BMP-REALCOST

Best Management Practices – Rational Estimation of Actual Likely Costs of Stormwater Treatment

A SPREADSHEET TOOL FOR EVALUATING BMP EFFECTIVENESS AND LIFE CYCLE COSTS

User's Manual and Documentation

Version 2.0

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History and Revisions

BMP Whole Life Cycle Cost Effectiveness Analysis Tool - Version 1.0 (released August 2009) - Prepared by Chris Olson (Colorado State University) with Ben Urbonas (Urban Watersheds Research Institute), Dr. Larry Roesner (Colorado State University) and Ken MacKenzie (Urban Drainage Flood Control District).

BMP-REALCOST – Version 1.2 (April 2010)

This model supersedes the previously-unnamed version 1.0 released in August 2009.

- Permeable pavements now applied as site control BMPs instead of source controls.

- Changed land cost computations to be a function of the BMP size using the land consumption coefficient (C_{LC}) which relates the area of land consumed to the size of the BMP.

- BMP capture efficiency can now be edited by user on "RunoffMitigation" worksheet.

- Rehabilitation/replacement costs are now amortized based on the number of years of benefits that follow each occurrence. Generally this results in lower net present costs than computed in previous versions.

- Some land costs were revised to better reflect Denver-area costs.

- Column for maintenance activity "beta" values were added to maintenance cost tables.

- Cost charts were revised to show annual costs and cumulative costs.

- New chart was added to display scenario runoff reduction effectiveness.

BMP-REALCOST – Version 1.21 (July 2013)

- Default values were edited on the following tabs: Concrete Grid Pavers (CGP), Constructed Wetland Basin (CWB), Constructed Wetland Channel (CWC), Extended Detention Basin – WQCV (EDB(WQCV)), Extended Detention Basin – EURV (EDB(EURV)), Hydrodynamic Separators (HS), Inlet Inserts (II), Media Filter Vault (MFV), Porous Concrete Pavement (PCP), Porous Gravel Pavement (PGP), Permeable Interlocking Concrete Pavers (PICP), Porous Landscape Detention (PLD), Reinforced Grass Pavement (RGP), Retention (Wet) Ponds – WQCV (RP(WQCV)), Retention (Wet) Ponds – EURV (RP(EURV)), Sand Filter Basin (SFB), Sand Filter Vault (SFV), Sediment/Oil/Grease Separator – Underground (SOG), and Vault with Capture Volume – Underground (VCV).

- Vegetation Replacement was added to CMB

- Lawn Mowing/Care was added to CWC

- Traffic Control was added to HS, II, MFV, SFV, SOG, and VCV

- Closed Entry Testing/Controls was added to MFV, SFV, SOG, and VCV

- Vacuum/Remove Gravel was added to PICP

- Replace Gravel was added to PICP

- Remove Sand was added to SFB

- Replace Sand was added to SFB and SFV

- Scarify Surface was added to SFB and SFV

BMP-REALCOST – Version 2.0 (November 2017)

- The 2-year, 1-hour rainfall depths for locations near Denver, Colorado region were updated to be consistent with NOAA Atlas 2, Volume 14 (NOAA 2013).

- Land use and BMP performance EMC values updated to be consistent with the Urban Storm Drainage Criteria Manual (USDCM) Volume 3, based on 2016 International Stormwater BMP Database and Colorado Stormwater Regulation 85 Nutrient Summary (2013).

- Calculated long-term volumetric runoff coefficients using WQCOSM to replace the 2-year runoff coefficients used in previous versions of BMP-REALCOST. These coefficients were only slightly different than the previous 2-year runoff coefficients.

- Water quality analyte options remove total and dissolved lead and were replaced with *E. coli* and "Other" to allow user to enter another analyte of interest.

- Median EMCs for runoff characterization and BMP performance are being used. Previously mean runoff EMCs were being used to characterize runoff and median EMCs were being used to characterize BMP performance, which overestimated performance for some practices.

- Maintenance costs were updated for several BMPs based on experience gained by UDFCD and the Colorado Stormwater Center.

- Volume reduction estimates were modified for EDBs and bioretention based on SWMM analysis.

- Equations in User's Guide were updated to match spreadsheet package (addressing updates made in 2013 and 2017).

- Porous landscape detection (PLD) was renamed to bioretention (BIO), consistent with UDFCD Volume 3.

- Permeable pavement options included are limited to PAP, PICP and PCP. Porous asphalt construction costs were updated.

- CVCs and SOGs were removed from the tool.

- Land cost value estimates were updated based on land values in the 2016 Denver Tax Assessor's database.

- Minor editorial revisions to User's Guide.

1. <u>INTRODUCTION</u>

This section includes important information related to the purpose, development and appropriate use of the model.

1.1.   BMP-REALCOST Overview

BMP-REALCOST was developed to assist engineers, planners, developers, consultants and decision makers in evaluating the life cycle costs and effectiveness of structural stormwater runoff best management practices (BMPs) as they are applied within an urban/suburban setting. The intent of this model is to provide the practicing professional and decision maker with planning-level information on the expected costs and benefits of BMPs. BMPs selected for implementation within a municipality and its new developments/redevelopments will have many long-term ramifications that include (1) the effectiveness in the protection of the receiving waters, (2) long-term cost of operating and maintaining the BMPs, and (3) the administrative costs that the municipality will need to budget for over the years to make sure that the BMPs deployed within its boundaries continue to function as originally designed.

This model is built into Microsoft Excel format and many of the operations are performed using macros written in Visual Basic for Applications. The model operates by first having the user input information describing the physical characteristics of a watershed that affect runoff quality and quantity (e.g., contributing area, land use, imperviousness, etc.). Second, the user enters information that describes what type(s) of BMP(s) will be applied to the watershed/development and the area (number of impervious acres) from which each BMP will receive runoff. Next the user decides whether to use default cost and BMP effectiveness values, or input their own. The model then takes the user-entered (or default) information and estimates the size of each BMP, determines the number of BMP(s) needed to treat the watershed, produces estimates of average annual runoff quality and quantity for the entire watershed/development, and calculates life cycle costs for the BMP(s) selected.

1.2.   Appropriate Use

The model was developed as a planning-level tool, 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 within this report. <u>The results should not be used as a substitute or a comparative resource for final BMP designs, more intensive rainfall/runoff modeling techniques or "engineer's estimates."</u>

The model was developed using many of the recommendations and methods provided in the Urban Drainage Flood Control District's (UDFCD) Urban Storm Drainage Criteria Manual (USDCM) (UDFCD 2016); therefore, this model should only be applied to areas where the USDCM design criteria are valid.

1.3.   Assumptions

The following are fundamental assumptions used in developing the model.

1. The user has adequate knowledge of stormwater management to apply BMPs appropriately, considering the land use and relative size of BMP. For example, specifying a BMP to treat an area much larger or smaller than is typically specified could cause both the costs and effectiveness to be highly inaccurate.

2. BMPs with water quality capture volume (WQCV) are assumed to effectively treat 85% of the annual runoff. BMPs designed to capture the excess urban runoff volume (EURV) effectively treat 98% of the annual runoff.

3. Unless otherwise noted (with EURV naming convention), BMPs with storage volume are sized to store the WQCV only. They do not include additional storage for larger storms.

4. Computations for peak runoff rates using the Rational Method are made using several simplifying assumptions for waterway length and conveyance length. See Section 5.4.2.

5. Values for effluent event mean concentrations were not available for all of the BMPs included in the model; therefore, some values were substituted and/or assumed until better information is available.

6. Values for land use event mean concentrations were not available for all of the constituents included in the model; therefore, some values were substituted and/or assumed until better information is available.

7. The model assumes that adequate maintenance will be performed to keep BMP effectiveness relatively consistent from year to year; therefore, BMP effectiveness does not change over time in the model.

8. The default maintenance costs were developed assuming proactive maintenance (i.e. keeping facilities properly maintained), as opposed to reactive maintenance (i.e. only performing maintenance once something breaks and/or the BMP effectiveness is compromised). Through a series of interviews with agencies responsible for BMP maintenance, overall it was generally agreed upon that proactive maintenance is less costly than reactive maintenance.

9. The default costs for proprietary systems are assumed to be an average cost considering the wide variety of systems available.

10. The computed costs for permeable pavement do not account for potential cost savings from the reduced need for additional stormwater infrastructure, nor do they account for the "foregone" costs of installing and/or maintaining typical impervious pavement. Without accounting for these cost savings, permeable pavement will always appear to be a more expensive option.

2. <u>MODEL STRUCTURE</u>

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 1.

Table 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, event mean concentrations, 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 2.

Table 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.

3. G<small>ETTING</small> S<small>TARTED</small>

This section describes the step-by-step process for setting up and evaluating the results of the model. Being a "getting started" guide, these are the minimum steps necessary to operate the model using default values for costs and BMP effectiveness parameters. More advanced options exist for overriding the default values that are used by the model and the steps for doing so are described in Section 4.

NOTE: Before getting started, ensure that macros are enabled in Microsoft Excel. Upon opening the workbook, an informational pop-up box (shown below) should appear, indicating that macros have been enabled.
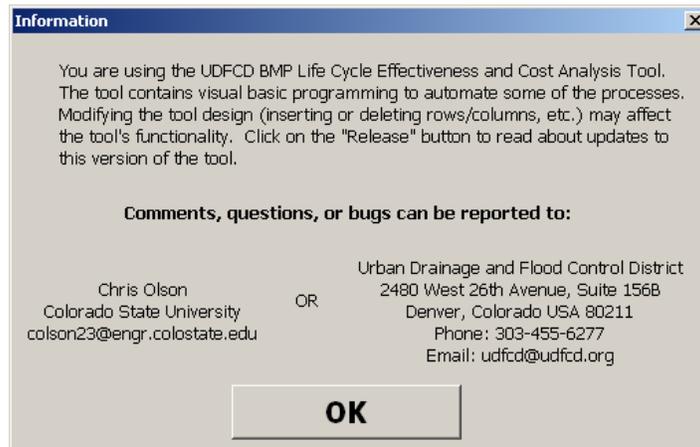
3.1.   Entering Required Inputs

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

Recall from Section 2 that cells or columns color-coded in blue require the user to input a value or use the default value (if provided). Green cells or columns cannot be modified by the user.

3.1.1.   Project-Specific Cost and Precipitation Parameters

The model requires several parameters for project-specific precipitation and life cycle cost calculations. Some default values have been entered that generally should be 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. Each required parameter is described below.

Project-Specific Precipitation and Cost Parameters			
Planning Horizon (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)	?	0.83	
Mean Storm Depth (in)	?	0.43	Default

Restore Default Values

Planning Horizon

The planning horizon of the project(s) defines the time over which the net present value of the project costs will be estimated. The default value is 50 years and is the value recommended by UDFCD and other water resource organizations, recognizing the longevity of such projects and the difficulty in financing their construction.

Current ENR Construction Cost Index

The user should input the current Engineering News Record (ENR) Construction Cost Index (CCI) for the region of analysis, to adjust the default costs used in the model for time and location. Default costs were programmed into the model in May 2008 dollars, based on the 20-City averaged ENR CCI (ENR CCI: 8141).

Inflation Rate

The inflation rate describes how costs will increase in the future. The default value is 4.6%, which is the historical annual increase of the ENR CCI from 1958 to May, 2008 (ENR 2008). UDFCD recommends using a 50-year planning horizon analysis for large projects; however, the user may choose to use a different inflation rate value (based on more recent trends) if the planning horizon of the project is not 50 years.

Rate of Return (Discount Rate)

The rate of return, or discount rate, is used to convert future costs and benefits into a common year to compare present value. The default value used is 5%; however, the rate may vary from agency to agency and a reasonable estimate is probably available from the municipality's financial manager. Because this model allows entry of the inflation rate separately, the discount rate is considered to be a "nominal" discount rate.

Administrative Costs

The additional costs for the administration of a BMP maintenance program are accounted for by entering a value (percentage) that defines the administration costs as a percentage of the annual maintenance costs.   The default rate is 12%; however, this rate may vary from agency to agency and a reasonable estimate may be available from the department's manager.

Precipitation

The user selects a location (from the drop-down box) that is closest to the location of the project. This selection then specifies the precipitation data to be used by the model. The user also has the option of selecting "Other" as the location of the project and entering precipitation values specific to the project location. Two separate precipitation values are used by the model. The first is the average annual precipitation depth, which is used in calculating annual runoff volume and pollutant loadings generated from the watershed. The second is the 2-Year, 1-Hour rainfall depth which is used for calculating the appropriate size of BMPs that are designed to treat a specified flowrate. The precipitation values for each available location are presented in Table 3.

Table 3: Precipitation data for selected locations in Front Range of Colorado

Precipitation Locations	Mean Annual Precip (in)	2-Year, 1-Hour Precip (in)
Arvada	15.8	0.78
Aurora	15.8	0.86
Boulder	15.8	0.77
Denver	15.8	0.83
Lakewood	15.8	0.79
Longmont	15.8	0.79
Parker	15.8	0.82
Westminster	15.8	0.81

Source: NOAA Atlas 2, Volume 14 (NOAA 2013, accessible at http://hdsc.nws.noaa.gov/hdsc/pfds/) provides the 2-year, 1-hour rainfall depths for locations near Denver, Colorado region. National Weather Service (2008) provides mean annual precipitation.

Mean Storm Depth

The user inputs the mean storm depth for the location of the project. (The default value of 0.43 inches is applicable for the Front Range of Colorado). This value is used to compute the size of volume-based BMPs. A map of mean storm depths across the contiguous United States can be accessed by clicking on the "?" button.

3.1.2.   Watershed Parameters

This section describes how runoff-generating characteristics of a watershed of interest should be input into the model.

Delineating Subcatchments

First, the user must identify the total number of subcatchments located within the area 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, then 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 no, 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.

Watershed Parameters									
Subcatchment No.	Subcatchment ID	Area (ac)	Land Use	Total Imperviousness (%)	Source Control (LID)	Effective Imperviousness (%)	NRCS Soil Type	Subarea Slope (%)	Effective Runoff Coefficient

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. The available land use types are presented in Table 4.

Table 4: Land use types available within the model

Land Use Type
Commercial
Industrial – Light
Industrial – Heavy
Residential – Single Family (1,000 sf)
Residential – Single Family (2,000 sf)
Residential – Single Family (3,000 sf)
Residential – Single Family (4,000 sf)
Residential – Single Family (5,000 sf)
Residential – Multi-Unit (detached)
Residential – Large Lot (>1/2 acre)
Residential – Apartments
Parks, Cemeteries
Institutional (universities, office parks)
Paved Areas
Undeveloped

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 (shown in Table 5 below). 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. (For more information on applying/selecting source controls, see Section 5.2.2).

