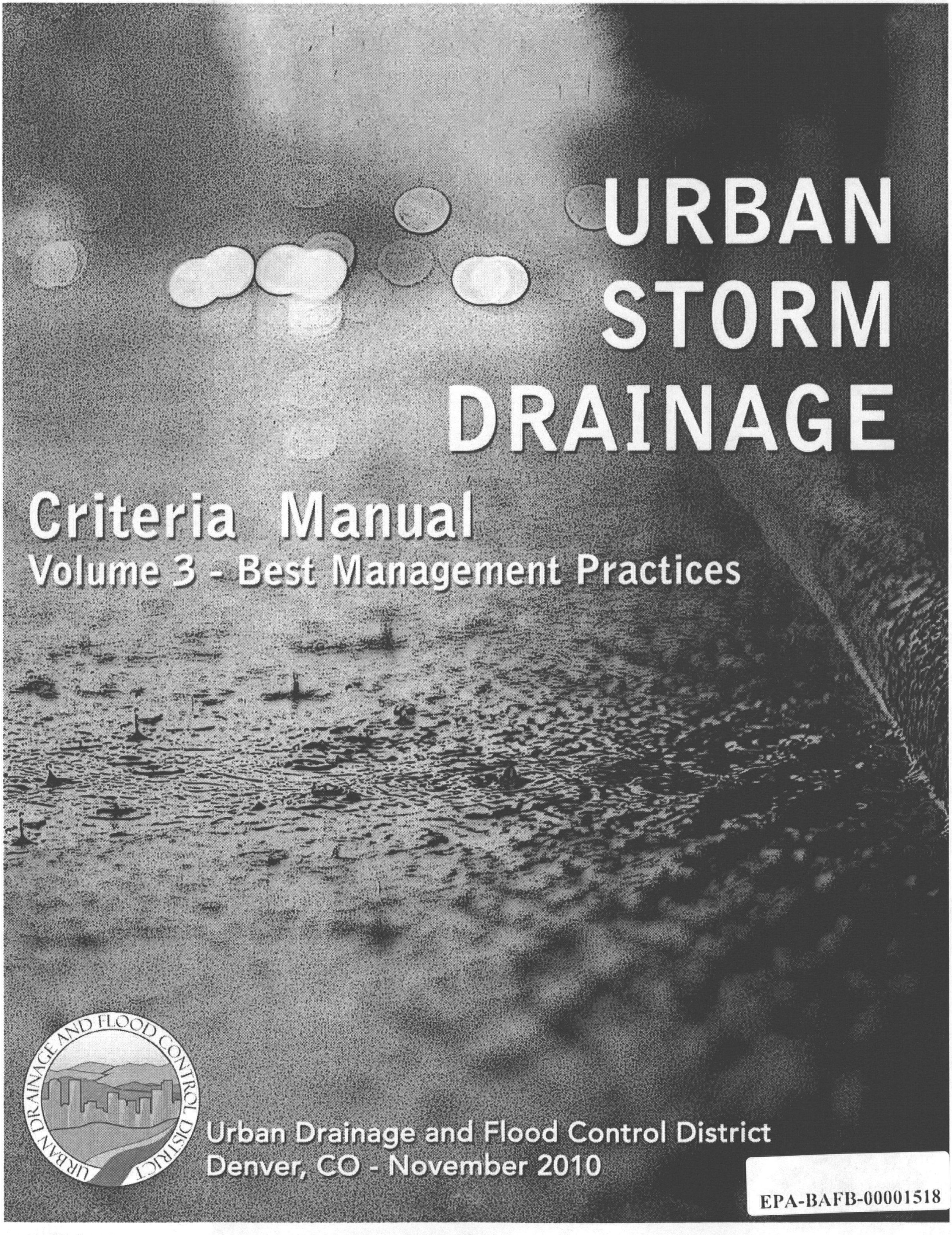

URBAN STORM DRAINAGE

Criteria Manual

Volume 3 - Best Management Practices

Urban Drainage and Flood Control District
Denver, CO - November 2010

Urban Storm Drainage Criteria Manual
Volume 3, Best Management Practices

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2480 West 26th Avenue, Suite 156B
Denver, Colorado 80211
www.udfcd.org

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By Urban Drainage and Flood Control District

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Preface

Contents

1.0 Acknowledgements

The Urban Storm Drainage Criteria Manual (USDCM), Volume 3, was first released in 1992 under the direction and leadership of Ben Urbonas, P.E., D.WRE. Although Mr. Urbonas retired from the Urban Drainage and Flood Control District (UDFCD) in 2008, he continued to serve as an advisor throughout the 2010 revision to Volume 3, for which we are grateful. This update builds upon the core philosophy, principles and practices developed by Mr. Urbonas and others in previous releases of Volume 3.

This revised and updated guidance manual is the product of an 18-month long process that included a large stakeholder committee, a technical advisory committee, and several core groups of experts in various aspects of stormwater management. These engineers, stormwater coordinators, planners and regulators represented government at every level during this process. Stormwater and land development professionals, as well as consulting engineers and landscape architects throughout Colorado also provided valuable input. UDFCD wishes to acknowledge and to thank all individuals and organizations that contributed to the development of this manual. The list of contributors is too long to acknowledge and thank everyone individually, for which we apologize.

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Urban Drainage and Flood Control District

Paul A. Hindman, PE, CFM	Executive Director
Ken MacKenzie, PE, CFM	Editor In Chief
Holly Piza, PE	Lead Author
Shea Thomas, PE	Overall Review
Ben Urbonas, PE, D.WRE (retired)	Advisor
Darren Bradshaw	AutoCAD® Details
Ramon Martinez	AutoCAD® Details
Margaret Corkery	Administrative Assistant
Michelle DeLaria	Contributing Author

Wright Water Engineers Team

T. Andrew Earles, PhD, PE, D.WRE	Co-author and Review
Jane Clary, LEED AP, CPESC	Co-author and Review
Jonathan Jones, PE, D.WRE	Advisor
Hayes Lenhart	AutoCAD® Details
Shannon Tillack	UD-BMP Workbook

Colorado State University	Larry Rosner
Design Concepts	Axel Bishop
Kumar & Associates	Greg Monley
Kumar & Associates	Alan Claybourn
Muller Engineering Company	Jim Wulliman
University of Colorado	James Guo

Public Agency Review/Contributors

Adams County
Arapahoe County
City of Arvada
City of Aurora
Boulder County
City and County of Broomfield
City of Castle Rock
Cherry Creek Basin Water Quality Authority
Colorado Department of Public Health and Environment
Colorado State University
Colorado Stormwater Council
City and County of Denver
Denver Botanic Gardens
Douglas County
Environmental Protection Agency, Region 8
City of Fort Collins
City of Golden
City of Greenwood Village
Jefferson County
City of Lakewood
City of Littleton
City of Loveland
City of Lone Tree
City of Northglenn
Town of Parker
Southeast Metro Stormwater Authority
University of Colorado
City of Westminster

Additional Contributors/Reviewers

Adam Nelson
Alan Searcy
Amy Schneider
Ashley Byerley
Basil Hamdan
Ben Mehmen
Bernie Cawley
Bill McCormick
Bill Ruzzo
Bill Wenk
Billy Grigg
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Pieter Van Ry
Rich Borchardt
Robert Krehbiel
Saeed Farahmandi
Stacey Thompson
Suzanne Moore
Tanna Boisvert
Ted Christianson
Terri Kohls
Terry Baus
Tom Williams
Walt Hime
Ward Mahanke

2.0 Purpose

Volume 3 of the Urban Storm Drainage Criteria Manual (USDCM) is designed to provide guidance for engineers, planners, landscape architects, developers, and Municipal Separate Storm Sewer System (MS4) permit holders in selecting designing, maintaining, and carrying out best management practices (BMPs) to minimize water quality and quantity impacts from stormwater runoff. Whereas Volumes 1 and 2 of this manual focus primarily on stormwater quantity management for drainage and flood control purposes, Volume 3 focuses on smaller, more frequently occurring events that have the greatest overall impact on the quality of receiving waters.

