008$ $$MCost = \$1{,}956 * BMPSize(AF) \quad \textbf{(A-31)}$$

A.4.4. Constructed Wetland Channel

Table A-9 summarizes the maintenance activities and their individual annual costs for CWCs. Equation (A-32) is used to compute total annual maintenance costs.

Table A-9: CWC maintenance activity costs

Activity	Type	F	A	β-value	Annual Cost*
-	-	-	-	-	-
				Total =	**-**
Litter and Debris Removal	Unit	1	$620	1	$620
Vegetation/Woody Debris Removal	Unit	0.2	$1,969	1	$339
				Total =	**$960**

Notes:

* – for unit-type activities, the annual cost is per acre of surface area

2008$ $$MCost = \$960 * BMPSize(acres) \quad \textbf{(A-32)}$$

A.4.5. Extended Detention Basin

Table A-10 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-33) is used to compute total annual maintenance costs for EDBs.

Table A-10: EDB maintenance activity costs

Activity	Type	F	A	β-value	Annual Cost*
Inlet/Outlet Cleaning	Lump sum	6	$52	-	$310
Nuisance Control	Lump sum	12	$63	-	$761
Outlet Maintenance	Lump sum	0.25	$3,113	-	$778

				Total =	**$1,849**
Lawn Mowing/Lawn Care	Unit	6	$269	1	$2,151
Sediment Removal (routine)	Unit	0.5	$60	16.13	$480
Sediment Removal (non-routine)	Unit	0.05	$43	322.67	$686
				Total =	**$2,782**

Notes:

* – for unit-type activities, the annual cost is per AF of EDB storage

2008$

$$MCost = \$1{,}849 + \$2{,}782 * BMPSize(AF) \tag{A-33}$$

A.4.6. Hydrodynamic Separator

Table A-11 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-34) is used to compute total annual maintenance costs.

Table A-11: HS maintenance activity costs

Activity	**Type**	**F**	**A**	**β-value**	**Annual Cost***
-	-	-	-	-	-
				Total =	**-**
Sediment Removal	Unit	4	$344	0.4	$550
Traffic Control	Unit	4	$124	0.4	$199
				Total =	**$749**

Notes:

* – for unit-type activities, the annual cost is per cfs of design flowrate

2008$

$$MCost = \$749 * BMPSize(cfs) \tag{A-34}$$

A.4.7. Inlet Inserts

Table A-12 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-35) is used to compute total annual maintenance costs.

Table A-12: II maintenance activity costs

Activity	Type	F	A	β-value	Annual Cost
Filter Replacement	Lump sum	4	$1,128	-	$4,514
				Total =	**$4,514**
-	-	-	-	-	-
				Total =	-

Notes:

2008$ $$MCost = \$4{,}514 \qquad \textbf{(A-35)}$$

A.4.8. Media Filter Vault

Table A-13 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-36) is used to compute total annual maintenance costs.

Table A-13: MFV maintenance activity costs

Activity	Type	F	A	β-value	Annual Cost*
-	-	-	-	-	-
				Total =	-
Remove Top Media Layer	Unit	1	$310	0.006	$1.86
				Total =	**$1.86**

Notes:

* – for unit-type activities, the annual cost is per CF of storage volume

2008$ $$MCost = \$1.86 * BMPSize(CF) \qquad \textbf{(A-36)}$$

A.4.9. Porous Concrete Pavement

Table A-14 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-37) is used to compute total annual maintenance costs.

Table A-14: PCP maintenance activity costs

Activity	Type	F	A	β-value	Annual Cost[*]
-	-	-	-	-	-
				Total =	-
Sweeping/Vacuuming	Unit	2	\$62	1	\$125
				Total =	**\$125**

Notes:

* – for unit-type activities, the annual cost is per acre of installation surface area.

2008\$ $$MCost = \$125 * BMPSize(acres) \quad \textbf{(A-37)}$$

A.4.10. Porous Gravel Pavement

Table A-15 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-38) is used to compute total annual maintenance costs.

Table A-15: PGP maintenance activity costs

Activity	Type	F	A	β-value	Annual Cost[*]
-	-	-	-	-	-
				Total =	-
Gravel Finish Grading	Unit	12	\$471	1	\$5,647
				Total =	**\$5,647**

Notes:

* – for unit-type activities, the annual cost is per acre of installation surface area.

2008\$ $$MCost = \$5,647 * BMPSize \quad \textbf{(A-38)}$$

A.4.11. Porous Landscape Detention

Table A-16 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-39) is used to compute total annual maintenance costs.