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 5.2.3).

Table 5: Default values of total imperviousness for each land use type

Land Use Type	Percent Imperviousness
Commercial	95
Industrial – Light	80
Industrial – Heavy	90
Residential – Single Family (1,000 sf)	28*
Residential – Single Family (2,000 sf)	39*
Residential – Single Family (3,000 sf)	51*
Residential – Single Family (4,000 sf)	62*
Residential – Single Family (5,000 sf)	72*
Residential – Multi-Unit (detached)	60
Residential – Large Lot (>1/2 acre)	27*
Residential – Apartments	80
Parks, Cemeteries	5
Institutional	50
Paved Area	100
Undeveloped	2
Source: Urban Storm Drainage Criteria Manual, Vol.1 – Table RO-3. (UDFCD 2006) * - Average values taken from Figures RO 3-5 in UDFCD Design Manual, Vol. 1 Note: USDCM, Vol. 1 (UDFCD 2016) revised these land use types; however, the previous land use types were retained for BMP-REALCOST.	

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 the subcatchment for best 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. (For more information on how effective runoff coefficients are computed, see Section 5.3).

3.2.   BMP Parameters

This 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. The BMP types available for each type of control are presented in Table 6.

Table 6: Available BMP types for site control and regional control

Site Control BMPs	Regional Control BMPs
Bioretention – Infiltration[4]	Constructed Wetland Basin
Bioretention – Underdrain[5]	Constructed Wetland Channel
Constructed Wetland Basin	Extended Detention Basin- WQCV[2]
Constructed Wetland Channel	Extended Detention Basin - EURV[3]
Extended Detention Basin - WQCV[2]	Retention Pond - WQCV[2]
Extended Detention Basin - EURV[3]	Retention Pond - EURV[3]
(U) Inlet Inserts	Sand Filter Basin – Infiltration[4]
None	Sand Filter Basin - Underdrain[5]
Permeable Pavements[1]	
Retention Pond – WQCV[2]	
Retention Pond – EURV[3]	
Sand Filter Basin – Infiltration[4]	
Sand Filter Basin - Underdrain[5]	
(U) Media Filter Vault	
Sand Filter Vault	
(U) Hydrodynamic Separator	
Notes: (1) – Permeable pavement (Permeable Interlocking Concreter Pavers, Pervious Asphalt Pavement, Porous Concrete Pavement), designed for infiltration or underdrained (2) – BMPs designed to capture water quality capture volume only (3) – BMPs designed to capture the excess urban runoff volume (4) – BMPs designed to infiltrate full water quality capture volume (5) – BMPs designed with underdrains (U) – Underground BMP	

Regional-Control BMPs

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

1. Select the regional-control BMP button

⊙ **Select Regional-Control BMP**

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. For all BMPs that are NOT permeable pavements, enter the number of impervious acres that will runoff to each individual BMP located within the subcatchment into Column P. The value entered should be within the ranges presented in Table 7 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. For these types of BMPs, no value is needed in Column Q.

4. For permeable pavement BMPs, enter the number of impervious acres that will "run-on" to the permeable pavement (RAPP), not including the permeable pavement into Column P. Then, enter the surface area of the permeable pavement (SAPP) into Column Q. The ratio of RAPP:SAPP should be less than or equal to 5 to ensure that PPs do not clog too fast. In other words, no more than 5 impervious acres may "run-on" to 1 acre of permeable pavement.

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

3.3.   Water Quality Parameters

Default water quality event mean concentration (EMC) data for urban runoff and BMP effluent concentrations are provided for nine water quality analytes. Version 2.0 of BMP-REALCOST allows the user to enter water quality data for one "Other" additional analyte of interest.

Table 7: Range of impervious acres applicable for each BMP

BMPs	Impervious Acres to each BMP	
	Minimum	Maximum
Bioretention – Infiltration[3]	0.1	5
Bioretention – Underdrain[4]	0.1	5
Constructed Wetland Basin	2	-
Constructed Wetland Channel	2	-
Extended Detention Basin - WQCV[1]	2	-
Extended Detention Basin - EURV[2]	2	-
(U) Inlet Inserts	0.1	0.25
Retention Pond – WQCV[1]	2	-
Retention Pond – EURV[2]	2	-
Sand Filter Basin – Infiltration[3]	0.1	5
Sand Filter Basin - Underdrain[4]	0.1	5
Media Filter Vault	0.1	2
Sand Filter Vault	0.1	2
(U) Hydrodynamic Separator	0.1	2
Permeable Pavements	See Note 1.	
Notes: (1) - Permeable pavements can have unlimited size as long as the impervious run-on area is equal to or less than 5x the PP surface area		

3.4.   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.

Update Summary Report

3.4.1.   "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 8.

Table 8: Summary of water quality results table

Summary of Water Quality Results				
Constituent	**Watershed Pollutant Load** (lb/yr)	**Discharged Pollutant Load** (lb/yr)	**Pollutant Reduction** (%)	**Cost per Unit Removed** ($/lb)
TSS	288421	57724	80%	$30
TP	650	192	70%	$14,450
TN	9897	2198	78%	$860
TKN	7449	1820	76%	$1,170
T. Zinc	217	44	80%	$38,070
D. Zinc	46	12	74%	$192,490
T. Copper	44	10	76%	$195,020
D. Copper	17	4	76%	$506,670
Other	0	0	0%	NA
E. coli	2.62E+13	6.10E+12	77%	$328,700 *

*Note: E. coli reported in $/$10^{12}$ cfu removed.

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 water if no source controls or BMPs 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 load 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 1) graphically presents the values in the summary table.

Figure 1: Summary of pollutant load reporting chart

Summary of Runoff Table

The Runoff summary table is presented as Table 9.

Table 9: Summary of runoff results table

Summary of Average Annual Runoff Results

Subcatch ment No.	Watershed Runoff (ft³/yr)	Discharge to Receiving Water (ft³/yr)	Runoff Reduction (%)	Peak Flow Control
1	2,068,777	1,506,131	27%	Yes
2	620,633	446,515	28%	Yes
3	3,073,661	2,243,772	27%	Yes
4	3,996,626	2,917,537	27%	Yes
5	2,115,370	2,009,601	5%	Yes
Totals	**1,273,079**	**667,761**	**48%**	**590,228**

The values displayed under the heading **"Watershed Runoff"** are the total annual runoff volumes (in cubic feet) 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, then 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, then only one row of values will appear representing the total discharge volume from the regional BMP.

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 Control"** inform the user which subcatchments utilize BMPs that can be designed to control peak flows discharged to receiving waters.

The **"Summary of Annual Runoff Volume Reduction"** chart (Figure 2) graphically presents the total runoff generated from the subcatchments, the runoff reduced due to source controls and BMPs and the total runoff discharged to the receiving waters.
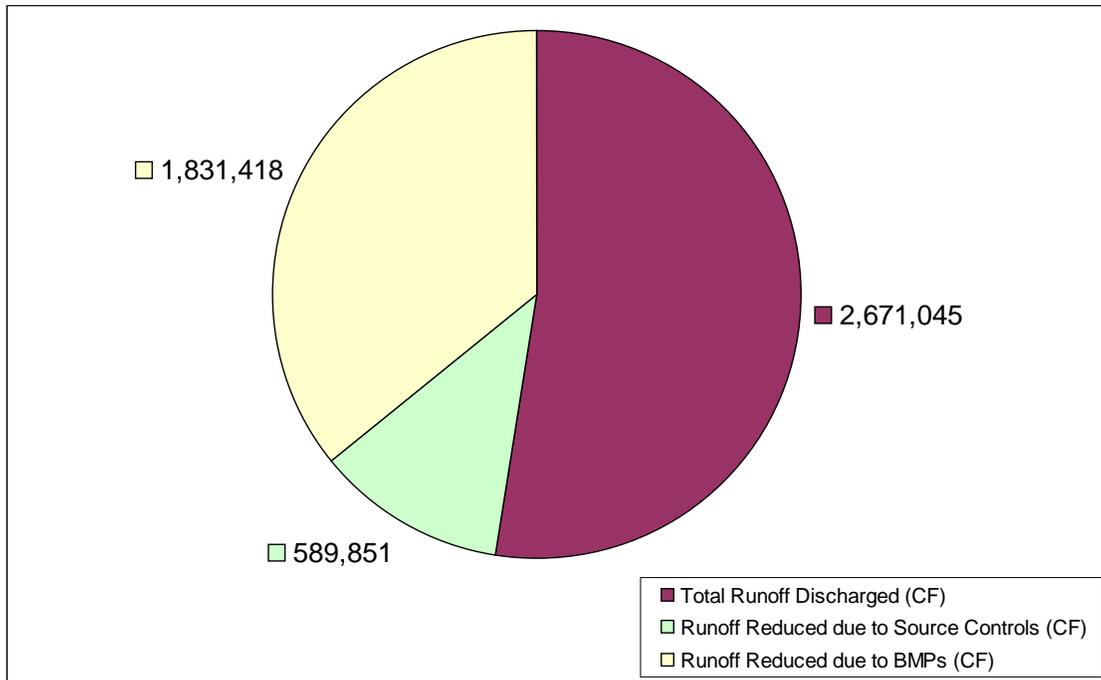
Figure 2: Summary of annual runoff volume reduction chart

Summary of Costs

The Cost summary table with example data is presented as Table 10.

Table 10: Summary of net present value cost table

Summary of Net Present Value of Costs

NPVC of Capital Costs	NPVC of Rehabilitation Costs	NPVC of Maintenance Costs	NPVC 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
$987,290	**$975,018**	**$1,061,633**	**$135,372**

Total NPVC	$3,159,313
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 modeled, then 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 NPVC" value.

The **"Annual Cost Summary"** charts (Figure 3 and Figure 4) graphically displays the annual and cumulative costs for capital, rehabilitation, maintenance, and administration of all BMPs for the defined planning horizon.
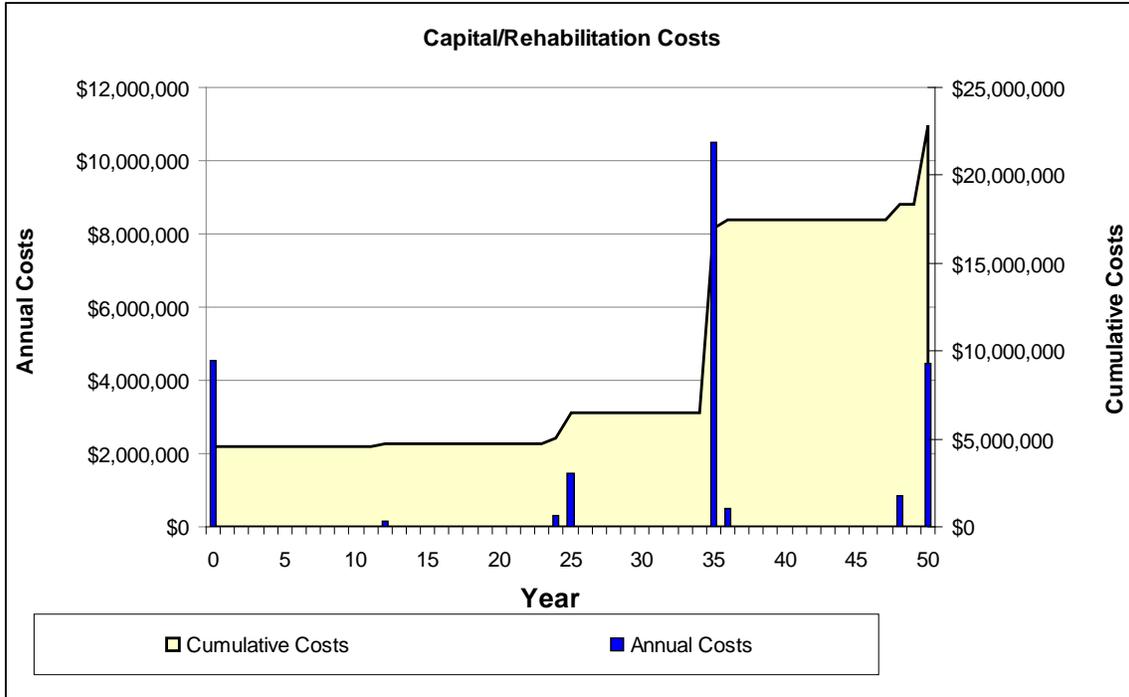
Figure 3: Annual capital and rehabilitation cost summary chart
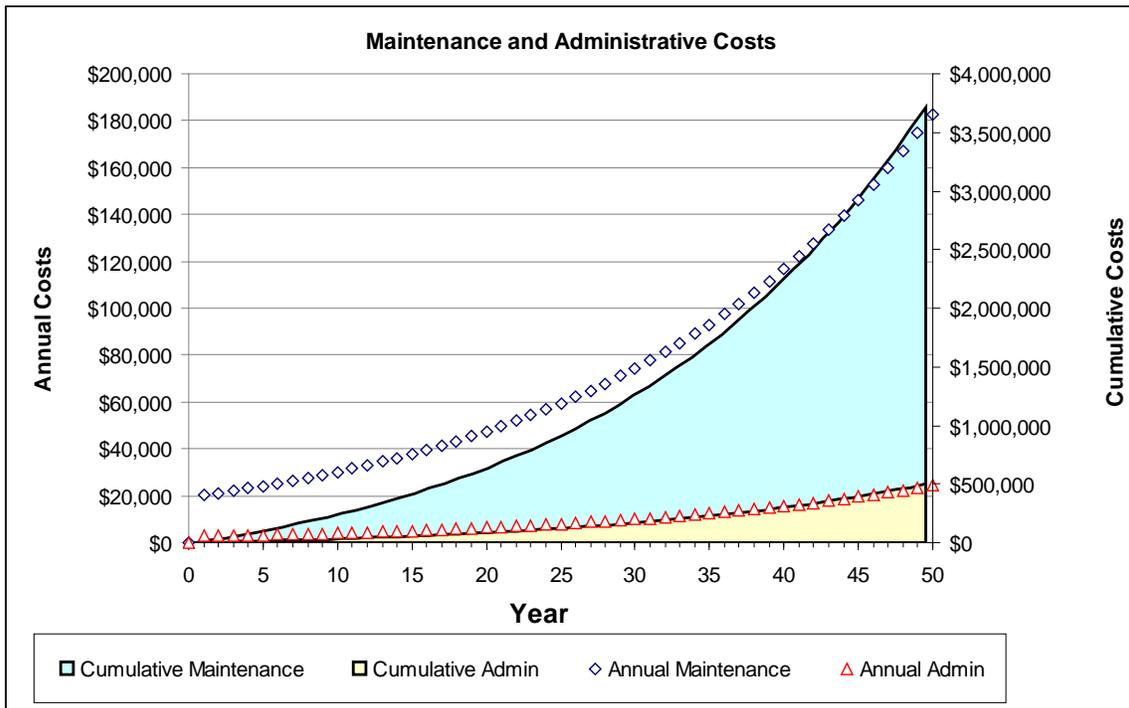
Figure 4: Annual maintenance and administrative cost summary chart

3.4.2. *"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 5.15.