3.0 Overview

This manual is organized according to these topics:

- **Chapter 1: Stormwater Management and Planning.** In order to effectively design stormwater quality BMPs, it is important to understand the impacts of urbanization on receiving waters, as well as to understand the federal and state regulatory requirements under the Clean Water Act. Chapter 1 provides basic information on these topics and introduces UDFCD's approach to reducing the impacts of urban runoff through implementation of a holistic Four Step Process (see inset below). UDFCD continues to emphasize the importance of implementing all four steps in this process. Chapter 1 provides expanded guidance on Step 1 (Runoff Reduction), which has historically been implemented only minimally, but will be increasingly important to comply with new federal regulations and state stormwater discharge permits.

The Four-Step Process for Stormwater Quality Management

Step 1 Employ Runoff Reduction Practices: To reduce runoff peaks, volumes, and pollutant loads from urbanizing areas, implement Low Impact Development (LID) strategies, including measures to "minimize directly connected impervious areas" (MDCIA). These practices reduce unnecessary impervious areas and route runoff from impervious surfaces over permeable areas to slow runoff (increase time of concentration) and promote onsite storage and infiltration.

Step 2 Implement BMPs that Provide a Water Quality Capture Volume (WQCV) with Slow Release: After runoff has been reduced, the remaining runoff must be treated through capture and slow release of the WQCV. WQCV facilities may provide both water quality and runoff reduction benefits, depending on the BMP selected. This manual provides design guidance for BMPs providing treatment of the WQCV.

Step 3 Stabilize Drainageways: During and following urban development, natural drainageways are often subject to bed and bank erosion due to increases in the frequency, rate, duration, and volume of runoff. Although Steps 1 and 2 help to minimize these effects, some degree of drainageway stabilization is required. Many drainageways within UDFCD boundaries are included in major drainageway or outfall systems plans, identifying recommended channel stabilization measures. If this can be done early, it is far more likely that natural drainageway functions can be maintained with the addition of grade control to accommodate future development. It is also less costly to stabilize a relatively stable drainageway rather than to repair an unraveled channel.

Step 4 Implement Site Specific and Other Source Control BMPs: Frequently, site-specific needs or operations require source control BMPs. This refers to implementation of both structural and procedural BMPs.

- **Chapter 2: BMP Selection.** Long-term effectiveness of BMPs depends not only on proper engineering design, but also on selecting the right combination of BMPs for the site conditions. In addition to physical factors, other factors such as life cycle costs and long-term maintenance requirements are also important considerations for BMP selection. This chapter provides information to aid in BMP selection and provides the foundation for the *UD-BMP* and *BMP-REALCOST* design aid tools that accompany this manual.
- **Chapter 3: Calculation the WQCV and Volume Reduction.** Chapter 3 provides the computational procedures necessary to calculate the WQCV, forming the basis for design of many treatment BMPs. This chapter also covers the Excess Urban Runoff Volume (EURV) and full spectrum detention, developed to best replicate predevelopment peak flows. Additionally, procedures for quantifying runoff reduction due to the implementation of practices that reduce the effective imperviousness of the site are also provided. These procedures provide incentive to implement MDCIA practices and LID strategies.
- **Chapter 4: Treatment BMPs.** Chapter 4 provides design criteria for a variety of BMPs, generally categorized as conveyance practices and storage practices that provide treatment of the WQCV or EURV. A BMP Fact Sheet is provided for each BMP, providing step-by-step design criteria, design details, an accompanying design worksheet, and selection guidance related to factors such as performance expectations, site conditions and maintenance requirements.
- **Chapter 5: Source Control BMPs.** It is generally more effective to prevent pollutants from coming into contact with precipitation and/or from being transported in urban runoff than it is to remove these pollutants downstream. For this reason, guidance is provided on a variety of source control BMPs, which can be particularly beneficial for municipal operations and at industrial and commercial sites. Source controls and good housekeeping practices are also required under MS4 permits.
- **Chapter 6: BMP Maintenance.** Long-term effectiveness and safety of BMPs is dependent on both routine maintenance and periodic rehabilitation. Maintenance recommendations are provided for each post-construction treatment BMP in this manual.
- **Chapter 7: Construction BMPs.** Many different types of BMPs are available for use during construction. This chapter provides design details and guidance for appropriate use of these temporary BMPs.

Volume 3 BMPs

Treatment BMPs

Grass Swale
Grass Buffer
Bioretention/Rain Garden*
Green Roof
Extended Detention Basin
Retention Pond
Sand Filter
Constructed Wetland Pond
Constructed Wetland Channel
Permeable Pavement Systems
Underground BMPs

Source Control BMPs

Covering Outdoor Storage & Handling Areas
Spill Prevention, Containment and Control
Disposal of Household Waste
Illicit Discharge Controls
Good Housekeeping
Preventative Maintenance
Vehicle Maintenance, Fueling & Storage
Use of Pesticides, Herbicides and Fertilizers
Landscape Maintenance
Snow and Ice Management
Street Sweeping and Cleaning
Storm Sewer System Cleaning

**Referred to as Porous Landscape Detention in Previous Releases of Volume 3*

- **Glossary:** A glossary is included to provide users of Volume 3 with a basic understanding of terms used in this manual.

- **Bibliography:** Many references have been used to develop this Manual. The Bibliography provides a listing of these references for more detailed information on key topics.

4.0 Revisions to USDCM Volume 3

Volume 3 of the USDCM has been updated and expanded several times since it was first published in 1992 as our understanding of urban hydrology and BMP performance expanded, and as the design of various BMPs has been refined. Updates will continue as the needs of communities and regulatory requirements change, and as UDFCD continues to build, use, and monitor BMPs. In 2010, this major revision to Volume 3 was completed, including the following:

- Increased emphasis on runoff reduction, which is Step 1 of the Four Step Process. Although UDFCD has previously included runoff reduction as the first step in stormwater management, this step has not been routinely implemented. A significant change to the manual includes quantifying stormwater management facility sizing credits using quantitative methods when MDCIA and LID practices are implemented.

- Substantial revision to design criteria for several BMPs already in this manual and inclusion of BMPs not previously in this manual. Green roofs and Underground BMPs were added. Although UDFCD continues to strongly recommend treatment of runoff above ground, we also recognize the need to provide guidance related to underground BMPs when surface treatment is not practicable.

- Revision and expansion of the Construction BMPs chapter.

- Addition of supplemental guidance to promote more effective implementation of BMPs. This information is typically provided in the form of "call-out" boxes. While this manual remains focused on engineering design criteria, UDFCD also recognizes that it is helpful for designers to be aware of why certain criteria have been developed, how various practices can best be implemented on a site, opportunities to consider, and common problems to avoid.

- New Excel® worksheets to assist in BMP selection based on site-specific conditions, BMP design including integration of the EURV for use with full spectrum detention, and BMP performance expectations and life cycle costs.

5.0 Acronyms and Abbreviations

>	Greater Than
<	Less Than
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BOD	Biochemical Oxygen Demand
BMPs	Best Management Practices
CDPHE	Colorado Department of Public Health and Environment
CDPS	Colorado Discharge Permit System
cfs	Cubic Feet Per Second
COD	Chemical Oxygen Demand
CRS	Colorado Revised Statutes
CSO	Combined Sewer Overflow
CUHP	Colorado Urban Hydrograph Procedure
CWC	Constructed Wetland Channel
CWCB	Colorado Water Conservation Board
CWQCC	Colorado Water Quality Control Commission
CWQCD	Colorado Water Quality Control Division
DCIA	Directly Connected Impervious Areas
DO	Dissolved Oxygen
DRCOG	Denver Regional Council of Governments
DRURP	Denver Regional Urban Runoff Program
EDB	Extended Detention Basin
EMC	Event Mean Concentration
EPA	U.S. Environmental Protection Agency
ET	Evapotranspiration
EURV	Excess Urban Runoff Volume

fps	Feet per second
ft	Feet
FHWA	Federal Highway Administration
GB	Grass Buffer
GS	Grass Swale
H:V	Horizontal to Vertical Ratio of a Slope
HSG	Hydrologic Soil Group
i	Impervious Ratio of a Catchment (I_a/100)
I_a	Percent Imperviousness of Catchment
LEED	Leadership in Energy and Environmental Design
LID	Low Impact Development
MCM	Minimum Control Measure
mg/L	Milligrams per Liter
µg/L	Micrograms per Liter
MDCIA	Minimize Directly Connected Impervious Areas
MS4	Municipal Separate Storm Sewer System
MSDS	Material Safety Data Sheets
MWCOG	Metropolitan Washington Council of Governments
N/A	Not applicable
NPDES	National Pollution Discharge Elimination System
NPV	Net Present Value
NRCS	Natural Resources Conservation Services
NTIS	National Technical Information Service
NTU	Nephelometric turbidity units
NURP	Nationwide Urban Runoff Program
NVDPC	Northern Virginia District Planning Commission
PA	Porous Asphalt