Table A-16: PLD maintenance activity costs

Activity	Type	F	A	β-value	Annual Cost[*]

-	-	-	-	-	-
				Total =	-
Annual Cleanup	Unit	1	$414	0.001	$0.41
Annual Planting	Unit	1	$207	0.001	$0.21
				Total =	**$0.62**

Notes:

* – for unit-type activities, the annual cost is per CF of storage volume

2008$ $$MCost = \$0.62 * BMPSize(CF)$$ **(A-39)**

A.4.12. Reinforced Grass Pavement

Table A-17 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-40) is used to compute total annual maintenance costs.

Table A-17: RGP maintenance activity costs

Activity	**Type**	**F**	**A**	**β-value**	**Annual Cost***
-	-	-	-	-	-
				Total =	-
Lawn Mowing/Lawn Care	Unit	15	$269	1	$4,040
				Total =	**$4,040**

Notes:

* – for unit-type activities, the annual cost is per acre of installation surface area

2008$ $$MCost = \$4{,}040 * BMPSize(acres)$$ **(A-40)**

A.4.13. Retention Pond

Table A-18 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-41) is used to compute total annual maintenance costs.

Table A-18: RP maintenance activity costs

Activity	**Type**	**F**	**A**	**β-value**	**Annual Cost**[*]
Nuisance Control	Lump sum	12	$127	-	$1,521
				Total =	**$1,521**
Lawn Mowing/Lawn Care	Unit	6	$269	1	$404
Sediment Removal (routine)	Unit	0.5	$60	16.13	$480
Sediment Removal (non-routine)	Unit	0.05	$43	322.67	$686
Vegetation/Woody Debris Removal	Unit	0.33	$1,696	0.05	$28
				Total =	**$1,598**

Notes:

* – for unit-type activities, the annual cost is per AF of storage volume

2008$ $$MCost = \$1{,}521 + \$1{,}598 * BMPSize(AF) \qquad \textbf{(A-41)}$$

A.4.14. Sand Filter Basin

Table A-19 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-42) is used to compute total annual maintenance costs.

Table A-19: SFB maintenance activity costs

Activity	**Type**	**F**	**A**	**β-value**	**Annual Cost**[*]
-	-	-	-	-	-
				Total =	**-**
Lawn Mowing/Lawn Care	Unit	6	$269	0.33	$533
Sediment Removal (routine)	Unit	0.5	$60	16.13	$480
Scarify Top Sand Layer	Unit	1	$253	0.33	$83
				Total =	**$1,096**

Notes:

* – for unit-type activities, the annual cost is per AF of storage volume

2008$ $$MCost = \$1{,}096 * BMPSize(AF) \qquad \textbf{(A-42)}$$

A.4.15. Sand Filter Vault

Table A-20 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-43) is used to compute total annual maintenance costs.

Table A-20: SFV maintenance activity costs

Activity	Type	F	A	β-value	Annual Cost*
-	-	-	-	-	-
				Total =	-
Remove Top Sand Layer	Unit	1	$310	0.006	$1.86
				Total =	**$1.86**

Notes:

* – for unit-type activities, the annual cost is per CF of storage volume

2008$ $$MCost = \$1.86 * BMPSize(CF) \quad \textbf{(A-43)}$$

A.4.16. Sediment/Oil/Grease Separator

Table A-21 summarizes the maintenance activities and their individual annual costs for EDBs. Equation (A-44) is used to compute total annual maintenance costs.

Table A-21: SOG maintenance activity costs

Activity	Type	F	A	β-value	Annual Cost*
-	-	-	-	-	-
				Total =	-
Sediment Removal	Unit	4	$344	0.44	$605
Traffic Control	Unit	4	$129	0.44	$227
				Total =	**$832**

Notes:

* – for unit-type activities, the annual cost is per cfs of design flowrate.

2008$ $$MCost = \$832 * BMPSize(cfs) \quad \textbf{(A-44)}$$

A.4.17. Vault with Capture Volume

Table A-22 summarizes the maintenance activities and their individual annual costs for VCVs. Equation (A-45) is used to compute total annual maintenance costs.