3.4.3. *"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.

3.4.4. *"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.

3.4.5. *"WatershedLoading" Worksheet*

The "WatershedLoading" worksheet summarizes the annual pollutant loads 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.

3.4.6. *"DischargeLoading" Worksheet*

The "DischargeLoading" worksheet summarizes the annual pollutant loads 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.

3.4.7. *"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. **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 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.*

4.1.   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 three values associated with it. The first value under the "Runoff Capture Efficiency" heading is the percentage of annual runoff that is captured and fully treated by the BMP. The second value under the "BMP Runoff Volume Reduction" heading is 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 evapotranspiration processes. The third value indicates whether or not the BMP is capable of reducing peak runoff flows through losses and/or storage. The default values for each parameter are presented in Table 11. Sources and methods used to develop default parameter values are documented in Section 5.16.1.

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."

4.2.1.   *BMP Effluent Event Mean Concentrations*

Values in this table are the concentrations of pollutants expected in the effluent (discharge) of each BMP. The primary source of data for these values was the International Stormwater BMP Database (November 2016 release).[1] Summary statistics for most analytes were obtained from an accompanying summary statistics report (WWE and Geosyntec 2017); however, custom statistical analysis for various manufactured devices was also completed to supplement the published report. See Appendix A for additional information on the basis of the EMC data used in model. 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 report cited above. Any updated versions of the analyses report should be available at *www.bmpdatabase.org.*

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[1]Version 1.0 of BMP REAL COST was based on data provided in the 2008 Version of the International Stormwater BMP Database and associated reports titled Analysis of Treatment Performance Report (Geosyntec Consultants & Wright Water Engineers 2008), which documents expected BMP effluent EMCs based on statistical analyses of the data in the International BMP Database (Geosyntec Consultants & Wright Water Engineers 2009).

Table 11: Default values for runoff capture efficiency, volume and peak runoff reduction

BMP	Runoff Capture Efficiency (%)	Runoff Volume Reduction (%)	Peak Runoff Reduction Capability
Bioretention - Infiltration	85%	100%	Yes
Bioretention - Underdrain	85%	55%	Yes
Constructed Wetland Basin	85%	5%	Yes
Constructed Wetland Channel	85%	0%	Yes
Extended Detention Basin - WQCV	85%	20%	Yes
Extended Detention Basin - EURV	98%	14%	Yes
Hydrodynamic Separator	85%	0%	No
Inlet Inserts	85%	0%	No
Media Filter Vault	85%	0%	No
Porous Concrete Pavement - Infiltration	[1]	100%	Yes
Porous Concrete Pavement - Underdrain	[1]	[2]	Yes
Pervious Asphalt Pavement - Infiltration	[1]	100%	Yes
Pervious Asphalt Pavement - Underdrain	[1]	[2]	Yes
Permeable Interlocking Concrete Pavers - Infiltration	[1]	100%	Yes
Permeable Interlocking Concrete Pavers - Underdrain	[1]	[2]	Yes
Retention (Wet) Pond - WQCV	85%	7%	Yes
Retention (Wet) Pond – EURV	98%	7%	Yes
Sand Filter Basin - Infiltration	85%	100%	Yes
Sand Filter Basin – Underdrain	85%	40%	Yes
Sand Filter Vault	85%	0%	No
Notes: [1] - $\lambda = \min(100\% - (RAPP/SAPP)*5\%, 95\%)$ [2] - $\theta = \max(50\% - (RAPP/SAPP)*3\%, 10\%)$			

4.2.2. *Land Use Event Mean Concentrations*

The values in this table represent the concentrations of pollutants expected in runoff generated from a variety of land uses. Values are based on the results of sampling stormwater runoff in and around Denver, CO, as documented in Chapter 1 of Volume 3 of the USDCM (UDFCD 2016) and included in Table 12a below. Information sources used to develop values in this table include a combination of the Denver Regional Urban Runoff Program (DRURP) (Gibbs 1981; Gibbs and Doerfer 1982), Phase 1 stormwater permittee monitoring data, the National Stormwater Quality Database (Maestre and Pitt 2015), inflow data to Denver-area BMPs in the International Stormwater BMP Database (2014 release), and the Regulation 85 Data Gap Analysis Report (Wright Water Engineers et al. 2013). UDFCD's long-term monitoring data in the metro-Denver area through 2013 are included in this data set.

The default values may be edited by the user if valid site-specific data over a range of representative storm events are available. UDFCD may also update this table periodically based on additional monitoring in the metro Denver area. Values for other states may be derived from Version 4.02 or later of the National Stormwater Quality Database, accessible at: http://www.bmpdatabase.org/nsqd.html.

At the time that Table 12a was developed for Volume 3, the bacteria data sets in the metro-Denver area were relatively limited. Nonetheless, due to the prevalence of *E. coli* impairments and Total Maximum Daily Loads in the Denver metro area, best estimates of *E. coli* have been added to the 2016 update of BMP-REALCOST based on work completed for the City and County of Denver to support planning-level BMP prioritization for priority basins in the South Platte Segment 14 *E. coli* TMDL (Wright Water Engineers 2015). As shown in Table 12b, *E. coli* data are highly variable and should be used with caution, recognizing the uncertainty associated with these estimates. Estimates for *E. coli* will be updated in the future as more stormwater monitoring data become available in the metro Denver area.

Table 12a: Table of median land use event mean concentrations for the Denver, CO region
(Source: USDCM Volume 3, Chapter 1, updated by UDFCD 2016)

Analyte	Commercial				Residential				Industrial				Natural Grassland			
	n	Mean (95% CIs)	Median (95% CIs)		n	Mean (95% CIs)	Median (95% CIs)		n	Mean (95% CIs)	Median (95% CIs)		n	Mean (95% CIs)	Median (95% CIs)	
Total Nitrogen (mg/L)	246	3.70 (3.33-4.06)	2.92 (2.75-3.20)		204	4.74 (4.34-5.13)	3.86 (3.59-4.40)		9	4.35 (2.58-6.12)	3.60 (1.20-5.70)		7	3.40 (1.90-4.90)	3.76 (1.49-4.11)	
Total Kjeldahl Nitrogen (mg/L)	250	2.80 (2.50-3.09)	2.20 (2.03-2.40)		192	3.33 (3.00-3.66)	2.70 (2.47-3.00)		20	3.12 (2.29-3.95)	2.97 (2.01-4.2)		7	2.88 (1.56-4.21)	3.10 (1.30-3.26)	
Nitrate Plus Nitrite (mg/L)	253	0.89 (0.79-0.99)	0.72 (0.63-0.78)		238	1.02 (0.91-1.12)	0.81 (0.76-0.94)		9	1.23 (0.78-1.68)	1.00 (0.30-1.60)		7	0.52 (0.23-0.80)	0.56 (0.09-0.66)	
Phosphorus as P, Total (mg/L)	273	0.35 (0.29-0.42)	0.19 (0.17-0.24)		254	0.52 (0.48-0.57)	0.42 (0.38-0.46)		21	0.42 (0.27-0.58)	0.30 (0.17-0.41)		7	0.41 (0.25-0.58)	0.41 (0.21-0.53)	
Phosphorus as P, Dissolved (mg/L)	192	0.13 (0.10-0.15)	0.07 (0.05-0.08)		233	0.24 (0.22-0.27)	0.19 (0.17-0.20)		9	0.34 (0.13-0.54)	0.18 (0.10-0.52)		7	0.13 (0.08-0.18)	0.15 (0.07-0.17)	
Phosphorus, Ortho-P (mg/L)	136	0.15 (0.10-0.20)	0.06 (0.06-0.08)		97	0.22 (0.16-0.27)	0.15 (0.13-0.18)			NA	NA		7	0.13 (0.08-0.18)	0.12 (0.07-0.13)	
TSS (mg/L)	280	219 (173-265)	85 (63-125)		270	221 (185-256)	122 (103-143)		9	502 (240-764)	370 (126-540)		7	397 (166-627)	257 (194-464)	
TDS (mg/L)	9	149 (81-217)	117 (33-214)		7	146 (46-245)	95 (60-126)		9	84 (52-117)	75 (30-102)			NA	NA	
COD (mg/L)	156	187 (159-215)	139 (114-162)		140	120 (105-136)	93 (80-108)			NA	NA		7	72 (51-94)	71 (42-71)	
DOC (mg/L)	51	35 (24-45)	22 (17-34)		55	17 (13-21)	12 (10-14)			NA	NA		7	16 (6-27)	12 (9-12)	
TOC (mg/L)	156	36 (28-44)	21 (18-27)		80	27 (23-31)	21 (18-25)		9	66 (48-84)	57 (24-82)		7	26 (11-42)	23 (13-23)	
Cadmium, Total (ug/L)	147	NP	NP		119	NP	NP		9	NP	NP			NA	NA	
Copper, Total (ug/L)	249	27 (20-34)	13 (12-16)		182	22 (19-25)	15 (11-20)		9	86 (31-141)	46 (39-86)		7	37 (-0.1-74)	20 (10-60)	
Lead, Total (ug/L)	209	13 (10-16)	5 (5-6)		126	14 (11-17)	8 (5-10)		9	205 (3-408)	120 (63-160)			NA	NA	
Zinc, Total (ug/L)	251	156 (120-192)	64 (55-80)		181	115 (99-131)	80 (68-110)		9	760 (280-1240)	520 (340-620)		7	101 (56-147)	90 (40-120)	

Monitoring locations limited to Denver Metro area. 1980's lead data excluded from summary due to the phase-out of leaded gasoline.
CI = 95% confidence interval provided for mean and median values. n = number of samples. NP = Not provided due to large percentage of non-detects.

Table 12b: Median *E. coli* stormwater runoff concentrations assumptions by land use
(Source: Wright Water Engineers 2016)

Land Use Groups and Statistic	Simple Statistical Value *E. coli* (MPN/100 mL)	Bootstrapped Statistical Values with Confidence Intervals[1] *E. coli* (MPN/100 mL)
Commercial, Industrial, Roads/Paved Areas		
Mean	10,252	10,243 (6,578-16,920)
Median	1,800	**1,725 (1,200-2,230)**
Geometric Mean	1,274	1,288 (965-1,696)
Residential and Urban Open Space/Parks		
Mean	26,102	26,078 (18,172-37,400)
Median	2,599	**2,732 (2,000-4,300)**
Geometric Mean	2,580	2,617 (1,899-3,515)

[1]The bootstrap resampling method introduced by Efron and Tibisharni (1993) was applied to the data set using XLSTAT 2013. It is a statistical method for estimating the sampling distribution of an estimator by sampling with replacement from the original sample. The number of resampling iterations was set at 10,000 for purposes of these calculations. Bias corrected 95% percentile confidence intervals are also calculated following Efron and Tibisharni (1993).

[2]Hypothesis testing using Kruskal Wallis test and Dunn's Procedure was conducted to develop land use groupings. If more local data become available in the future, it may be appropriate to revise these groupings.

4.3.   Modifying Land Cost Values

The values in the table on the "LandCost" worksheet and shown in Table 20 are the unit land costs ($ per acre) used by the model to compute total land costs for BMP implementation. These costs are considered applicable for *new* developments on previously undeveloped land or land on which any existing structures have minimal value. The costs associated with redevelopment, are likely to be higher due to the value of structures already existing on that land. The user may edit the values in the table with values more representative of the project location if necessary.

Table 13: Unit land costs based on land use (in 2008$)

Land Use	Inputs ($ per acre)	Low ($ per acre)	Medium ($ per acre)	High ($ per acre)
Commercial	$ 540,000	$ 290,000	$ 540,000	$ 900,000
Industrial - Light	$ 170,000	$ 90,000	$ 170,000	$ 270,000
Industrial - Heavy	$ 210,000	$ 90,000	$ 210,000	$ 290,000
Residential - Single Family (1,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Single Family (2,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Single Family (3,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Single Family (4,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Single Family (5,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Multi-Unit (detached)	$ 550,000	$ 210,000	$ 550,000	$ 680,000
Residential - Large Lot (>1/2 acre)	$ 410,000	$ 130,000	$ 410,000	$ 730,000
Residential - Apartments	$ 710,000	$ 320,000	$ 710,000	$ 930,000
Parks, Cemeteries	$ 20,000	$ 20,000	$ 20,000	$ 30,000
Institutional	$ 320,000	$ 150,000	$ 320,000	$ 620,000
Paved Area	$ 400,000	$ 220,000	$ 400,000	$ 785,000
Undeveloped	$ 110,000	$ 40,000	$ 110,000	$ 360,000

Source: Denver Tax Assessor's Database (accessed January 2017, with values converted to 2008 dollars for consistency with base year costs in BMP-REALCOST).

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 (Table 14).

Table 14: BMP cost worksheet names

Worksheet Name	BMP
BIO	Bioretention
CWB	Constructed Wetland Basin
CWC	Constructed Wetland Channel
EDB (WQCV)	Extended Detention Basin w/ WQCV only
EDB (EURV)	Extended Detention Basin w/ EURV
HS	Hydrodynamic Separator
II	Inlet Inserts
MFV	Media Filter Vault
PAP	Pervious Asphalt Pavement
PCP	Porous Concrete Pavement
PICP	Permeable Interlocking Concrete Pavers
RP (WQCV)	Retention (Wet) Pond w/ WQCV only
RP (EURV)	Retention (Wet) Pond w/ EURV
SFB	Sand Filter Basin
SFV	Sand Filter Vault

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.