PC	Pervious Concrete
PICP	Permeable Interlocking Concrete Pavers
PLD	Porous Landscape Detention *(term replaced by Bioretention in 2010 update)*
PPS	Pervious Pavement System
ppm	Parts Per Million
RP	Retention Pond
RPA	Receiving Pervious Area
SCS	Soil Conservation Service (now the NRCS)
SEWRPC	Southeastern Wisconsin Regional Planning Commission
SF	Sand Filter Extended Detention
SPA	Separate Pervious Area
SWMM	Stormwater Management Model (EPA)
TOC	Total Organic Carbon
TMDL	Total Maximum Daily Load
TP	Total Phosphorus
TSS	Total Suspended Solids
UDFCD	Urban Drainage and Flood Control District
UIA	Unconnected Impervious Area
USCC	United States Composting Council
USDCM	Urban Storm Drainage Criteria Manual
USGS	United States Geological Survey
WERF	Water Environment Research Foundation
WQCV	Water Quality Capture Volume

Chapter 1
Stormwater Management and Planning

Contents

Figures

Tables

1.0 Introduction

The physical and chemical characteristics of stormwater runoff change as urbanization occurs, requiring comprehensive planning and management to reduce adverse effects on receiving waters. As stormwater flows across roads, rooftops, and other hard surfaces, pollutants are picked up and then discharged to streams and lakes. Additionally, the increased frequency, flow rate, duration, and volume of stormwater discharges due to urbanization can result in the scouring of rivers and streams, degrading the physical integrity of aquatic habitats, stream function, and overall water quality (EPA 2009). This chapter provides information fundamental to effective stormwater quality management and planning, including:

- An overview of the potential adverse impacts of urban stormwater runoff.
- A summary of key regulatory requirements for stormwater management in Colorado. These regulations set the minimum requirements for stormwater quality management. It is essential that those involved with stormwater management understand these requirements that shape stormwater management decisions at the construction and post-construction stages of development and redevelopment.
- UDFCD's Four Step Process to reduce the impacts of urban runoff.
- Discussion of on-site, sub-regional, and regional stormwater management alternatives at a planning level.

UDFCD highly recommends that engineers and planners begin the development process with a clear understanding of the seriousness of stormwater quality management from regulatory and environmental perspectives, and implement a holistic planning process that incorporates water quality upfront in the overall site development process. Chapters 2 and 3 provide BMP selection tools and detailed calculation procedures based on the concepts introduced in this chapter.

2.0 Urban Stormwater Characteristics

Numerous studies conducted since the late 1970s show stormwater runoff from urban and industrial areas can be a significant source of pollution (EPA 1983; Driscoll et al. 1990; Pitt et al. 2008). Stormwater impacts can occur during both the construction and post-construction phases of development. As a result, federal, state, and local regulations have been promulgated to address stormwater quality. Although historical focus of stormwater management was either flooding or chemical water quality, more recently, the hydrologic and hydraulic (physical) changes in watersheds associated with urbanization are recognized as significant contributors to receiving water degradation. Whereas only a few runoff events per year may occur prior to development, many runoff events per year may occur after urbanization (Urbonas et al. 1989). In the absence of controls, runoff peaks and volumes increase due to urbanization. This increased runoff is environmentally harmful, causing erosion in receiving streams and generating greater pollutant loading downstream. Figure 1-1 illustrates the many physical factors associated with stormwater runoff and the responses of receiving waters.

With regard to chemical water quality, Table 1-1 identifies a variety of pollutants and sources often found in urban settings such as solids, nutrients, pathogens, dissolved oxygen demands, metals, and oils. Several national data sources are available characterizing the chemical quality of urban runoff (e.g., EPA 1983; Pitt 2004). For purposes of this manual, Denver metro area data are the primary focus. In 1983, the Denver Regional Urban Runoff Program (DRURP) conducted by the Denver Regional Council of Governments (DRCOG), provided data for nine watersheds with various land uses for 15 constituents of concern and for U.S. Environmental Protection Agency (EPA) "Priority Pollutants." In 1992, additional urban stormwater monitoring was completed by UDFCD in support of the Stormwater National Pollutant Discharge Elimination System (NPDES) Part 2 Permit Application Joint Appendix (City of Aurora et al. 1992) for the Denver area communities affected by the Phase I stormwater regulation. Table 1-2 contains a summary of the results of these monitoring efforts, followed by a discussion of key findings from the DRURP study and other research since that time.

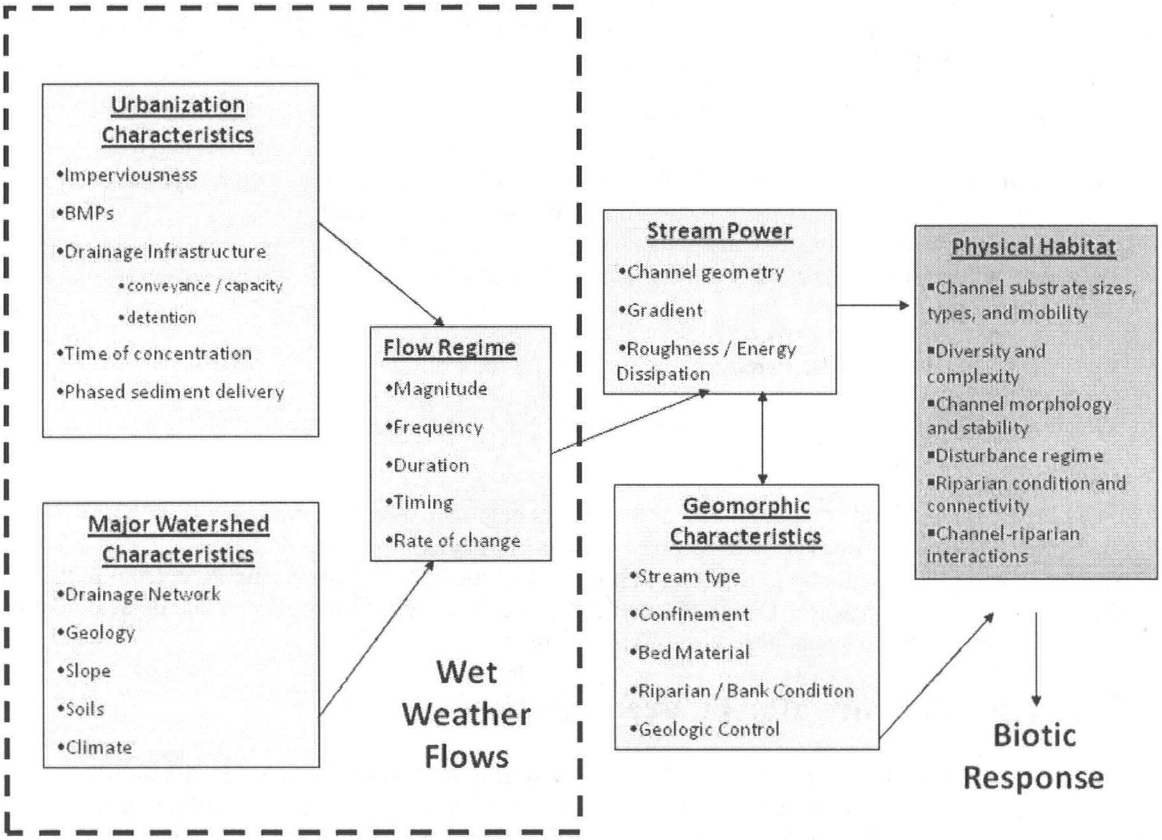

Figure 1-1. Physical Effects of Urbanization on Streams and Habitat

(Source: Roesner, L. A. and B. P. Bledsoe. 2003. *Physical Effects of Wet Weather Flows on Aquatic Habitats.* Water Environment Research Foundation: Alexandria, VA. Co-published by IA Publishing: United Kingdom.)