Table A-22: VCV maintenance activity costs

Activity	**Type**	**F**	**A**	**β-value**	**Annual Cost***
-	-	-	-	-	-
				Total =	-
Sediment Removal	Unit	0.2	$344	0.007	$0.48
Traffic Control	Unit	0.2	$129	0.007	$0.18
				Total =	**$0.66**

Notes:

* – for unit-type activities, the annual cost is per CF of storage volume

2008$

$$MCost = \$0.66 * BMPSize(CF) \quad \textbf{(A-45)}$$

Appendix B: Methods and assumptions used to determine land use and BMP effluent event mean concentration

This appendix documents how land use and BMP effluent event mean concentrations were identified for use in the model.

B.1. Land Use Event Mean Concentrations

UDFCD (UDFCD, 2004) has reported average land use EMC values for 13 constituents in urban stormwater from four different land uses in the Denver, Colorado metropolitan region (Table B-1) It is recognized that the data from which these value were estimated were highly variable from site to site and event to event, however over the long term they may be expected to be reasonably accurate and thus are used in the model.

Table B-1: Land Use Average EMCs for Denver Metropolitan Area

Constituent	Units	Industrial	Commercial	Residential	Undeveloped
Total Suspended Solids	mg/L	399	225	240	400
Total Nitrogen	mg/L	2.7	3.3	3.4	3.4
TKN	mg/L	1.8	2.3	2.7	2.9
Nitrate + Nitrite	mg/L	0.91	0.96	0.65	0.50
Total Phosphorus	mg/L	0.43	0.42	0.65	0.40
Dissolved Phosphorus	mg/L	0.20	0.15	0.22	0.10
Copper, Total	µg/L	84	43	29	40
Lead, Total	µg/L	130	59	53	100
Zinc, Total	µg/L	520	240	180	100

Source: Table SQ-5 (UDFCD, 2004)

UDFCD did not provide values for dissolved zinc, dissolved lead and dissolved copper for each land use, therefore ratios of the total recoverable/dissolved fractions of each metal were estimated based on analyses performed by Maestre and Pitt (2005) on data contained in the National Stormwater Quality Database (NSQD), Version 1.1. The results of their analysis are summarized in **Error! Reference source not found.**.

Table B-2: Computed total:dissolved metals fractions based on values reported in the National Stormwater Quality Database, Version 1.1

Constituent	Industrial	Commercial	Residential
Lead	4.98:1	3.6:1	4:1
Copper	2.6:1	2.25:1	1.71:1
Zinc	1.78:1	2.54:1	2.32:1

There were no dissolved values reported for undeveloped or open space in the NSQD, therefore the total:dissolved fractions computed for residential land use was applied for undeveloped land use also.

B.2. BMP Effluent Event Mean Concentrations

The primary source of data for these values was the Analysis of Treatment Performance Report (report) (Geosyntec Consultants & Wright Water Engineers 2008), which reports expected BMP effluent EMCs based on statistical analyses of the data in the International BMP Database (database) (Geosyntec Consultants & Wright Water Engineers 2009). The data were analyzed using two methods, one method weighs the average results from each individual BMP equally and reports "Median of Average Effluent EMC" values and another method weighs each individual event equally (potentially putting more weight on the results from one specific BMP which was thoroughly monitored) and reports "Median of Effluent EMC" values. The first method that provides "Median of Average Effluent EMC" values is a better indicator of how well a particular type of BMP may be expected to perform across a variety of sites, and those values (with a few exceptions discussed below) are used in the model. However, effluent EMC values were not reported for all of the BMPs included in the model, therefore some additional analyses and assumptions were necessary.

When additional analyses were required, first the BMP codes and descriptions included in the database were used to sort which specific BMPs fell under each BMP category. Second the names of each specific BMP were cross-referenced within the "Statistical Summary_wo_WSDOT.xls" spreadsheet (developed by the database team and available at

<http://www.bmpdatabase.org/ResearchToolsMasterDB.htm#StatSummary> and the "raw outflow mean [EMC]" value for each constituent was found. Last, the median of all reported average EMC values for each BMP was computed, thus giving the "Median of Average Effluent EMC" value that is used in the model.

The following paragraphs explain what values are used for each BMP and the justification for doing so.

B.2.1. Vault w/ Capture Volume

The report does not provide results specifically for this BMP, however data collected from these BMPs were included in the analyses for the "Detention Basin" category, therefore the model uses the EMC values reported for that category.

B.2.2. Constructed Wetland Basin

EMC values reported for "Wetland Basins" are used in the model, with the following exceptions:

- Dissolved Zinc – the data set was insufficient to compute a "Median of Average Effluent EMC" value for this constituent, therefore the value reported using the "Median of Effluent EMC" method (17.90 µg/L) is used.