4.4.1. Editing Capital Cost Parameters

The capital cost input table is presented in Figure 5. 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 parametric equation (Option 1) or using a cost-curve generating option (Option 2). Option 1 is the default option.

Figure 5: Capital cost input table

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.

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 6) 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.
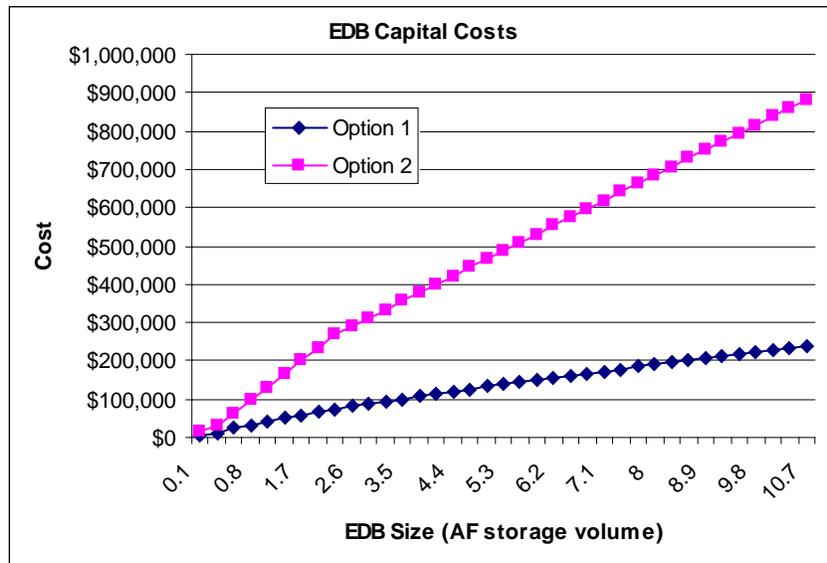

Figure 6: Chart showing example cost curves generated using the capital cost input tables

4.4.2.   Editing Maintenance Cost Parameters

The procedures for editing maintenance cost parameters on the maintenance cost table (Table 15) are explained below.

Table 15: Maintenance cost input tables

ANNUAL MAINTENANCE COSTS

Activity	Units	Frequency per Year Default	User	Input	Hours per Unit Default	User	Input	Labor Crew Size Default	User	Input	Hourly Labor Rate Default	User	Input	Overhead Factor (%) Default	User	Input	Equipment Cost per Hr Default	User	Input	Other Costs per Unit Default	User	Input	Lump Sum Per Unit	Total Cost per Unit	Beta Value	Annual Cost
Compliance Inspection[1]	each	1		1	0.33		0.33	1		1	$23.31		$18.39	100%		100%	$10.15		$8.01	$0.00	$0.00	$0.00		$14.78	-	$14.78
Inlet/Outlet Cleaning	each	6		6	0.5		0.5	2		2	$23.31		$18.39	100%		100%	$10.15		$8.01	$0.00	$0.00	$0.00		$40.79	-	$244.71
Nuisance Control	each	12		12	0.5		0.5	1		1	$23.31		$18.39	100%		100%	$10.15		$8.01	$35.00		$27.61		$50.01	-	$600.11
Outlet Maintenance	each	0.25		0.25	12		12	3		3	$23.31		$18.39	100%		100%	$102.88		$81.17	$200.00	$200.00	$157.79		$2,455.97	-	$613.99
				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 are a function of the BMP size — Annual Cost per AF

Activity	Units	Frequency per Year Default	User	Input	Hours per Unit Default	User	Input	Labor Crew Size Default	User	Input	Hourly Labor Rate Default	User	Input	Overhead Factor (%) Default	User	Input	Equipment Cost per Hr Default	User	Input	Other Costs per Unit Default	User	Input	Lump Sum Per Unit	Total Cost per Unit	Beta Value	Annual Cost
Lawn Mowing/Lawn Care	acre	6		6	2		2	2		2	$23.31		$18.39	100%		100%	$41.42		$32.68	$0.00	$0.00	$0.00		$212.49	1	$1,274.91
Sediment Removal (non-routine)	CY	0.05		0.05	0.08		0.08	4		4	$23.31		$18.39	100%		100%	$220.19		$173.72	$10.00	$10.00	$7.89		$33.56	323	$541.96
Sediment Removal (routine)	CY	0.5		0.5	0.33		0.33	2		2	$23.31		$18.39	100%		100%	$56.73		$44.76	$10.00	$10.00	$7.89		$46.94	16	$375.49
				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

Subtotal 1 $1,458.81
Subtotal 2 $2,192.36

(1) - Compliance Inspection is added as an administrative cost

OR

Annual maintenance costs as percentage of capital costs

"Constant" cost activities

"Variable" cost activities

"Percentage" cost option

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 are deleted correctly, the value in Column AG of that row should equal $0.00.

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.

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

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, simply 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 easily 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. **TECHNICAL DETAILS**

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

5.1.　　Precipitation Data

The model requires two precipitation parameter inputs, mean annual precipitation depth and the 2-Year, 1-Hour total rainfall depth. 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 7, based on NOAA Atlas 2, Volume 14 (NOAA 2013, accessible at http://hdsc.nws.noaa.gov/hdsc/pfds/). A summary of precipitation data for selected sites is provided in Table 3 in Section 3.1.1.

5.2.　　Watershed Imperviousness

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

5.2.1.　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 presented in Table 5.
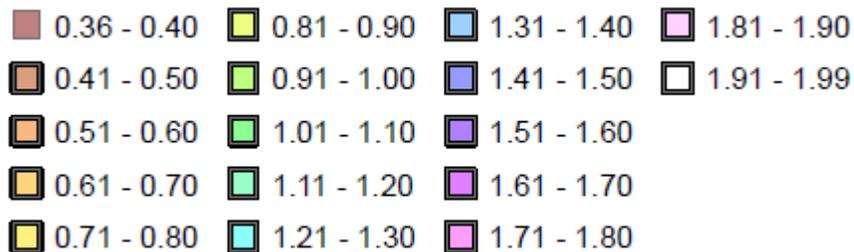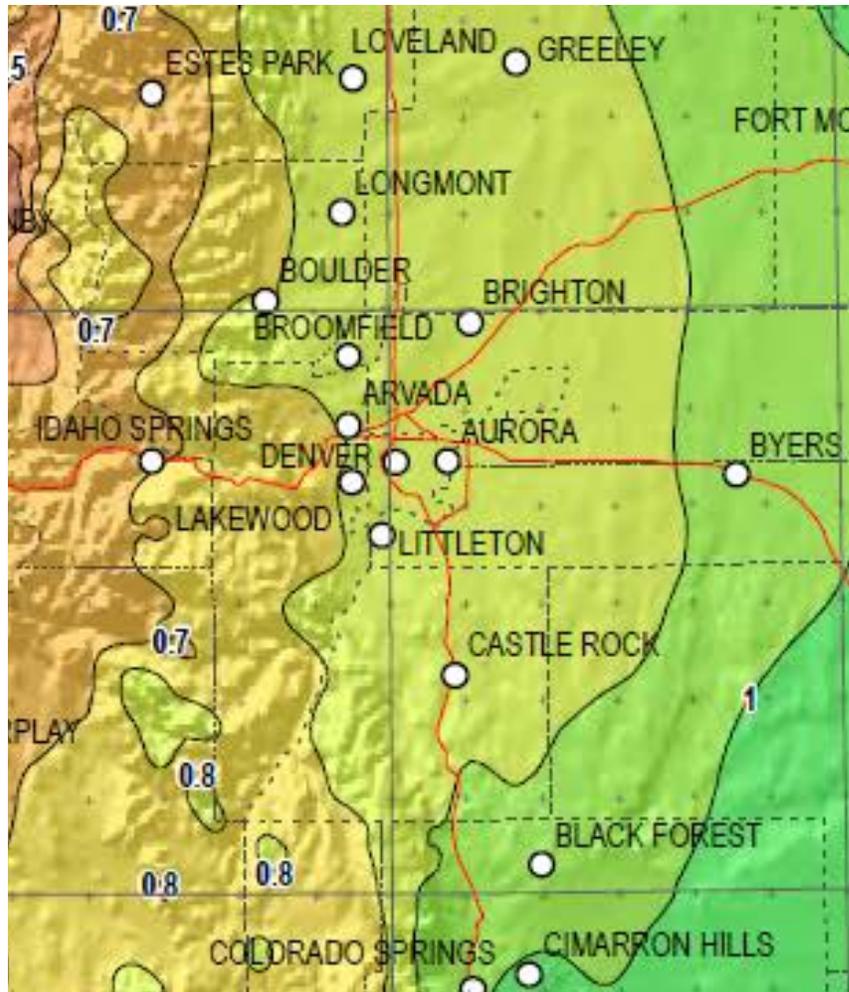
Figure 7: Map showing 2-year, 1-hour rainfall depths for locations near Denver, CO (NOAA 2013)

5.2.2.   Source Controls

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

5.2.3.   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 dependent on the total imperviousness of the watershed. The model uses UDFCD's methods for reducing effective imperviousness, as illustrated in Figure 8.
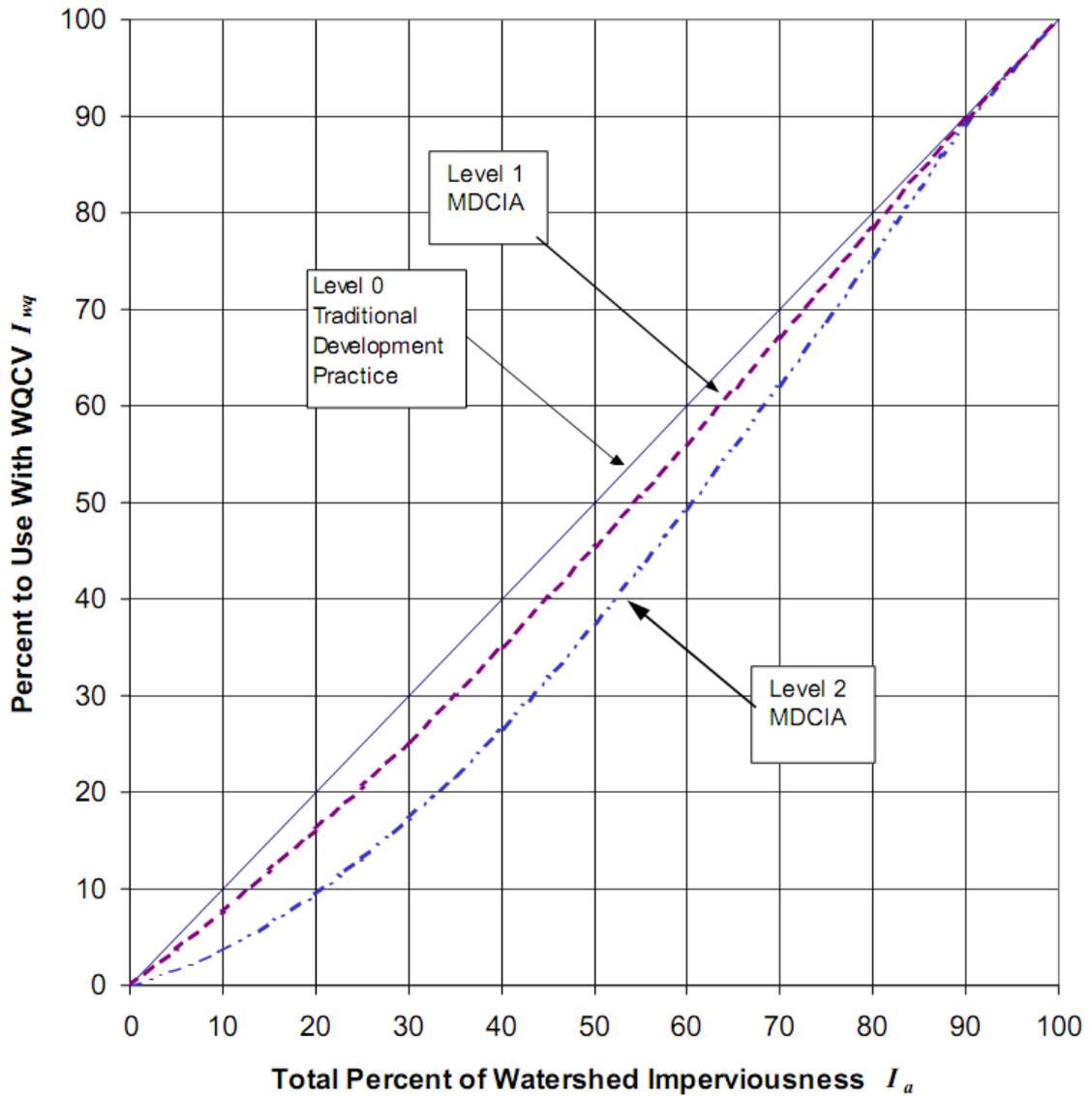
Figure 8: Effective imperviousness adjustments for Level 1 and Level 2 MDCIA

For programming purposes, the plots in Figure 8 were converted to the regression equations (1), (2) and (3), which are imbedded within the model macros.

Level 0 $\quad EI = TI$ **(1)**

Level 1 $\quad EI = 0.2156TI^2 + 0.8005TI$ **(2)**

Level 2 $\quad EI = -0.5014TI^3 + 1.2301TI^2 + 0.2764TI$ **(3)**

Where *EI* = Effective imperviousness and *TI* = Total imperviousness.

5.3.   Runoff Coefficients

UDFCD has developed guidance for estimating volumetric runoff coefficients to represent the ratio of total runoff volume to total precipitation volume. The 2017 release of BMP-REALCOST utilizes long-term volumetric runoff coefficients for all four NRCS soil types calculated using WQCOSM as summarized in Table 16, and as described in Appendix A.

Table 16: Volumetric Runoff Coefficients for Hydrologic Soil Groups

Long Term Volumetric Runoff Coefficient for Hydrologic Soil Groups			
% Impervious	C_A	C_B	$C_{C/D}$
10%	0.08	0.10	0.10
20%	0.16	0.19	0.19
30%	0.25	0.27	0.28
40%	0.33	0.36	0.36
50%	0.41	0.45	0.45
60%	0.49	0.54	0.54
70%	0.58	0.62	0.62
80%	0.66	0.71	0.71
90%	0.74	0.80	0.80
100%	0.88	0.88	0.88

(Note: The originally released BMP-REALCOST model in 2009 used a 2-year return storm period (correction factors = 0) for generating runoff and the 5-year correction factors were used to calculate the time of concentration for the Rational Method. The 2017 method is slightly more accurate than use of the previous method for certain imperviousness and soil type combinations.)