Table 1-1. Common Urban Runoff Pollutant Sources

(Adapted form: Horner, R.R., J.J. Skupien, E.H. Livingston and H.E. Shaver. 1994. *Fundamentals of Urban Runoff Management: Technical and Intuitional Issues*. Washington, DC: Terrene Institute and EPA.)

Pollutant Category Source	Solids	Nutrients	Pathogens	Dissolved Oxygen Demands	Metals	Oils	Synthetic Organics
Soil erosion	X	X		X	X		
Cleared vegetation	X	X		X			
Fertilizers		X	X	X			
Human waste	X	X	X	X			
Animal waste	X	X	X	X			
Vehicle fuels and fluids	X			X	X	X	X
Fuel combustion						X	
Vehicle wear	X			X	X		
Industrial and household chemicals	X	X		X	X	X	X
Industrial processes	X	X		X	X	X	X
Paints and preservatives					X	X	X
Pesticides				X	X	X	X
Stormwater facilities w/o proper maintenance[1]	X	X	X	X	X	X	X

Table 1-2. Event Mean Concentrations (mg/L) of Constituents in Denver Metropolitan Area Runoff
(per DRURP and Phase I Stormwater CDPS Permit Application for Denver, Lakewood and Aurora)
(Source: Aurora et al. 1992. *Stormwater NPDES Part 2 Permit Application Joint Appendix*
and DRCOG 1983. *Urban Runoff Quality in the Denver Region.*

Constituent	Units	Natural Grassland	Commercial	Residential	Industrial
Total Phosphorus (TP)	mg/L	0.40	0.42	0.65	0.43
Dissolved or Orthophosphorus (PO_4)	mg/L	0.10	0.15	0.22	0.2
Total Nitrogen (TN)	mg/L	3.4	3.3	3.4	2.7
Total Kjeldahl Nitrogen (TKN)	mg/L	2.9	2.3	2.7	1.8
Ammonia Nitrogen (NH_3)	mg/L	0.1	1.5	0.7	1.2
Nitrate + Nitrite Nitrogen (NO_3/NO_2)	mg/L	0.50	0.96	0.65	0.91
Lead (Total Recoverable) (Pb)	µg/L	0.100	0.059	0.053	0.130
Zinc (Total Recoverable) (Zn)	µg/L	0.10	0.24	0.18	0.52
Copper (Total Recoverable) (Cu)	µg/L	0.040	0.043	0.029	0.084
Cadmium (Total Recoverable) (Cd)	µg/L	Not Detected	0.001	Not Detected	0.003
Chemical Oxygen Demand (COD)	mg/L	72	173	95	232
Total Organic Carbon (TOC)	mg/L	26	40	72	22-26
Total Suspended Solids (TSS)	mg/L	400	225	240	399
Total Dissolved Solids (TDS)	mg/L	678	129	119	58
Biochemical Oxygen Demand (BOD)	mg/L	4	33	17	29

Selected findings of DRURP include:

- Urban runoff was identified as a significant source of stormwater pollutants including sediment, fecal indicator bacteria, nutrients, organic matter, and heavy metals (e.g., lead, zinc, cadmium). Sediment loading occurred regardless of the existence of major land disturbances causing erosion. In addition, nutrients from urban runoff were identified as a concern for lakes and reservoirs.
- Very few EPA Priority Pollutants were detected in runoff samples. Organic pollutants found were particularly sparse; the most commonly occurring was a pesticide. The most significant non-priority pollutant found was 2,4-D, which is an herbicide.
- Pollutant loading was not closely related to basin imperviousness or land use. Vague relationships between event mean concentrations and imperviousness were noted, but proved statistically insignificant. Concentrations of pollutants did not vary in a predictable or anticipated pattern.
- Non-storm urban runoff (e.g., dry weather discharges such as irrigation runoff) was also identified as a source of pollutants. This was not expected and was determined indirectly in the study analysis.

In addition to these pollutants, Urbonas and Doerfer (2003) have reported that atmospheric fallout is a significant contributor to urban runoff pollution in the Denver area. Snow and ice management activities also affect the quality of urban runoff since snow and ice may be contaminated by hydrocarbons, pet waste, deicing chemicals and sand.

Although Table 1-2 indicates that constituent concentrations in urban runoff in the metro Denver area are not necessarily greater than that for natural grasslands (background) for some constituents (e.g., TSS, TDS, TKN), it is important to recognize that the table does not provide data on pollutant loads, which are the product of runoff volume and pollutant concentrations. Runoff volume from urbanized areas is much greater than that from a natural grassland; therefore, resultant differences in pollutant loads are generally greater than the difference in concentrations.

Stormwater runoff issues can be discussed in general terms for both streams and lakes; however, there are some unique effects with regard to lakes. Some of these include:

- Lakes respond to cumulative pollutant loading over time in terms of days, weeks, and longer time frames, unlike streams, which typically show effects within hours or days.
- Floating trash and shore damage are notable visible impacts of stormwater on lakes.
- Nutrient enrichment from stormwater runoff can have a significant water quality impact on lakes. This can result in the undesirable growth of algae and aquatic plants, increasing BOD and depleting dissolved oxygen.
- Lakes do not flush contaminants as quickly as streams and act as sinks for nutrients, metals, and sediments. This means that lakes take longer to recover once contaminated.

With regard to construction-phase stormwater runoff, EPA reports sediment runoff rates from construction sites can be much greater than those from agricultural lands and forestlands, contributing large quantities of sediment over a short period of time, causing physical and biological harm to receiving waters (EPA 2005). Fortunately, a variety of construction-phase and post-construction BMPs are available to help minimize the impacts of urbanization. Proper selection, design, construction and maintenance of these practices are the focus of the remainder of this manual.

Additional Resources Regarding Urban Stormwater Issues and Management

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3.0 Stormwater Management Requirements under the Clean Water Act

3.1 Clean Water Act Basics

The Federal Water Pollution Control Act of 1972, as amended (33 U.S.C. 1251 et seq.) is commonly known as the Clean Water Act and establishes minimum stormwater management requirements for urbanized areas in the United States. At the federal level, the EPA is responsible for administering and enforcing the requirements of the Clean Water Act. Section 402(p) of the Clean Water Act requires urban and industrial stormwater be controlled through the NPDES permit program. Requirements affect both construction and post-construction phases of development. As a result, urban areas must meet requirements of Municipal Separate Storm Sewer System (MS4) permits, and many industries and institutions such as state departments of transportation must also meet NPDES stormwater permit requirements. MS4 permittees are required to develop a Stormwater Management Program that includes measurable goals and to implement needed stormwater management controls (i.e., BMPs). MS4 permittees are also required to assess controls and the effectiveness of their stormwater programs and to reduce the discharge of pollutants to the "maximum extent practicable." Although it is not the case for every state, the EPA has delegated Clean Water Act authority to the State of Colorado. The State must meet the minimum requirements of the federal program.

3.2 Colorado's Stormwater Permitting Program

The Colorado Water Quality Control Act (25-8-101 et seq., CRS 1973, as amended) established the Colorado Water Quality Control Commission (CWQCC) within the Colorado Department of Public Health and Environment (CDPHE) to develop water quality regulations and standards, classifications of state waters for designated uses, and water quality control regulations. The Act also established the Colorado Water Quality Control Division (CWQCD) to administer and enforce the Act and administer the discharge permit system, among other responsibilities. Violations of the Act are subject to significant monetary penalties, as well as criminal prosecution in some cases.

Colorado's stormwater management regulations have been implemented in two phases and are included in *Regulation No. 61 Colorado Discharge Permit System (CDPS) Regulations* (CWQCC 2009). After the 1990 EPA "Phase I" stormwater regulation became effective, Colorado was required to develop a stormwater program that covered specific types of industries and storm sewer systems for municipalities with populations of more than 100,000. Phase I affected Denver, Aurora, Lakewood, Colorado Springs, and the Colorado Department of Transportation (CDOT). Phase 1 requirements included inventory of stormwater outfalls, monitoring and development of municipal stormwater management requirements, as well as other requirements. Construction activities disturbing five or more acres of land were required to obtain construction stormwater discharge permits.