- Dissolved Copper – the data set was insufficient to compute a "Median of Average Effluent EMC" value for this constituent, therefore the value reported using the "Median of Effluent EMC" method (7.36 µg/L) is used.

B.2.3. Constructed Wetland Channel

EMC values reported for "Wetland Channels" are used in the model, with the following exceptions:

- Total Zinc – the data set was insufficient to compute a "Median of Average Effluent EMC" value for this constituent, therefore the value reported for Constructed Wetland Basins (30.71 µg/L) is used.
- Dissolved Zinc – the data set was insufficient to compute a "Median of Average Effluent EMC" value for this constituent, therefore the value reported using the "Median of Effluent EMC" method (17.90 µg/L) for is used.
- Dissolved Lead – the data set was insufficient to compute a "Median of Average Effluent EMC" value for this constituent, therefore the value reported for Constructed Wetland Basins (0.87 µg/L) is used.
- Total Copper – There is no reported values for this constituent, therefore the value reported for Constructed Wetland Basins (4.23 µg/L) is used.

- Dissolved Copper – There is no reported value for this constituent and the data set for Constructed Wetland Basins was insufficient to compute a "Median of Average Effluent EMC" value for this constituent, therefore the value reported using the "Median of Effluent EMC" method (7.36 μg/L) for Constructed Wetland Basins is used.

B.2.4. Extended Detention Basin

Extended detention basins were included within the category "Detention Basins", therefore the EMC values reported for that category are used in the model.

B.2.5. Sand Filter Vault

Data collected from sand filter vaults were analyzed under the category "Media Filter", along with several other filtering-type BMPs. In an attempt to differentiate between the different types of BMPs, EMC values were computed for the following BMPs which were categorized as "Sand Filters" in the database: 5/78, Eastern SF, La Costa PR, Lakewood Sand Filter, Parkrose SF, Sand Filter and Termination. Table B-3 summarizes the data retrieved and computed average effluent value.

B.2.6. Media Filter Vault

Data collected from media filter vaults were analyzed under the category "Media Filter", along with several other filtering-type BMPs. In an attempt to differentiate between the different filtering BMPs, EMC values were computed for the following BMPs which were categorized either "Combination of Media or Layered Media Filter", "Compost Mixed with Sand", "Peat Mixed with Sand" or "Other Media Filter" in the database:

Table B-3: Summary of sand filter data obtained from the International BMP Database

Parameter	# of BMPs	# of Samples	Median of Average Outflow EMC	Units
Total Suspended Solids	7	83	10.25	mg/L
Total Phosphorus	6	66	0.13	mg/L
Total Nitrogen	5	63	0.80	mg/L
Total Kjeldahl Nitrogen	6	66	1.44	mg/L
Total Zinc	7	90	34.56	µg/L
Dissolved Zinc	5	62	25.85	µg/L
Total Lead	5	63	1.37	µg/L
Dissolved Lead	5	63	1.03	µg/L
Total Copper	6	66	9.56	µg/L
Dissolved Copper	6	66	8.25	µg/L

BMP 57, Tree Filter, Bioretention System (D1), Lakewood, MCTT Filtering Chamber, Via Verde, Compost 1 and Hal Marshall Bioretention Cell. Table B-4 summarizes the data retrieved and computed average effluent value.

Table B-4: Summary of media filter data obtained from the International BMP Database

Parameter	# of BMPs	# of Samples	Median of Average Outflow EMC	Units
Total Suspended Solids	6	60	9.19	mg/L
Total Phosphorus	5	47	0.16	mg/L
Total Nitrogen	3	33	0.98	mg/L
Total Kjeldahl Nitrogen	3	33	1.26	mg/L
Total Zinc	7	74	34.69	µg/L
Dissolved Zinc	3	30	16.84	µg/L
Total Lead	5	53	2.05	µg/L
Dissolved Lead	3	30	1.16	µg/L
Total Copper	5	53	7.38	µg/L
Dissolved Copper	3	30	7.14	µg/L

B.2.7. (U) Hydrodynamic Separator

Although values are reported for "hydrodynamic devices" in the Analysis of Treatment Performance Report (Geosyntec Consultants & Wright Water Engineers 2008), the analysis included some devices (i.e. treatment trains, up-flow devices, etc.) that do not adequately represent the devices that are being simulated in the model. Data from the following BMPs were used to compute the values summarized in Table B-5: Addison-Wesley Interceptor, Aqua Swirl, Continuous Deflectie Separation, Continuous Deflective Separation Unit, Filmore CDS, Vortechnics, Vortechnics Model 11000 and Vortechs No 5000.