5.4.   BMP Size

BMPs are classified as either storage BMPs, conveyance BMPs or PP (Table 17). Storage BMPs capture and treat a specified volume of runoff and are measured according to their design storage volume. Conveyance BMPs convey and treat a specified flow rate and are measured according to their 2-year design flow capacity and PPs are measured according to their surface area. The size of storage and conveyance BMPs are computed as described in the following sections. PP surface area (*SAPP*) is input by the user; therefore, there is no "PP sizing" algorithm.

Table 17: BMP design classification

BMP	Design Classification
Bioretention	Storage
Constructed Wetland Basin	Storage
Constructed Wetland Channel	Conveyance
Extended Detention Basin	Storage
Hydrodynamic Separator	Conveyance
Inlet Inserts	Conveyance
Media Filter Vault	Conveyance
Permeable Interlocking Concrete Pavers	PP
Pervious Asphalt Pavement	PP
Porous Concrete Pavement	PP
Retention (Wet) Pond	Storage
Sand Filter Basin	Storage
Sand Filter Vault	Storage

5.4.1.   Storage BMPs

UDFCD has developed design criteria for sizing volume-based structural BMPs so that the runoff from approximately 85% 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 85% 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 (4) is UDFCD's empirical equation for estimating the WQCV of a BMP.

$$WQCV = a*(0.91EI^3 - 1.19EI^2 + 0.78EI) \qquad \textbf{(4)}$$

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 (5), (6), and (7) are used to compute the EURV for soil types A, B and C/D, respectively.

$$EURV_A = 1.1 * (2.0491EI - 0.1113) \tag{5}$$

$$EURV_B = 1.1 * (1.2846EI - 0.0461) \tag{6}$$

$$EURV_{C/D} = 1.1 * (1.1381EI - 0.0339) \tag{7}$$

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 (8) for volume measured in acre-feet (AF) or Equation (9) for volume measured in cubic feet (ft^3).

$$DesignVolume(AF) = StorageVolume/12 * CA * ASF \tag{8}$$

$$DesignVolume(ft^3) = StorageVolume/12 * CA * ASF * 43,560 \tag{9}$$

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 18. The drawdown time coefficients are values recommended by UDFCD. The ASF values were determined as described below.

Table 18: Volume-based BMP design factors

BMP	Drawdown Time Coefficient, a	Additional Storage Factor, ASF
Bioretention	0.8	1.0
Constructed Wetland Basin	0.9	1.75
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
Sand Filter Vault	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.

5.4.2. Conveyance 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 (10).

$$Q = C * i * CA \tag{10}$$

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

The rainfall intensity is computed using Equation (11), derived by UDFCD and applicable to the Front Range region of Colorado.

$$i = \frac{28.5 P_1}{(10 + Tc)^{0.786}} \tag{11}$$

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.

$$Tc = Ti + Tt \tag{12}$$

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 (13) and (14).

$$Ti = \frac{0.395(1.1 - C_5)\sqrt{L_{OF}}}{S^{0.33}} \tag{13}$$

$$Ti = \frac{L_{OF}}{180} + 10 \tag{14}$$

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 (15).

$$Tt = \frac{L_{CF}}{V} \tag{15}$$

Where L_{CF} = channelized flow length (ft) and V = average velocity (ft/s) computed using Equation (16).

$$V = C_v S^{0.5} \tag{16}$$

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 9. These assumed lengths are considered reasonable for planning-level studies.
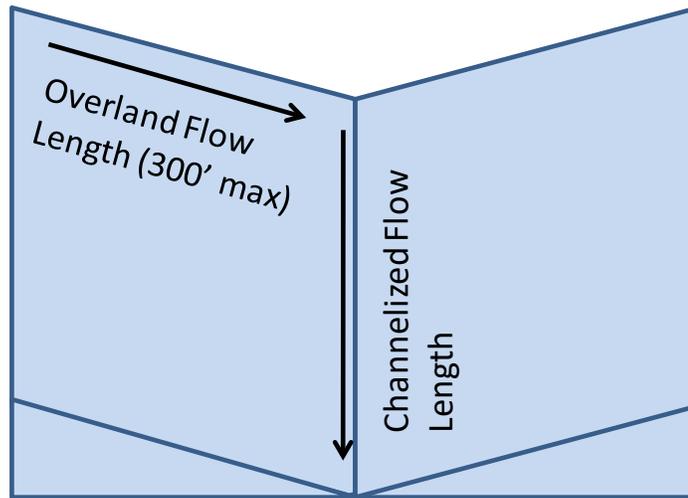
Figure 9: Diagram showing overland and channelized flow lengths assuming v-shaped watershed

Overland and channelized flow lengths are computed using Equations (17) and (18), respectively.

$$L_{OF} = 0.5 * \sqrt{CIA * 43560} \tag{17}$$

$$L_{CF} = \sqrt{CIA * 43560} \tag{18}$$

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

5.4.3. *Permeable Pavements (PP)*

The surface areas of PPs are input by the user.

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[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.

5.5.   Number of BMPs

When applying BMPs to a subcatchment, *BMP-REALCOST* assumes that no area in that subcatchment is left untreated; therefore, the number of BMPs (*N*) in each subcatchment is computed using Equation (19) and rounded to the next highest integer.

$$N = (CA * I_T)/CIA \qquad\qquad (19)$$

where *CA* = subcatchment total area (acres) and *CIA* = contributing impervious area (acres) for BMPs (input by the user) or CIA = (*RAPP* + *SAPP*) for PP.

To evaluate untreated areas in a scenario, the user can select BMP type "None" to be applied to a subcatchment. Using the regional control option, *N* =1.

5.6.   Construction Costs

Construction costs are represented in the form of a parametric Equation (20) where costs are expressed as a function of the size of the BMP, a base cost and an exponent term that can reflect economies of scale realized with some construction projects.

$$ConCost = C + XU^{\alpha} \qquad\qquad (20)$$

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 storage BMPs, design flow rate for conveyance BMPs and surface area for PPs. 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.

5.6.1.   *Development of Construction Cost Equations*

Muller Engineering (2009) developed construction cost estimates for each of the BMPs included in the model based on UDFCD BMP design criteria and unit costs available from Denver-area construction projects completed in the past 5 years. For each BMP, construction costs for three different sizes were estimated. The estimates were adjusted to May 2008 national average costs using the ENR CCI (ENR CCI = 8141), assuming that the original estimates were representative of 2008 costs in the Denver region (ENR CCI = 5782). Plots of BMP cost versus size were created and best-fit lines were applied to generate a cost equation. The methods and assumptions used to develop the construction cost estimates are documented in the memorandum prepared by Muller Engineering (2009), which is included in as Appendix B in this manual. The following sections present the plots and equations generated for each BMP. In 2013 and 2017, some adjustments to the cost equations have been made based on experience gained since 2009; however, the methodology used to develop the 2009 cost estimates was generally followed.

Constructed Wetland Basins, Extended Detention Basins and Retention Ponds with Water Quality Control Volume

Figure 10 presents the plots and cost equations generated for constructed wetland basins, extended detention basins and retention ponds designed for the WQCV.

Figure 10: Cost equations developed for constructed wetland basins, extended detention ponds and retention ponds with WQCV

Sand Filter Basins, Bioretention, Vaults with Capture Volume and Sand Filter Vaults

Figure 11 presents the plots and cost equations generated for sand filter basins, porous landscape detention (now called bioretention), vaults with capture volume and sand filter vaults designed for the WQCV. Note that the costs for bioretention (shown as PLD on the figure) assume that the bioretention is "unconstrained", meaning that is does not have concrete sidewalls.

Note: VCV no longer included in BMP-REALCOST. PLD is now referred to as BIO (Bioretention).

Figure 11: Cost equations developed for sand filter basins, bioretention, vaults with capture volume and sand filter vaults designed for the WQCV

Permeable Pavements

Figure 12 presents the plots and cost equations generated for permeable interlocking concrete pavers (also known as cobblestone block pavers), porous concrete pavement and pervious asphalt pavement.
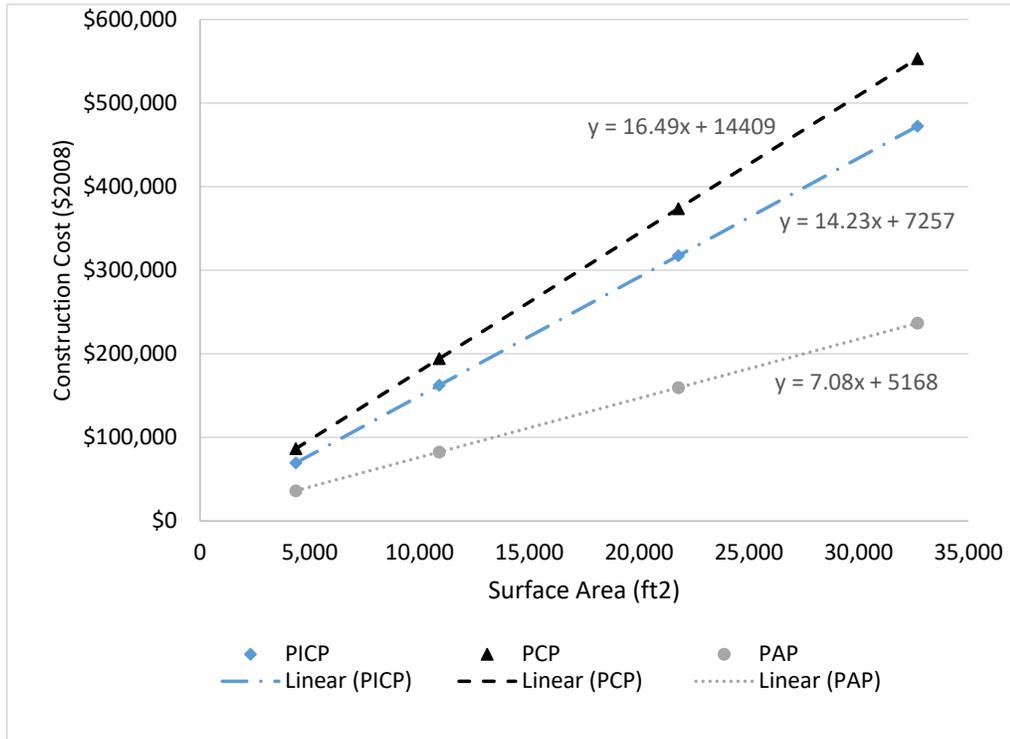
Figure 12: Cost equations developed for permeable pavements

Hydrodynamic Separators, Media Filter Vaults and Inlet Inserts

Figure 13 presents the plots and cost equations generated for hydrodynamic separators, media filter vaults[3] and inlet inserts.[4] Hydrodynamic separators can be used to approximate costs for Sediment Oil and Grit Separators, which are no longer included in the 2017 update to BMP-REALCOST.
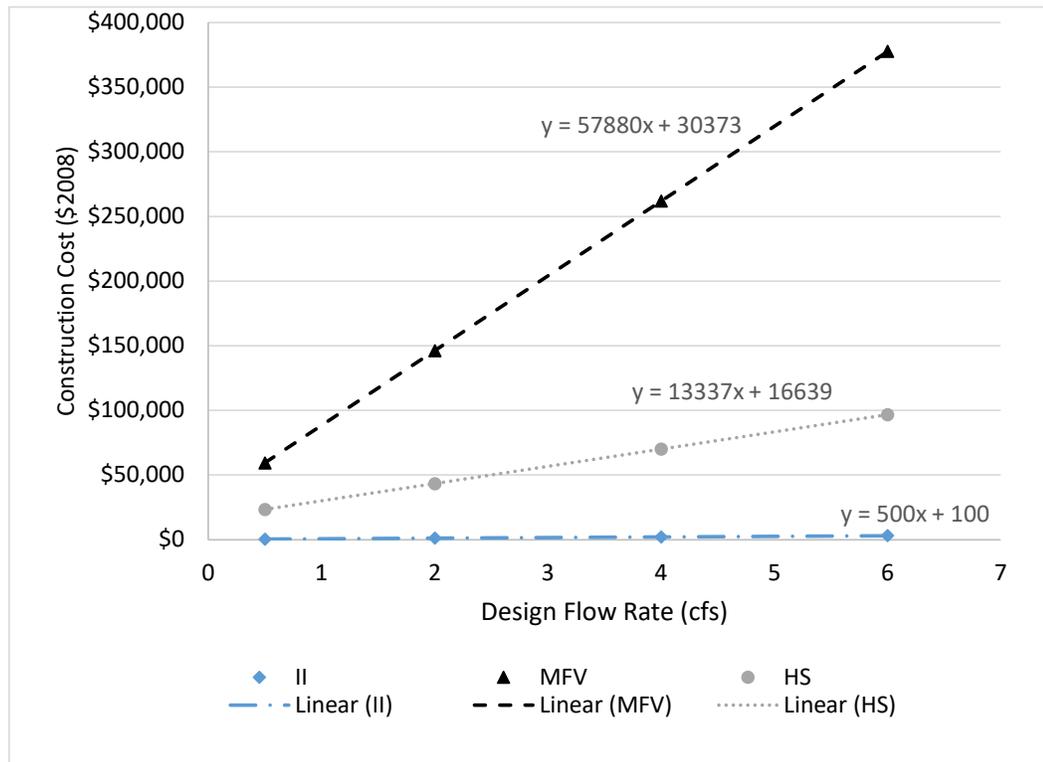
Figure 13: Cost equations developed for proprietary devices.

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[3] The costs for media filter vaults are based on two proprietary devices, the EcoStorm Plus and StormFilter. The Filterra system is not representative of the devices being evaluated for this category; therefore, its costs were removed from consideration in the model.

[4] The costs of inlet inserts are based on two propriety devices, the Ultra Urban Filter with Smart Sponge and the FlexStorm. The Hydroscreen device is not representative of the devices being evaluated for this category; therefore, its costs were removed from consideration in the model.