Phase II of Colorado's stormwater program was finalized in March 2001, establishing additional stormwater permitting requirements. Two major changes included regulation of small municipalities ($\geq$ 10,000 and <100,000 population) in urbanized areas and requiring construction permits for sites disturbing one acre or more. The Phase II regulation resulted in a large number of new permit holders including MS4 permits for almost all of the metro Denver area communities. MS4 permit holders are required to develop, implement, and enforce a CDPS Stormwater Management Program designed to reduce the discharge of pollutants from the MS4 to the maximum extent practicable, to protect water quality, and to satisfy the appropriate water quality requirements of the Colorado Water Quality Control Act (25-8-101 et seq., C.R.S.) and the Colorado Discharge Permit Regulations (Regulation 61).

The CWQCD administers and enforces the requirements of the CDPS stormwater program, generally including these general permit categories:

- **Municipal**: CDPS General Permit for Stormwater Discharges Associated with Municipal Separate Storm Sewer Systems (MS4s) (Permit No. COR-090000). The CWQCD has issued three municipal general permits:
    1. A permit for MS4s within the Cherry Creek Reservoir Basin,
    2. A permit for other MS4s statewide, and
    3. A permit specifically for non-standard MS4s. (Non-standard MS4s are publicly owned systems for facilities that are similar to a municipality, such as military bases and large education, hospital or prison complexes.)
- **Construction**: CDPS General Permit for Stormwater Discharges Associated with Construction Activity (Permit No. COR-030000).
- **Industrial**: CDPS General Permits are available for light industry, heavy industry, metal mining, sand and gravel, coal mining and the recycling industries.

The Phase II municipal MS4 permits require implementation of six minimum control measures (MCM):

1. Public education and outreach on stormwater impacts
2. Public involvement/participation
3. Illicit connections and discharge detection and elimination
4. Construction site stormwater management
5. Post-construction stormwater management in new development and redevelopment
6. Pollution prevention/good housekeeping for municipal operations

This manual provides guidance to address some of the requirements for measures 4, 5, and 6.

Resources for More Information on Colorado's Stormwater Regulations

CDPHE Stormwater Permitting Website: http://www.cdphe.state.co.us/wq/permitsunit/

CDPHE Regulation No. 61 Colorado Discharge Permit System Regulations:

http://www.cdphe.state.co.us/regulations/wqccregs/100261dischargepermitsystem.pdf

Colorado's Stormwater Program Fact Sheet:

http://www.cdphe.state.co.us/wq/PermitsUnit/POLICYGUIDANCEFACTSHEETS/factsheets/SWFactsheet.pdf

Common Stormwater Management Terms

Best Management Practice (BMP): A device, practice, or method for removing, reducing, retarding, or preventing targeted stormwater runoff constituents, pollutants, and contaminants from reaching receiving waters. (Some entities use the terms "Stormwater Control Measure," "Stormwater Control," or "Management Practice.")

Low Impact Development (LID): LID is a comprehensive land planning and engineering design approach to managing stormwater runoff with the goal of mimicking the pre-development hydrologic regime. LID emphasizes conservation of natural features and use of engineered, on-site, small-scale hydrologic controls that infiltrate, filter, store, evaporate, and detain runoff close to its source. The terms Green Infrastructure and Better Site Design are sometimes used interchangeably with LID.

LID Practice: LID practices are the individual techniques implemented as part of overall LID development or integrated into traditional development, including practices such as bioretention, green roofs, permeable pavements and other infiltration-oriented practices.

Minimizing Directly Connected Impervious Area (MDCIA): MDCIA includes a variety of runoff reduction strategies based on reducing impervious areas and routing runoff from impervious surfaces over grassy areas to slow runoff and promote infiltration. The concept of MDCIA has been recommended by UDFCD as a key technique for reducing runoff peaks and volumes following urbanization. MDCIA is a key component of LID.

Maximum Extent Practicable (MEP): MS4 permit holders are required to implement stormwater programs to reduce pollutant loading to the maximum extent practicable. This narrative standard does not currently include numeric effluent limits.

Municipal Separate Storm Sewer System (MS4): A conveyance or system of conveyances (including roads with drainage systems, municipal streets, catch basins, curbs, gutters, ditches, man-made channels, or storm drains) owned or operated by an MS4 permittee and designed or used for collecting or conveying stormwater.

Nonpoint Source: Any source of pollution that is not considered a "point source." This includes anthropogenic and natural background sources.

Point Source: Any discernible, confined and discrete conveyance from which pollutants are or may be discharged. Representative sources of pollution subject to regulation under the NPDES program include wastewater treatment facilities, most municipal stormwater discharges, industrial dischargers, and concentrated animal feeding operations. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture.

Water Quality Capture Volume (WQCV): This volume represents runoff from frequent storm events such as the 80th percentile storm. The volume varies depending on local rainfall data. Within the UDFCD boundary, the WQCV is based on runoff from 0.6 inches of precipitation.

Excess Urban Runoff Volume (EURV): EURV represents the difference between the developed and pre-developed runoff volume for the range of storms that produce runoff from pervious land surfaces (generally greater than the 2-year event). The EURV is relatively constant for a given imperviousness over a wide range of storm events.

Full Spectrum Detention: This practice utilizes capture and slow release of the EURV. UDFCD found this method to better replicate historic peak discharges for the full range of storm events compared to multi-stage detention practices.

3.2.1 Construction Site Stormwater Runoff Control

Under the Construction Program, permittees are required to develop, implement, and enforce a pollutant control program to reduce pollutants in stormwater runoff to their MS4 from construction activities that result in land disturbance of one or more acres. MS4 permittees frequently extend this requirement to smaller areas of disturbance if the total site acreage is one acre or larger or if it drains to an environmentally sensitive area. See Chapter 7 for detailed information on construction BMPs.

3.2.2 Post-construction Stormwater Management

Under the post-construction stormwater management in new development and redevelopment provisions, the MS4 General Permit (CWQCD 2008) requires the permittee to develop, implement, and enforce a program to address stormwater runoff from new development and redevelopment projects that disturb greater than or equal to one acre, including projects less than one acre that are part of a larger common plan of development or sale, that discharge into the MS4. The program must ensure controls are in place that would prevent or minimize water quality impacts. See Chapter 4, Treatment BMPs and Chapter 5, Source Control BMPs, for detailed information on post-construction BMPs.

Redevelopment

The EPA Stormwater Phase 2 Final Rule Fact Sheet 2.7 states that redevelopment projects alter the footprint of an existing site or building in such a way that that there is a disturbance of equal to or greater than one acre of land.

This means that a "roadway rehabilitation" project, for example, where pavement is removed and replaced with essentially the same footprint would not be considered "redevelopment", whereas a "roadway widening project", where additional pavement (or other alterations to the footprint, pervious or impervious) equal to or in excess of one acre would be considered "redevelopment".

Although MS4 general permits have historically focused on water quality, it is noteworthy that there has been increased emphasis on reducing stormwater runoff volumes through use of Low Impact Development (LID) techniques. For example, MS4 permit language for some Phase I municipalities has also included the following:

> Implement and document strategies which include the use of structural and/or non-structural BMPs appropriate for the community, that address the discharge of pollutants from new development and redevelopment projects, or that follow principles of low-impact development to mimic natural (i.e., pre-development) hydrologic conditions at sites to minimize the discharge of pollutants and prevent or minimize adverse in-channel impacts associated with increased imperviousness (City and County of Denver 2008 MS4 permit).

Similarly, at the national level, the Energy Independence and Security Act of 2007 (Pub.L. 110-140) includes Section 438, Storm Water Runoff Requirements for Federal Development Projects. This section requires:

> …any sponsor of any development or redevelopment project involving a federal facility with a footprint that exceeds 5,000 square feet shall use site planning, design, construction, and maintenance strategies for the property to maintain or restore, to the maximum extent technically feasible, the predevelopment hydrology of the property with regard to the temperature, rate, volume, and duration of flow.

Finally, in October 2009, EPA issued a notice in the Federal Register (Federal Register Vol. 74, No. 209, 56191-56193) expressing its intent to implement new comprehensive stormwater regulations for new developments and redevelopments by 2012. EPA intends to propose requirements, including design or performance standards, for stormwater discharges from, at a minimum, newly developed and redeveloped sites. In the notice, EPA cites the National Research Council (2008) recommendations that "EPA address stormwater discharges from impervious land cover and promote practices that harvest, infiltrate and evapotranspirate stormwater to reduce or prevent it from being discharged, which is critical to reducing the volume and pollutant loading to our nation's waters."