Table B-5: Summary of hydrodynamic separator data obtained from the International BMP Database

Parameter	# of BMPs	# of Samples	Median of Average Outflow EMC	Units
Total Suspended Solids	8	116	47.28	mg/L
Total Phosphorus*	5	133	0.20	mg/L
Total Nitrogen	1	9	2.54	mg/L
Total Kjeldahl Nitrogen	2	47	1.99	mg/L
Total Zinc	6	68	60.81	µg/L
Dissolved Zinc	3	33	47.33	µg/L
Total Lead	2	23	6.30	µg/L
Dissolved Lead	2	23	3.14	µg/L
Total Copper	2	23	15.87	µg/L
Dissolved Copper	2	23	25.21	µg/L

(*) one BMP was not included due to an unusually high value - possibly input error

B.2.8. (U) Sediment/Oil/Grease Separator

The Analysis of Treatment Performance Report (Geosyntec Consultants & Wright Water Engineers 2008) did not report EMC values specifically for SOGs, however the database did contain information on these devices. Data from the following devices were used to compute the EMC values summarized in Table B-6: Alameda, ARC Oil Separator, Baffle Box, Baysaver 1, Boeing Oil/Water Separator, Environment 21 V2B1, Stormceptor STC 3600, Urban Storm Treatment Unit in Madison, WI (Stormceptor), Warr Oil and Grit Separator and Willis Drive Baffle Box.

Table B-6: Summary of sediment/oil/grease separator data obtained from the International BMP Database

Parameter	# of BMPs	# of Samples	Median of Average Outflow EMCs	Units
Total Suspended Solids	10	106	43.86	mg/L
Total Phosphorus	6	34	0.62	mg/L
Total Nitrogen	2	7	1.99	mg/L
Total Kjeldahl Nitrogen	2	12	3.05	mg/L
Total Zinc	5	43	97.08	µg/L
Dissolved Zinc	2	17	191.23	µg/L
Total Lead	3	26	15.86	µg/L
Dissolved Lead	2	17	3.66	µg/L
Total Copper	5	33	11.25	µg/L
Dissolved Copper	2	17	11.60	µg/L

B.2.9. Inlet Inserts

Although values are reported for "media filters" in the Analysis of Treatment Performance Report (Geosyntec Consultants & Wright Water Engineers 2008), the analysis included some devices that are not inlet inserts (i.e. sand filters, media filter vaults, etc.). In order to differentiate between types of media filters, EMC values reported for BMPs under the categories "Geotextile Fabric Membrane (Vertical) Filter" were sorted and analyzed separate from all other media filter BMPs. The names of those BMPs in the database are: Rosemead SG, Las Flores SG, Foothill SG, Rosemead FF, Las Flores FF and Footfill FF. The "SG" and "FF" in the names are presumed to stand for "stream guard" and "fossil filter", two types of propriety inlet insert devices. Table B-7 summarizes the data retrieved and computed average effluent value.

Table B-7: Summary of inlet insert data obtained from the International BMP Database

Parameter	# of BMPs	# of Samples	Median of Average Outflow EMCs	Units
Total Suspended Solids	6	88	67.79	mg/L
Total Phosphorus	6	77	0.13	mg/L
Total Nitrogen	6	78	1.10	mg/L
Total Kjeldahl Nitrogen	6	78	2.15	mg/L
Total Zinc	6	88	124.40	µg/L
Dissolved Zinc	6	89	87.01	µg/L
Total Lead	6	88	7.80	µg/L
Dissolved Lead	6	88	1.85	µg/L
Total Copper	6	88	15.49	µg/L
Dissolved Copper	6	89	10.34	µg/L

B.2.10. Porous Landscape Detention

Porous landscape detention (i.e. raingardens, bioretention, etc.) are categorized under "Media Filters" and have a similar treatment mechanism as other media filters that have a mixture of sand and some organic media. PLDs were lumped with other types of similar media filters to determine EMC values for "media filter vaults", therefore the same EMC values are applied to PLDs in the model.

B.2.11. Retention Pond

The EMC values documented in the report for the category "Retention Ponds" are used in the model.

B.2.12. Sand Filter Basin

The EMC values computed for “sand filter vaults” also are applied to sand filter basins in the model.