Extended Detention Basins and Retention Ponds with Excess Urban Runoff Volume

Figure 14 presents the plots and cost equations generated for constructed wetland basins, extended detention basins and retention ponds designed for the EURV.
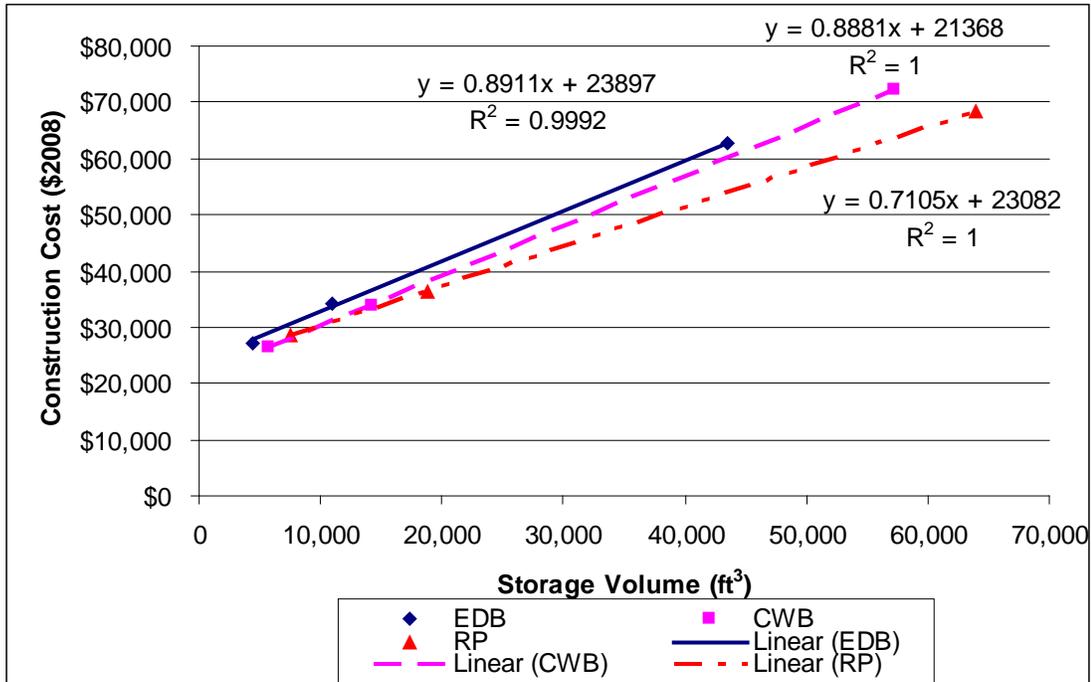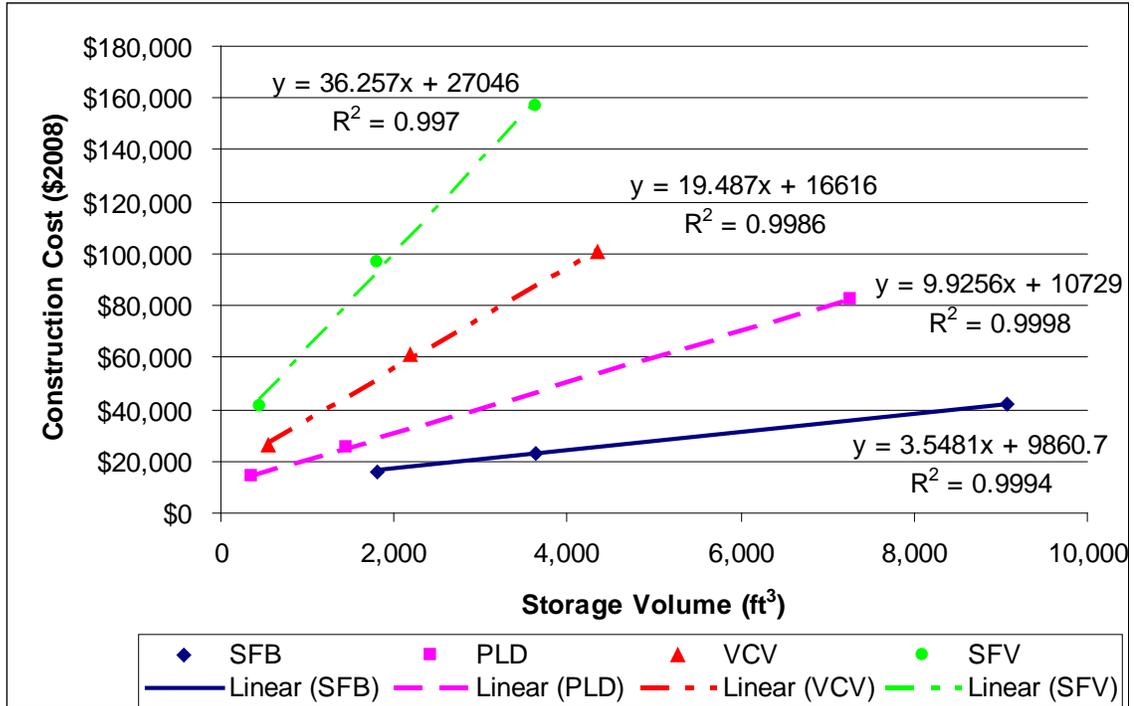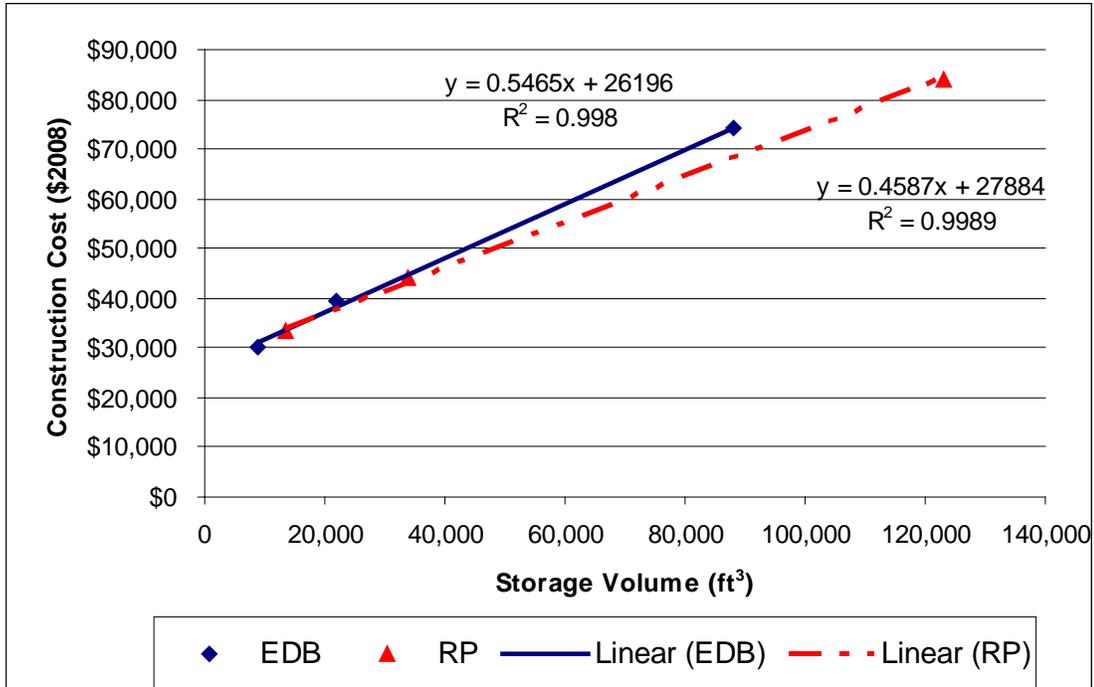

Figure 14: Cost equations developed for extended detention ponds and retention ponds with EURV

Constructed Wetland Channel

Construction costs for CWCs are dependent on both the design flowrate of the channel (which controls the cross sectional area of the channel) and the length of the channel. Figure 15 shows the relationship of construction costs per 100 linear feet of channel to the design flowrate.
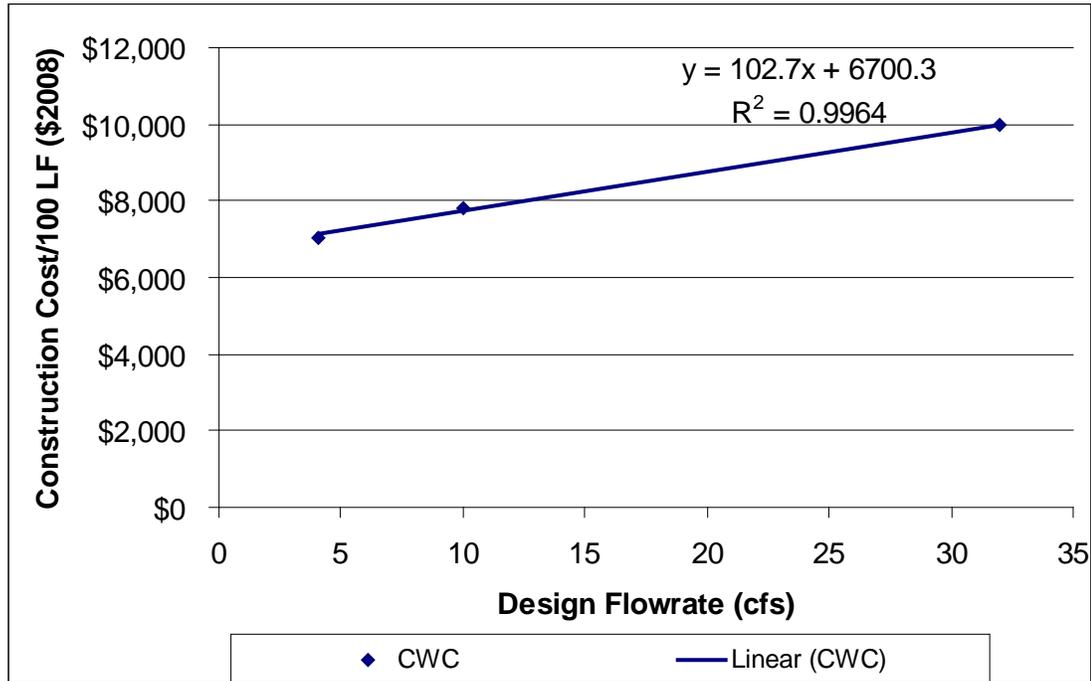
Figure 15: Unit construction cost equation developed for constructed wetland channels

To estimate the total construction costs, the unit cost taken from Figure 15 is then multiplied by the length of the channel, which is assumed to be equal to the square root of the area draining to the channel, Equation (21). This assumes that the contributing area is square and the channel bisects the area as in a classic "V-shaped" watershed model.

$$L = \sqrt{CIA * 43{,}560} \qquad (21)$$

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

5.6.2. *Construction Cost Equations Used in Model*

Table 19 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 5.13 and 5.14.

Table 19: Summary of construction cost equations used in the model

BMP	Cost Equation ($2008)
Bioretention	$10,729 + $9.93(V)
Constructed Wetland Basin	$21,368 + $0.89(V)
Constructed Wetland Channel[1]	$6,700 + $102.70(F)
Extended Detention Basin (WQCV)	$23,897 + $0.89(V)
Extended Detention Basin (EURV)	$26,196 + $0.55(V)
Hydrodynamic Separator	$16,639 + $13,337(F)
Inlet Inserts	$100 + $500(F)
Media Filter Vault	$30,373 + $57,880(F)
Retention (Wet) Pond (WQCV)	$23,082 + $0.71(V)
Retention (Wet) Pond (EURV)	$27,884 + $0.46(V)
Sand Filter Basin	$9,861 + $3.55(V)
Sand Filter Vault	$27,046 + $36.26(V)
Permeable Interlocking Concrete Pavers (Cobblestone Blocks)	$7,257 + $14.23(SA)
Pervious Asphalt Pavement	$5,168 + $7.08(SA)
Porous Concrete Pavement	$14,409 + $16.49(SA)
Notes: [1] - cost per 100 linear feet of channel F = design flowrate (cfs) SA = surface area (ft^2) V = storage volume (ft^3)	

5.7. 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 as a function of the BMP size and a derived coefficient referred to as the "land consumption coefficient" (C_{LC}), with land costs then being computed using Equation (22).

$$LandCost = LC * U * CLC \qquad \textbf{(22)}$$

Where *LandCost* = cost of land required for the BMP, *LC* = cost of land based on land use ($/acre), *U* = size of the BMP (ft^2, ft^3, AF, cfs, acres) and *CLC* = factor relating the land required for the BMP to its size (acres/unit).

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 (23).

$$LandCost = LC * Tw * L \qquad \textbf{(23)}$$

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 (21). The channel top width is computed using an iterative procedure that solves for the appropriate channel cross-section area required to convey the design flowrate, as recommended by UDFCD.

5.7.1.   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 (Table 13) are median values of land costs for various land uses from the Denver Tax Assessor's database, accessed in January 2017 and converted back to a 2008 base year (Table 20). Low, medium and high estimates are also provided for general reference. These costs are considered applicable for *new* developments on previously undeveloped land or land on which any existing structures have minimal value. The costs associated with redevelopment, are likely to be higher due to the value of structures already existing on that land. It is highly recommended that users utilize site-specific cost data, given the wide range of land values in the metro-Denver area.

Table 20: Land cost estimates as function of land use

Land Use	Inputs ($ per acre)	Low ($ per acre)	Medium ($ per acre)	High ($ per acre)
Commercial	$ 540,000	$ 290,000	$ 540,000	$ 900,000
Industrial - Light	$ 170,000	$ 90,000	$ 170,000	$ 270,000
Industrial - Heavy	$ 210,000	$ 90,000	$ 210,000	$ 290,000
Residential - Single Family (1,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Single Family (2,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Single Family (3,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Single Family (4,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Single Family (5,000 sf)	$ 260,000	$ 150,000	$ 260,000	$ 670,000
Residential - Multi-Unit (detached)	$ 550,000	$ 210,000	$ 550,000	$ 680,000
Residential - Large Lot (>1/2 acre)	$ 410,000	$ 130,000	$ 410,000	$ 730,000
Residential - Apartments	$ 710,000	$ 320,000	$ 710,000	$ 930,000
Parks, Cemeteries	$ 20,000	$ 20,000	$ 20,000	$ 30,000
Institutional	$ 320,000	$ 150,000	$ 320,000	$ 620,000
Paved Area	$ 400,000	$ 220,000	$ 400,000	$ 785,000
Undeveloped	$ 110,000	$ 40,000	$ 110,000	$ 360,000

5.7.2. Land Required for BMPs (CLC)

Recognizing that the area of land required for BMPs is related to the size of the BMP, a "land consumption coefficient" (CLC) was derived to quantify this relationship based on UDFCD BMP design recommendations. The following sections describe the methods and assumptions used to develop this relationship for each BMP that requires land.