Although it is important to be aware of increased regulatory emphasis on volume control, it is also noteworthy that UDFCD guidance has recommended volume reduction as the first step in urban stormwater quality management since the initial release of the USDCM Volume 3, in 1992. Chapter 2 of this manual provides the designer with additional tools to encourage site designs that better incorporate volume reduction, based on site-specific conditions.

3.2.3 Pollution Prevention/Good Housekeeping

Under the Pollution Prevention/Good Housekeeping requirements, permittees are required to develop and implement an operation and maintenance/training program with the ultimate goal of preventing or reducing pollutant runoff from municipal operations. Chapter 5 provides information on source controls and non-structural BMPs that can be used in support of some of these requirements. Stormwater managers must also be aware that non-stormwater discharges to MS4s are not allowed, with the exception of certain conditions specified in the MS4 permit.

3.3 Total Maximum Daily Loads and Stormwater Management

Section 303(d) of the Clean Water Act requires states to develop a list of water bodies that are not attaining water quality standards for their designated uses, and to identify relative priorities for addressing the impaired water bodies. States must then develop Total Maximum Daily Loads (TMDLs) to assign allowable pollutant loads to various sources to enable the water body to meet the designated uses established for that water body. (For more information about the TMDL program, see http://www.epa.gov/owow/tmdl.) Implementation plans to achieve the loads specified under TMDLs commonly rely on BMPs to reduce pollutant loads associated with stormwater sources.

In the context of this manual, it is important for designers, planners and other stormwater professionals to understand TMDLs because TMDL provisions can directly affect stormwater permit requirements and BMP selection and design. EPA provides this basic description of TMDLs:

> A TMDL is a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards, and an allocation of that load among the various sources of that pollutant. Pollutant sources are characterized as either regulated stormwater, sometimes called "point sources" that receive a waste load allocation (WLA), or nonpoint sources that receive a load allocation (LA). Point sources include all sources subject to regulation under the NPDES program (e.g., wastewater treatment facilities, most municipal stormwater discharges and concentrated animal feeding operations). Nonpoint sources include all remaining sources of the pollutant, as well as anthropogenic and natural background sources. TMDLs must also account for seasonal variations in water quality, and include a margin of safety (MOS) to account for uncertainty in predicting how well pollutant reductions will result in meeting water quality standards.

The TMDL calculation is:

$$\mathrm{TMDL} = \Sigma \mathrm{WLA} + \Sigma \mathrm{LA} + \mathrm{MOS} \qquad \text{Equation 1-1}$$

Where:

ΣWLA = the sum of waste load allocations (point sources),

ΣLA = the sum of load allocations (nonpoint sources and background)

MOS = the margin of safety.

Although states are primarily responsible for developing TMDLs, EPA is required to review and approve or disapprove TMDLs. EPA has developed a basic "TMDL Review Checklist" with the minimum recommended elements that should be present in a TMDL document.

Once EPA approves a TMDL, there are varying degrees of impact to communities involved in the process, generally differentiated among whether point sources or non-point sources of pollution are identified in the TMDL. Permitted stormwater discharges are considered point sources. Essentially, this means that wastewater or stormwater permit requirements consistent with waste load allocations must be implemented and are enforceable under the Clean Water Act through NPDES permits.

If the MS4 permittee discharges into a waterbody with an approved TMDL that includes a pollutant-specific waste load allocation under the TMDL, then the CWQCD can amend the permit to include specific requirements related to that TMDL. For example, the permit may be amended to require specific BMPs, and compliance schedules to implement the BMPs may be required. Numeric effluent limits may also be incorporated under these provisions. TMDLs can have substantive effects on MS4 permit requirements. As an example, the City and County of Denver's MS4 permit has additional requirements to control *E. coli* related to the *E. coli* TMDL approved for the South Platte River (Segment 14). Information on 303(d) listings and priorities for TMDL development can be obtained from the EPA and CWQCC websites (http://www.epa.gov/owow/tmdl/ and http://www.cdphe.state.co.us/op/wqcc/SpecialTopics/303(d)/303dtmdlpro.html).

EPA's Recommended TMDL Checklist
(http://www.epa.gov/owow/tmdl/overviewoftmdl.html)

- Identification of Waterbody, Pollutant of Concern, Pollutant Sources, and Priority Ranking
- Applicable Water Quality Standard & Numeric Water Quality Target[1]
- Loading Capacity[1]
- Load Allocations and Waste Load Allocations[1]
- Margin of Safety[1]
- Consideration of Seasonal Variation[1]
- Reasonable Assurance for Point Sources/Non-point Sources
- Monitoring Plan to Track TMDL Effectiveness
- Implementation Plan
- Public Participation

[1] Legally required components under 40 C.F.R. Part 130

4.0 Four Step Process to Minimize Adverse Impacts of Urbanization

UDFCD has long recommended a Four Step Process for receiving water protection that focuses on reducing runoff volumes, treating the water quality capture volume (WQCV), stabilizing drainageways, and implementing long-term source controls. The Four Step Process pertains to management of smaller, frequently occurring events, as opposed to larger storms for which drainage and flood control infrastructure are sized. Implementation of these four steps helps to achieve stormwater permit requirements described in Section 3. Added benefits of implementing the complete process can include improved site aesthetics through functional landscaping features that also provide water quality benefits. Additionally, runoff reduction can decrease required storage volumes, thus increasing developable land. An overview of the Four Step Process follows, with Chapters 2 and 3 providing BMP selection tools and quantitative procedures for completing these steps.

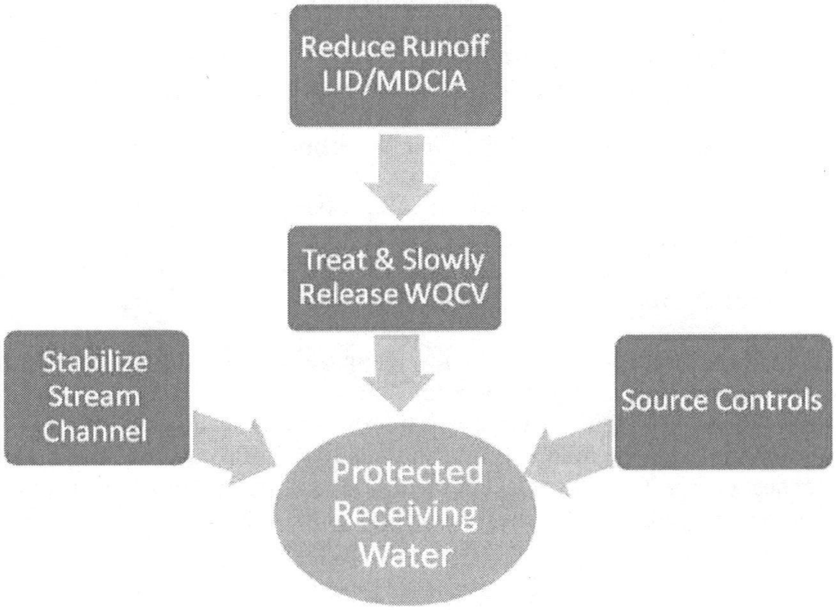


Figure 1-2. The Four Step Process for Stormwater Quality Management

4.1 Step 1. Employ Runoff Reduction Practices

To reduce runoff peaks, volumes, and pollutant loads from urbanizing areas, implement LID strategies, including MDCIA. For every site, look for opportunities to route runoff through vegetated areas, where possible by sheet flow. LID practices reduce unnecessary impervious areas and route runoff from impervious surfaces over permeable areas to slow runoff (increase time of concentration) and promote infiltration. When LID/MDCIA techniques are implemented throughout a development, the effective imperviousness is reduced, thereby potentially reducing sizing requirements for downstream facilities.