Constructed Wetland Basin

The CLC for CWBs = 0.00002 acres/ft^3, assuming average depth of 2 feet and an area equal to 75% of the CWB surface area be set aside for maintenance access and other considerations.

Constructed Wetland Channel

The CLC for CWCs = 1 acre/acre, assuming that the land required for CWCs is equal to the surface area of the BMP. Because the size of CWCs are calculated and reported in terms of their design flowrate (cfs), the tool computes the surface area of the CWC internally as a function of the channel top width and channel length.

Extended Detention Basin -WQCV/EURV

The CLC for EDBs = 0.000016 acres/ft^3, assuming average depth of 2.5 feet and an area equal to 75% of the EDB surface area be set aside for maintenance access and other considerations.

Bioretention

The CLC for BIOs = 0.000023 acres/ft^3, assuming that the WQCV can "pond" to a depth of 1 foot on the surface of the BIO.

Retention Pond -WQCV/EURV

The CLC for RPs = 0.000013 acres/ft^3, assuming average depth of 3 feet and an area equal to 75% of the RP surface area be set aside for maintenance access and other considerations.

Sand Filter Basin

The CLC for SFBs = 0.000013 acres/ft^3, assuming average depth of 3 feet and an area equal to 75% of the SFB surface area be set aside for maintenance access and other considerations.

Underground BMPs and Permeable Pavement

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

Table 21 summarizes the CLC values used in the model.

Table 21: CLC values used for computing BMP land costs

BMP	CLC	Units
Bioretention	0.000023	Acres/ft^3
Constructed Wetland Basin	0.000020	Acres/ft^3
Constructed Wetland Channel	1	Acres/acre
Extended Detention Basin-EURV	0.000016	Acres/ft^3
Extended Detention Basin-WQCV	0.000016	Acres/ft^3
Hydrodynamic Separator	0	Acres/cfs
Inlet Inserts	0	Acres/cfs
Media Filter Vault	0	Acres/cfs
Permeable Pavements	0	Acres/acre
Retention (Wet) Pond-EURV	0.000013	Acres/ft^3
Retention (Wet) Pond-WQCV	0.000013	Acres/ft^3
Sand Filter Basin	0.000013	Acres/ft^3
Sand Filter Vault	0	Acres/ft^3

5.8. 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 estimated for Denver-area projects by Urbonas (2008).

5.9. Capital Cost Calculations

Capital costs include construction costs, land costs and additional costs attributed to contingencies, engineering, administration etc., and are computed using Equation (24).

$$CCost = (1 + CEA) * (C + XU^{\alpha}) + LandCost \tag{24}$$

Where *CCost* = capital cost for an individual BMP, *CEA* = factor accounting for contingencies/engineering/administration (%), *C* = base cost ($), *X* = unit cost ($ per unit), *U* = 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 22.

Table 22: Default values of capital cost parameters used in the model

BMP	CEA (%)	C($)	X($/unit)	Units	α	CLC
Bioretention	40	$10,729	$9.93	ft^3	1	0.000023
Constructed Wetland Basin	40	$21,368	$0.89	ft^3	1	0.000020
Constructed Wetland Channel	40	$6,700	$102.70	ft^3	1	1
Extended Detention Basin (WQCV)	40	$23,897	$0.89	ft^3	1	0.000016
Extended Detention Basin (EURV)	40	$26,196	$0.55	ft^3	1	0.000016
Hydrodynamic Separator	40	$16,639	$13,337	cfs	1	0
Inlet Inserts	40	$100	$500	cfs	1	0
Media Filter Vault	40	$30,373	$57,880	cfs	1	0
Retention (Wet) Pond (WQCV)	40	$23,082	$0.71	ft^3	1	0.000013
Retention (Wet) Pond (EURV)	40	$27,884	$0.46	ft^3	1	0.000013
Sand Filter Basin	40	$9,861	$3.55	ft^3	1	0.000013
Sand Filter Vault	40	$27,046	$36.26	ft^3	1	0
Permeable Interlocking Concrete Pavers	40	$7,257	$14.23	ft^2	1	0
Pervious Asphalt Pavement	40	$5,168	$7.08	ft^2	1	0
Porous Concrete Pavement	40	$14,409	$16.49	ft^2	1	0

5.10.   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 types: those with costs that vary according to the size of the BMP ("variable" maintenance costs) and those that do not ("constant" maintenance costs). Equation (25) was developed for estimating annual maintenance costs.

$$MCost = C_C + C_V * U \qquad \text{(25)}$$

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

Table 23 shows the maintenance cost equations developed for each BMP. The methods and assumptions used to develop the cost equation are explained in Appendix C.

Table 23: Annual maintenance cost equations

BMP	C$_C$($)	C$_V$($/unit)	Units
Bioretention	$56.77	0.45	CF
Constructed Wetland Basin	$56.77	$6,195.07	AF
Constructed Wetland Channel	$56.77	$1,125.25	Acre
Extended Detention Basin (WQCV)	$1,103.76	$3,642.54	AF
Extended Detention Basin (EURV)	$1,103.76	$3,642.54	AF
Hydrodynamic Separator	$113.54	$434.41	cfs
Inlet Inserts	$586.03	$0.00	cfs
Media Filter Vault	$240.24	$4,191.67	cfs
Retention (Wet) Pond (WQCV)	$592.17	$1,280.87	AF
Retention (Wet) Pond (EURV)	$554.13	$1,280.87	AF
Sand Filter Basin	$56.77	$535.08	AF
Sand Filter Vault	$240.24	$2.59	CF
Permeable Interlocking Concrete Pavers	$56.77	$1,166.20	Acre
Pervious Asphalt Pavement	$56.77	$586.48	Acre
Porous Concrete Pavement	$56.77	$586.48	Acre

5.11.   Rehabilitation/Replacement Cost Calculations

Rehabilitation/replacement costs are computed as percentage of the original construction costs of the BMP using Equation (26).

$$RCost = R * ConCost \qquad \text{(26)}$$

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

5.11.1. 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 of two common inlet inserts is reported to be about 25 years on average; therefore, replacement is assumed to occur every 25 years in the model.

Hydrodynamic 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 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 30 years is assumed in this model.

5.11.2. 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. Underlying assumptions 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 bioretention, 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. 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 between 50% and 120% of the original construction costs based on partial to total rehabilitation. 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

The costs of replacing inlet inserts are assumed to be similar to the original costs which primarily include procurement and installation.

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 24 presents the percentage value and cost reoccurrence interval for each BMP.

Table 24: Rehabilitation/replacement cost percentages and frequency estimates

BMP	Frequency (years)	Cost (as % of construction costs)
Bioretention	10	30%
Constructed Wetland Basin	35	80%
Constructed Wetland Channel	25	75%
Extended Detention Basin (WQCV)	35	80%
Extended Detention Basin (EURV)	35	80%
Hydrodynamic Separator	30	50%
Inlet Inserts	25	100%
Media Filter Vault	25	100%
Retention (Wet) Pond (WQCV)	35	80%
Retention (Wet) Pond (EURV)	35	80%
Sand Filter Basin	25	80%
Sand Filter Vault	30	100%
Permeable Interlocking Concrete Pavers	35	80%
Pervious Asphalt Pavement	18	30%
Porous Concrete Pavement	18	80%

5.12. Administrative Cost Calculations

Administrative costs are calculated using the following equation (27).

$$ACost = I + D * MCost \tag{27}$$

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 C for details). The percentage of annual maintenance costs is assumed to be 12%.

5.13. Cost Adjustments for Time

Cost data reported in the literature were adjusted for inflation to May 2008 dollars using Equation (28) with the 20-city average value of the ENR CCI (ENR 2008). Table 25 presents average annual 20-city ENR CCI values from 1986 to 2015.

$$Cost(present) = Cost(base\ year) \bullet \frac{ENRCCI(present)}{ENRCCI(base\_year)} \tag{28}$$

Table 25: Engineering News Record 20-city construction cost index (1986-2015)

Year	20-City ENR CCI	Year	20-City ENR CCI
1986	4295	2001	6343
1987	4406	2002	6538
1988	4519	2003	6694
1989	4615	2004	7115
1990	4732	2005	7446
1991	4835	2006	7751
1992	4985	2007	7966
1993	5210	**May 2008**	**8141**
1994	5408	2009	8570
1995	5471	2010	8799
1996	5620	2011	9070
1997	5826	2012	9308
1998	5920	2013	9547
1999	6059	2014	9806
2000	6221	2015	10036
Source: ENR (2016)			

5.14. 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 (29).

Table 26 presents the regional index and factor for each city for May 2008. The regional factor can vary over time; however, it is generally consistent over short time periods. Recently, the regional factor for Denver has been in the range of 0.7-0.75. This factor is useful for determining the regional ENR CCI when only the 20-City average ENR CCI is available.

$$Cost(regional) = Cost(national) \bullet \frac{ENRCCI(regional)}{ENRCCI(national)} \qquad \textbf{(29)}$$

Table 26: Engineering News Record regional cost indices (May 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
Source: ENR (2008)		

5.15. Net Present Cost Calculations

The net present costs (NPC) for all BMPs in a subcatchment, k, is computed using Equation (30):

$$NPC_k = N_{n,k}\left[\sum_{y=0}^{PH}\left[\begin{array}{l}(1 + CEA)CCost_{n,k} + LCost_{n,k} + \\ \left(RCost_{n,k}^y * RDF_{n,k}^y + MCost_{n,k}^y + ACost_{n,k}^y\right)\left(\frac{1 + IR_f}{1 + ROR_f}\right)^y\end{array}\right]\right] \quad (30)$$

where N = number of BMPs, CEA = contingencies/engineering/administrative costs (%), $CCost$ = construction costs ($), $LCost$ = land costs ($), $RCost$ = rehabilitation/replacement costs ($), $MCost$ = operation and maintenance costs ($), $ACost$ = administrative/management costs ($), PH = planning horizon (yrs), IR_f = average inflation rate (%)/100, ROR_f = average rate of return (%)/100, y = time from present (yrs), subscript n denotes the specific BMP type and subscript k denotes the individual subcatchment.

RDF is the rehabilitation cost discount factor (unitless) that "discounts" rehabilitation costs in years when the design life of the rehabilitated BMP exceeds the number of years remaining in the planning horizon, thus ensuring that the same number of years are used for both cost and benefit calculations. RDF is computed as

$$RDF_{n,k}^{y} = \begin{cases} 1 & if\,(PH - y) \geq DL \\ \left[\dfrac{IR_f\left(1 + IR_f\right)^{DL_n}}{\left(1 + IR_f\right)^{DL_n} - 1}\right]\left[\dfrac{\left(1 + ROR_f\right)^{(PH-y)}}{ROR_f\left(1 + ROR_f\right)^{(PH-y)}}\right] & if\,(PH - y) < DL \end{cases} \tag{31}$$

Where DL = design life of the BMP (years).

The NPC for a complete scenario with BMPs in multiple subcatchments is computed as

$$NPC_K = \sum_{k=1}^{K} NPC_k \tag{32}$$

where K = number of subcatchments. If a regional BMP is being evaluated for the scenario, then k = K = 1, reflecting that costs are computed for one BMP only.

5.15.1. 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%.

5.15.2. 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.

5.15.3. 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, a rough estimate of 5% was assumed. Rate of return may also be known as the Discount Rate.

5.16.   BMP Effectiveness Calculations

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

1. The reduction in annual runoff volume discharged to the receiving waters and,

2. The reduction in annual pollutant loading to the receiving waters

As explained in the following sections, both measures are computed in accordance with Strecker et al.'s (2001) recommendations for evaluating the effectiveness of BMPs.

5.16.1.   *Runoff Volume Reduction*

Runoff volume reduction RVR (ft^3/yr) is computed for each subcatchment k by

$$RVR_k = RVT_k - RVRW_k \qquad (33)$$

where RVT = total volume of runoff generated from a subcatchment (ft^3/yr) and $RVRW$ = the volume of runoff discharged to the receiving water (ft^3/yr). RVT (ft^3/yr) is computed by multiplying the average annual runoff depth, estimated using the Simple Method (Schueler 1987), by the subcatchment area

$$RVT_k = P * Pj * RC_{T,k} * CA_k \qquad (34)$$

where P = annual precipitation depth (in), Pj = fraction of annual storms producing runoff (value = 0.9 assuming 90% of annual precipitation produces runoff), RC_T (unitless) is the volumetric runoff coefficient computed using the subcatchment *total* imperviousness, and CA is the subcatchment total area (acres).

The total volume of runoff that reaches the inlet of downstream BMPs, $RVIN_T$ (ft^3/yr), can be computed by

$$RVIN_{T,k} = P * Pj * RC_{E,k} * CA_k \qquad (35)$$

where RC_E = volumetric runoff coefficient computed using the subcatchment *effective* imperviousness, which accounts for volume reduction due to source controls in the subcatchment.

Runoff that reaches the inlet of downstream BMPs is either fully treated by the BMP or bypasses full treatment when the BMP capacity is exceeded. The volume of runoff that receives full treatment, $RVIN_F$ (ft^3/yr), and the volume that bypasses treatment, $RVIN_B$ (ft^3/yr), can be computed using Equations (36) and (37)

$$RVIN_{F,k} = RVIN_{T,k} * \lambda_n / 100 \qquad (36)$$

$$RVIN_{B,k} = RVIN_{T,k} * (1 - \lambda_n / 100) \qquad (37)$$

where λ_n = BMP capture efficiency (%) for a BMP type n (Table 11). For storage BMPs designed to capture the WQCV and EURV, λ = 85% and 98% respectively. The former value is derived from the fundamental basis of the WQCV which is to capture 80-90% of the average annual runoff (UDFCD 2004) and the latter value from UDFCD modeling EURV results (UDFCD unpublished data). No studies could be found documenting λ for conveyance BMPs; therefore, *BMP-REALCOST* uses λ = 85% assuming that those BMPs are designed to effectively treat the same number of storms as storage BMPs designed for the WQCV. Methods for estimating λ for PPs are described below.