Differences between LID and Conventional Stormwater Quality Management

Low Impact Development (LID) is a comprehensive land planning and engineering design approach to managing stormwater runoff with a goal of replicating the pre-development hydrologic regime of urban and developing watersheds. Given the increased regulatory emphasis on LID, volume reduction and mimicking pre-development hydrology, questions may arise related to the differences between conventional stormwater management and LID. For example, Volume 3 has always emphasized MDCIA as the first step in stormwater quality planning and has provided guidance on LID techniques such as grass swales, grass buffers, permeable pavement systems, bioretention, and pollution prevention (pollutant source controls). Although these practices are all key components of LID, LID is not limited to a set of practices targeted at promoting infiltration. Key components of LID, in addition to individual BMPs, include practices such as:

- An overall site planning approach that promotes conservation design at both the watershed and site levels. This approach to development seeks to "fit" a proposed development to the site, integrating the development with natural features and protecting the site's natural resources. This includes practices such as preservation of natural areas including open space, wetlands, soils with high infiltration potential, and stream buffers. Minimizing unnecessary site disturbances (e.g., grading, compaction) is also emphasized.

- A site design philosophy that emphasizes multiple controls distributed throughout a development, as opposed to a central treatment facility.

- The use of swales and open vegetated conveyances, as opposed to curb and gutter systems.

- Volume reduction as a key hydrologic objective, as opposed to peak flow reduction being the primary hydrologic objective. Volume reduction is emphasized not only to reduce pollutant loading and peak flows, but also to move toward hydrologic regimes with flow durations and frequencies closer to the natural hydrologic regime.

Even with LID practices in place, most sites will also require centralized flood control facilities. In some cases, site constraints may limit the extent to which LID techniques can be implemented, whereas in other cases, developers and engineers may have significant opportunities to integrate LID techniques that may be overlooked due to the routine nature and familiarity of conventional approaches. This manual provides design criteria and guidance for both LID and conventional stormwater quality management, and provides additional facility sizing credits for implementing Step 1, Volume Reduction, in a more robust manner.

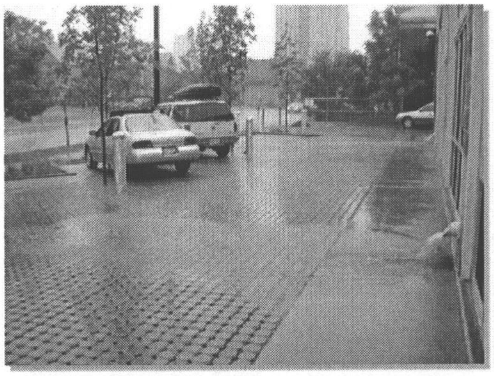
Key LID techniques include:

- **Conserve Existing Amenities**: During the planning phase of development, identify portions of the site that add value and should be protected or improved. Such areas may include mature trees, stream corridors, wetlands, and Type A/B soils with higher infiltration rates. In order for this step to provide meaningful benefits over the long-term, natural areas must be protected from compaction during the construction phase. Consider temporary construction fence for this purpose. In areas where disturbance cannot practically be avoided, rototilling and soil amendments should be integrated to restore the infiltration capacity of areas that will be restored with vegetation.

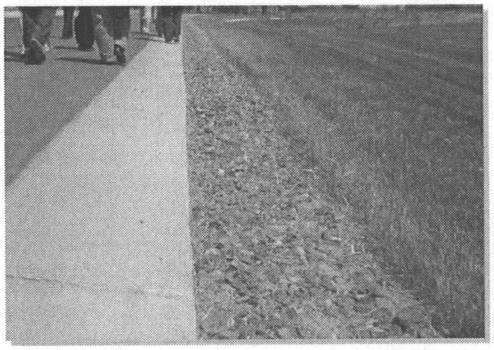
- **Minimize Impacts**: Consider how the site lends itself to the desired development. In some cases, creative site layout can reduce the extent of paved areas, thereby saving on initial capital cost of pavement and then saving on pavement maintenance, repair, and replacement over time. Minimize imperviousness, including constructing streets, driveways, sidewalks and parking lot aisles to the minimum widths necessary, while still providing for parking, snow management, public safety and fire access. When soils vary over the site, concentrate new impervious areas over Type C and D soils, while preserving Type A and B soils for landscape areas and other permeable surfaces. Maintaining natural drainage patterns, implementing sheet flow (as opposed to concentrated flow), and increasing the number and lengths of flow paths will all reduce the impact of the development.

Permeable pavement techniques and green roofs are common LID practices that may reduce the effects of paved areas and roofs:

- **Permeable Pavement**: The use of various permeable pavement techniques as alternatives to paved areas can significantly reduce site imperviousness.
- **Green Roofs**: Green roofs can be used to decrease imperviousness associated with buildings and structures. Benefits of green roofs vary based on design of the roof. Research is underway to assess the effectiveness of green roofs in Colorado's semi-arid climate.

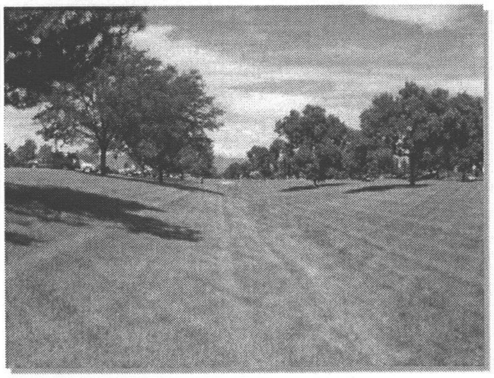


Photograph 1-1. Permeable Pavement. Permeable pavement consists of a permeable pavement layer underlain by gravel and sand layers in most cases. Uses include parking lots and low traffic areas, to accommodate vehicles while facilitating stormwater infiltration near its source. Photo coustesey of Bill Wenk.



Photograph 1-2. Grass Buffer. This roadway provides sheet flow to a grass buffer. The grass buffer provides filtration, infiltration, and settling to reduce runoff pollutants.

- **Minimize Directly Connected Impervious Areas (MDCIA)**: Impervious areas should drain to pervious areas. Use non-hardened drainage conveyances where appropriate. Route downspouts across pervious areas, and incorporate vegetation in areas that generate and convey runoff. Three key BMPs include:
  - **Grass Buffers**: Sheet flow over a grass buffer slows runoff and encourages infiltration, reducing effects of the impervious area.
  - **Grass Swales**: Like grass buffers, use of grass swales instead of storm sewers slows runoff and promotes infiltration, also reducing the effects of imperviousness.
  - **Bioretention (rain gardens)**: The use of distributed on-site vegetated features such as rain gardens can help maintain natural drainage patterns by allowing more infiltration onsite. Bioretention can also treat the WQCV, as described in the Four Step Process.



Photograph 1-3. Grass Swale. This densely vegetated drainageway is designed with channel geometry that forces the flow to be slow and shallow, facilitating sedimentation while limiting erosion.

Historically, this critical volume reduction step has often been overlooked by planners and engineers, instead going straight to WQCV requirements, despite WQCV reductions allowed based on MDCIA. Chapter 3 extends reductions to larger events and provides a broader range of reductions to WQCV sizing requirements than were previously recommended by UDFCD, depending on the extent to which Step 1 has been implemented. Developers should anticipate more stringent requirements from local governments to implement runoff reduction/MDCIA/LID measures (in addition to WQCV capture), given changes in state and federal stormwater regulations. In addition to benefiting the environment through reduced hydrologic and water quality impacts, volume reduction measures can also have the added economic benefit to the developer of increasing the area of developable land by reducing required detention volumes and potentially reducing both capital and maintenance costs.

Practical Tips for Volume Reduction and Better Integration of Water Quality Facilities
(Adapted from: Denver Water Quality Management Plan, WWE et al. 2004)

- **Consider stormwater quality needs early in the development process.** When left to the end of the site development process, stormwater quality facilities will often be shoe-horned into the site, resulting in few options. When included in the initial planning for a project, opportunities to integrate stormwater quality facilities into a site can be fully realized. Dealing with stormwater quality after major site plan decisions have been made is too late and often makes implementation of LID designs impractical.

- **Take advantage of the entire site when planning for stormwater quality treatment.** Stormwater quality and flood detention is often dealt with only at the low corner of the site, and ignored on the remainder of the site. The focus is on draining runoff quickly through inlets and storm sewers to the detention facility. In this "end-of-pipe" approach, all the runoff volume is concentrated at one point and designers often find it difficult to fit the required detention into the space provided. This can lead to use of underground BMPs that can be difficult to maintain or deep, walled-in basins that detract from a site and are also difficult to maintain. Treating runoff over a larger portion of the site reduces the need for big corner basins and allows implementation of LID principles.