Finally, *RVRW* (ft^3/yr) is computed as

$$RVRW_k = RVIN_{F,k} * (1 - \theta_n/100) + RVIN_{B,k} \qquad \textbf{(38)}$$

where θ_n = is the percentage of $RVIN_F$ that is removed from the surface water system via infiltration and/or evapotranspiration in BMP type n (Table 11). θ values are defined for storage and conveyance BMPs based on the findings of Strecker et al. (2005) who reported values for the ratio of measured inflow/measured outflow for several BMPs using data contained in the International BMP Database and UDFCD (unpublished data) who estimated the same ratios for other BMPs. The methods used to derive θ values for PPs are described below.

If a regional BMP is being evaluated, then RC_T and RC_E in equations (34) and (35), respectively, are area-weighted values for all of the subcatchments and CA (in the same equations) is the sum of all subcatchment contributing areas; such that the calculated value of RVT is the total runoff volume generated from all subcatchments and $RVIN$ is the runoff volume reaching the regional BMP.

Permeable Pavement Capture Efficiency and Runoff Volume Reduction

Capture Efficiency

Very few studies have been conducted to assess the capture efficiency of permeable pavements. Those studies that have were limited to only a few of types of permeable pavements with no impervious run-on area and were conducted in regions (southeast and northwest US) with very different hydrology than Colorado. Given the lack of applicable field data, PP capture efficiencies were estimated based on experience and engineering judgment. Field experiences have shown that PPs have considerable infiltration capacity (at times exceeding tens or hundreds of inches per hour), enough to safely assume that 100% of runoff would be captured when the impervious run-on area:PP area (RAPP:SAPP) ratio is less than or equal to 5:1 (the maximum recommended for use in this model). However, experiences have also shown that incorrect construction (e.g. inadequate grading, "over-smoothing" of porous concrete, etc.) in some portions of the installation can result in some runoff being generated from PP installations. The extent of those construction errors has not been quantified; however, using engineering judgment, we have reasoned that construction errors may result in up to 5% of the annual runoff not being adequately captured on a PP area with no run-on area. Assuming the volume of runoff not captured due to construction errors would increase linearly as the RAPP:SAPP ratio was increased, the following equation was developed to estimate the capture efficiency of PPs under RAPP:SAPP ratios less than or equal to 5:1. The equation reflects a maximum capture efficiency of 95% assuming no impervious run-on area, declining linearly with increasing RAPP:SAPP ratios.

$$\lambda = \min(100\% - (RAPP/SAPP)*5\%, 95\%)$$

Runoff Volume Reduction

If the PP is designed to infiltrate all captured runoff, then 100% of the captured runoff will infiltrate and be removed from the surface water system. If the PP is underdrained, then a certain percentage of the infiltrated water will be underdrained and the remaining percentage will be removed from the surface water system via infiltration (if subbase is unlined) and/or ET. Unpublished data collected from UDFCD, using two different PP types with a 3:1 run-on:PP area ratio, suggests that approximately 40% of the captured runoff is lost due to infiltration and/or ET in unlined, underdrained systems. It should be noted that these installations contained sand filter layer approximately 6" thick. Intuitively, that percentage might increase with lower run-on:PP ratios and decrease with higher run-on:PP ratios, with some minimum value (~10%) that always occur due to water retention in the subbase pore space. The following function is used to estimate the percentage (θ) of infiltrate that is lost to infiltration and/or ET:

$$\theta = \max(50\% - (RAPP/SAPP)*3\%, 10\%)$$

5.16.2.   Pollutant Load Reduction

Pollutant load reduction, *PLR* (lb/yr), for a subcatchment *k* and pollutant *m* is computed as

$$PLR_{k,m} = PLT_{k,m} - PLRW_{k,m} \tag{39}$$

where *PLT* = total pollutant load generated from the subcatchment (lb/yr) and *PLRW* = pollutant load discharged to the receiving water (lb/yr). *PLT* is given by

$$PLT_{k,m} = RVT_{k,m} * EMCLU_{k,m} \tag{40}$$

where *RVT* = total runoff volume generated from the subcatchment (ft^3/yr) and *EMCLU* = pollutant event mean concentration (mg/L) assigned to the subcatchment land use classification (Table 27). The basis of these values is discussed in Section 4.2.2. An "Other" column is left blank to allow the user to enter in median EMCs for other water quality analytes.

Table 27: Land use median EMCs in stormwater runoff for Denver, CO

Analyte	Industrial	Commercial	Residential	Undeveloped
Total Suspended Solids (mg/L)	370	85	122	257
Total Kjeldahl Nitrogen (mg/L)	3.0	2.2	2.7	3.1
Total Nitrogen (mg/L)	3.6	2.9	3.9	3.8
Phosphorus as P, Total (mg/L)	0.30	0.19	0.42	0.41
Phosphorus as P, Dissolved (mg/L)	0.18	0.07	0.19	0.15
Nitrate Plus Nitrite (mg/L)	1.00	0.72	0.81	0.56
Copper, Total (ug/L)	46	13	15	20
Copper, Dissolved (ug/L)*	9	4	9	12
Zinc, Total (ug/L)	520	64	80	90
Zinc, Dissolved (ug/L)*	292	25	34	39
E. coli (MPN/100 mL)*	1,730	1,730	2,730	2,730
Source: UDFCD 2016, WWE 2015.				
*= Estimated values; dissolved metals calculated using ratios developed by Maestre et al. (2005)				

Similar to runoff volume, the pollutant load discharged to the receiving water is the sum of the "fully-treated" load and the "bypassed" load. Bypassed runoff is assumed to retain the concentrations of pollutants as generated from the subcatchment (*EMCLU*), whereas runoff treated by a BMP type *n* has effluent concentrations (*EMCeff*) unique to that BMP. Accordingly, *PLRW* (lb/yr) is computed as

$$PLRW_{k,m} = RVIN_{B,k} * EMCLU_{k,m} + RVIN_{F,k} * (1 - \theta_n/100) * EMCeff_{n,m} \tag{41}$$

where *RVIN$_B$* = runoff volume that bypasses BMP treatment (ft^3/yr), *EMCLU* = pollutant event mean concentration (mg/L) assigned to the subcatchment land use classification, *RVIN$_F$* = runoff volume that received full BMP treatment (ft^3/yr), θ_n = is the percentage

of $RVIN_F$ that is removed from the surface water system via infiltration and/or evapotranspiration in BMP type n and $EMCeff$ = pollutant event mean concentration (mg/L) assigned to the particular BMP type (Table 28). The International Stormwater BMP Database (www.bmpdatabase.org) provides median values of effluent EMCs from a variety of structural BMPs (WWE and Geosyntec 2017). With some modifications and assumptions (described in Appendix A), the model uses the reported values for $EMCeff$ values from each BMP.

If a regional BMP is being evaluated PLT_m is the sum of $PLT_{k,m}$ for all subcatchments; $RVIN_{B,k}$ and $RVIN_{F,k}$ are computed using $RVIN$ for a regional BMP (as discussed at the end of the *Runoff Volume Reduction* section of this paper); and $EMCLU_{k\,m}$ is the volume-weighted average EMC for runoff from all subcatchments for pollutant m.

5.16.3. Cost Effectiveness

The unit cost of reducing pollutant loads, $CPLR$ (\$/lb) and runoff volume, $CRVR$ (\$/ft^3), for an entire scenario (i.e. all subcatchments, k) over the planning horizon (PH) of a project can be computing using equations (42) and (43), respectively.

$$CPLR_m = \sum_{k=1}^{K} NPC_k \Big/ \left(PLR_{k,m} * PH \right) \tag{42}$$

$$CRVR = \sum_{k=1}^{K} NPC_k \Big/ \left(RVR_k * PH \right) \tag{43}$$

where NPC = net present costs (\$), PLR = pollutant load reduction (\$/lb), subscript m denotes the pollutant, RVR = runoff volume reduction (ft^3/yr), PFR = peak flow reduction (ft^3/yr).

Table 28: 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 Zinc (mg/L)	Dissolved Zinc (mg/L)	Total Copper (mg/L)	Dissolved Copper (mg/L)	E. coli (#/100mL)
Bioretention - Infiltration	10.0	0.24	1.04	1.39	0.0120	0.0139	0.0057	0.0013	240
Bioretention - Underdrain	10.0	0.24	1.04	1.39	0.0120	0.0139	0.0057	0.0013	240
Constructed Wetland Basin	14.1	0.12	1.42	0.84	0.0200	0.0076	0.0033	0.0024	1000
Constructed Wetland Channel	17.0	0.15	1.43	1.25	0.0200	0.0100	0.0062	0.0074	NR
Extended Detention Basin - WQCV	24.0	0.19	1.19	1.20	0.0229	0.0080	0.0050	0.0029	500
Extended Detention Basin - EURV	24.0	0.19	1.19	1.20	0.0229	0.0080	0.0050	0.0029	500
(U) Hydrodynamic Separator	36.0	0.20	2.30	1.60	0.0599	0.0430	0.0125	0.0089	NR
(U) Inlet Inserts	32.0	0.11	1.90	1.60	0.1250	0.0785	0.0140	0.0080	NR
(U) Media Filter Vault	12.0	0.07	0.80	0.57	0.0388	0.0267	0.0066	0.0042	240
Porous Concrete Pavement - Infiltration	26.0	0.11	1.19	1.00	0.0122	0.0017	0.0077	0.0051	NR
Porous Concrete Pavement - Underdrain	26.0	0.11	1.19	1.00	0.0122	0.0017	0.0077	0.0051	NR
Pervious Asphalt Pavement - Infiltration	26.0	0.11	1.19	1.00	0.0122	0.0017	0.0077	0.0051	NR
Pervious Asphalt Pavement - Underdrain	26.0	0.11	1.19	1.00	0.0122	0.0017	0.0077	0.0051	NR
PICP - Infiltration	26.0	0.11	1.19	1.00	0.0122	0.0017	0.0077	0.0051	NR
PICP - Underdrain	26.0	0.11	1.19	1.00	0.0122	0.0017	0.0077	0.0051	NR
Retention Pond - WQCV	11.7	0.09	1.20	1.00	0.0214	0.0150	0.0043	0.0032	170
Retention Pond - EURV	11.7	0.09	1.20	1.00	0.0214	0.0150	0.0043	0.0032	170
Sand Filter Basin - Infiltration	9.0	0.09	1.05	0.50	0.0141	0.0057	0.0055	0.0033	240
Sand Filter Basin - Underdrain	9.0	0.09	1.05	0.50	0.0141	0.0057	0.0055	0.0033	240
(U) Sand Filter Vault	9.0	0.09	1.05	0.50	0.0141	0.0057	0.0055	0.0033	240
(U) Sediment/Oil/Grease Separator	25.1	0.11	2.70	1.30	0.0528	0.0430	0.0041	0.0089	NR
(U) Vault w/ Capture Volume	5.0	0.04	1.19	0.85	0.0790	0.0657	0.0148	0.0063	NR

Values derived from International Stormwater BMP Database (WWE and Geosyntec 2017).

NR = no reduction expected, outflow concentration assumed equal to inflow concentration.

Table 29: Summary of BMPs that provide peak flow attenuation

BMP	Peak Flow Attenuation
Bioretention	Yes
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
Retention (Wet) Pond (WQCV)	Yes
Retention (Wet) Pond (EURV)	Yes
Sand Filter Basin	Yes
Sand Filter Vault	No

6. <u>REFERENCES</u>

AbTech Industries (2009). "Ultra Urban Filter with SmartSponge Brochure and Technical Specifications." http://www.geoproductsinc.com/sales%20brochures/Ultraurban_filters_brochure &spec.pdf. (Accessed August 2009).

ADS (2009). "FlexStorm Inlet Filters". http://www.inletfilters.com/. (Accessed August 2009).

Contech (2009). "Operation and Maintenance Guidelines for CatchBasin StormFilter". http://www.contech-cpi.com/media/assets/asset/file_name/490/op_maint_sf_cb.pdf. (Accessed August 2009).

Engineering News Record. (2016). "Construction Cost Index History." <http://enr.construction.com/economics/historical_indices/default.asp>. (Accessed August 2016).

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, 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.

Gibbs, J. 1981. *Hydrologic Data for Urban Storm Runoff from Nine Sites in the Denver Metropolitan Area, Colorado, USGS Open File Report 81-682.*

Gibbs, J. and Doerfer, J. 1982. *Hydrologic Data for Urban Storm Runoff in the Denver Metropolitan Area, Colorado, USGS Open File Report 82-872.*

International Stormwater BMP Database (2016). International Stormwater BMP Database, November 2016, accessed from www.bmpdatabase.org. Project sponsored by the Water Environment Research Foundation, Environmental and Water Resources Institute of the American Society of Civil Engineers, Federal Highway Administration, U.S. Environmental Protection Agency and American Public Works Association. Maintained by Wright Water Engineers and Geosyntec Consultants.

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.

Maestre, A. and Pitt, R. (2015). National Stormwater Quality Database Version 4.02, accessible at: http://www.bmpdatabase.org/nsqd.html.

Muller Engineering. (2009). "Permanent BMP Construction Cost Estimates Memorandum." Lakewood, CO.

Municipal Water Infrastructure Council of the Environmental and Water Resources Institute of the American Society of Civil Engineers (2017). Green Infrastructure Maintenance Cost Survey. Cosponsored by Urban Drainage and Flood Control District. Eds. Jane Clary and Holly Piza.

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.

National Oceanic and Atmospheric Administration (NOAA) (2013). NOAA Atlas 14 Point Precipitation Frequency Estimates: CO Accessible at: http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=co.

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.

Strecker, E., Quigley, M., Urbonas, B., Jones, J., Clary, J. (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.

Urban Drainage and Flood Control District (UDFCD). (2016). *Urban Storm Drainage Criteria Manual, Volumes 1-3*. Denver, CO. www.udfcd.org

USDOT. (2002). "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).

U.S. Environmental Protection Agency, 1983. Results of Nationwide Urban Runoff Program, Volume 1, Final Report.

Wright Water Engineers (2015). Technical Memorandum to City and County of Denver Summarizing *E. coli* Values for Use in BMP REAL COST.

Wright Water Engineers and Geosyntec Consultants (2017). International Stormwater BMP Database Summary Statistics. Prepared for Urban Drainage and Flood Control District and City and County of Denver. BMP Database Co-sponsors include Water Environment Reuse Foundation, Federal Highway Administration and the Environmental and Water Resources Institute of the American Society of Civil Engineers. Accessible at www.bmpdatabase.org.

Wright Water Engineers, Geosyntec Consultants, Pitt, R. and Roesner, L. 2013. Colorado Regulation 85 Nutrient Data Gap Analysis Report. December.