- **Place stormwater in contact with the landscape and soil**. Avoid routing storm runoff from pavement to inlets to storm sewers to offsite pipes or concrete channels. The recommended approach places runoff in contact with landscape areas to slow down the stormwater and promote infiltration. Permeable pavement areas also serve to reduce runoff and encourage infiltration.

- **Minimize unnecessary imperviousness, while maintaining functionality and safety.** Smaller street sections or permeable pavement in fire access lanes, parking lanes, overflow parking, and driveways will reduce the total site imperviousness.

- **Select treatment areas that promote greater infiltration.** Bioretention, permeable pavements, and sand filters promote greater volume reduction than extended detention basins, since runoff tends to be absorbed into the filter media or infiltrate into underlying soils. As such, they are more efficient at reducing runoff volume and can be sized for smaller treatment volumes than extended detention basins.

4.2 Step 2. Implement BMPs That Provide a Water Quality Capture Volume with Slow Release

After runoff has been minimized, the remaining runoff should be treated through capture and slow release of the WQCV. WQCV facilities may provide both water quality and volume reduction benefits, depending on the BMP selected. This manual provides design guidance for BMPs providing treatment of the WQCV, including permeable pavement systems with subsurface storage, bioretention, extended detention basins, sand filters, constructed wetland ponds, and retention ponds. Green roofs and some underground BMPs may also provide the WQCV, depending on the design characteristics. Chapter 3 provides background information on the development of the WQCV for the Denver metropolitan area as well as a step-by-step procedure to calculate the WQCV.

4.3 Step 3. Stabilize Drainageways

During and following development, natural drainageways are often subject to bed and bank erosion due to increases in frequency, duration, rate, and volume of runoff. Although Steps 1 and 2 help to minimize these effects, some degree of drainageway stabilization is required. Many drainageways within UDFCD boundaries are included in major drainageway or outfall systems plans, identifying needed channel stabilization measures. These measures not only protect infrastructure such as utilities, roads and trails, but are also important to control sediment loading from erosion of the channel itself, which can be a significant source of sediment and associated constituents, such as phosphorus, metals and other naturally occurring constituents. If stream stabilization is implemented early in the development process, it is far more likely that natural drainageway characteristics can be maintained with the addition of grade control to accommodate future development. Targeted fortification of a relatively stable drainageway is typically much less costly than repairing an unraveled channel. The *Major Drainage* chapter in Volume 2 of this manual provides guidance on several approaches to channel stabilization, including stabilized natural channels and several engineered channel approaches. Volume 3 adds a Constructed Wetland Channel approach, which may provide additional water quality and community benefits. Brief descriptions of these three approaches to stabilized channels include:

- **Stabilized Natural Channel**. Many natural drainageways in and adjacent to new developments in the Denver area are frequently left in an undisturbed condition. While this may be positive in terms of retaining desirable riparian vegetation and habitat, urban development causes the channel to become destabilized; therefore, it is recommended that some level of stream stabilization always be provided. Small grade control structures sized for a 5-year or larger runoff event are often an effective means of establishing a mild slope for the baseflow channel and arresting stream degradation. Severe bends or cut banks may also need to be stabilized. Such efforts to stabilize a natural waterway also enhance aesthetics, riparian and stream habitat, and water quality. Always review master planning documents relevant to the drainageway prior to designing improvements.

- **Constructed Grass, Riprap, or Concrete-Lined Channel**. The water quality benefit associated with these channels is the reduction of severe bed and bank erosion that can occur in the absence of a stabilized channel. On the other hand, the hard-lined low-flow channels that are often used do not allow for infiltration or offer much in the way of water quality enhancement or wetland habitat.

- **Constructed Wetland Channel**: Constructed channels with wetland bottoms use dense natural vegetation to slow runoff and promote settling and biological uptake. These are particularly beneficial in treatment train approaches where pre-sedimentation occurs upstream of the wetland channel.

4.4 Step 4. Implement Site Specific and Other Source Control BMPs

Site specific needs such as material storage or other site operations require consideration of targeted source control BMPs. This is often the case for new development or significant redevelopment of an industrial or commercial site. Chapter 5 includes information on source control practices such as covering storage/handling areas and spill containment and control.

5.0 Onsite, Subregional and Regional Stormwater Management

Stormwater quality BMPs should be implemented as close to the source as practicable. This results in smaller BMPs (in parallel or in series) that are distributed throughout a site rather than the "end of pipe" alternative. Whereas flood control is best handled on a regional basis, stormwater quality is best managed when stormwater is viewed as a resource and distributed throughout the site. When the watershed of a BMP is so big that a base flow is present, this both limits the type of BMP appropriate for use and complicates the design. The treatment provided by a regional BMP will also vary when base flows differ from that assumed during design.

> Whereas flood control is best handled on a regional basis, stormwater quality is best managed as a resource and distributed throughout the site.

Although not preferred, WQCV facilities may be implemented regionally (serving a major drainageway with a drainage area between 130 acres and one square mile) or subregionally (serving two or more development parcels with a total drainage area less than 130 acres). Drainage master plans should be consulted to determine if regional or subregional facilities are already planned or in place for new developments or redevelopments. Life-cycle costs of onsite, subregional, and regional facilities, including long-term maintenance responsibilities, should be part of the decision-making process when selecting the combinations of facilities and channel improvements needed to serve a development or redevelopment. Potential benefits of regional/subregional facilities include consolidated maintenance efforts, economies of scale for larger facilities as opposed to multiple onsite WQCV facilities, simplified long-term adequate assurances for operation and maintenance for public facilities, and potential integration with flood control facilities. Additionally, regional storage-based facilities may be beneficial in areas where onsite BMPs are not feasible due to geotechnical or land use constraints or when retrofitting an existing flood control facility in a fully developed watershed.

One of the most common challenges regarding regional facilities relates to the timing of funding for construction of the facilities. Often, regional facilities are funded by revenues collected from new development activities. New developments (and revenues) are required to fund construction of the water quality facility, but the water quality facility is needed upfront to provide protection for new development. This timing problem can be solved by constructing onsite water quality facilities for new development that occur before a regional facility is in place. These onsite BMPs are temporary in that they can be converted to developable land once the regional facility is constructed. Another option is to build a smaller interim regional facility that can be expanded with future development.

When regional water quality facilities are selected, BMPs are still required onsite to address water quality and channel stability for the reach of the drainageway upstream of the regional facility. In accordance with MS4 permits and regulations, BMPs must be implemented prior to discharges to a State Water from areas of "New Development and Significant Redevelopment." Therefore, if a regional BMP is utilized downstream of a discharge from a development into a State Water, additional BMPs are required to protect the State Water between the development site and the regional facility. However, these BMPs may not have to be as extensive as would normally be required, as long as they are adequate to protect the State Water upstream of the regional BMP. Although the CWQCD does not require onsite WQCV per se, MS4 permits contain conditions that require BMPs be implemented to the Maximum Extent Practicable to prevent "pollution of the receiving waters in excess of the pollution permitted by an applicable water quality standard or applicable antidegradation requirement." Additional requirements may also apply in the case of streams with TMDLs. As a result, MS4 permit holders must have a program in place that requires developers to provide adequate onsite measures so that the MS4 permit holder remains in compliance with their permit and meets the conditions of current regulations.

State Waters

State Waters are any and all surface and subsurface waters which are contained in or flow in or through this State, but does not include waters in sewage systems, waters in treatment works of disposal systems, waters in potable water distribution systems, and all water withdrawn for use until use and treatment have been completed (from Regulation 61, Colorado Discharge Permit System Regulations).

When a regional or subregional facility is selected to treat the WQCV for a development, the remaining three steps in the Four Step Process should still be implemented. For example, minimizing runoff volumes on the developed property by disconnecting impervious area and infiltrating runoff onsite (Step 1) can potentially reduce regional WQCV requirements, conveyance system costs, and costs of the regional/subregional facility. Stream stabilization requirements (Step 3) must still be evaluated and implemented, particularly if identified in a master drainage plan. Finally, specific source controls (Step 4 BMPs) such as materials coverage should be implemented onsite, even if a regional/subregional facility is provided downstream. Although UDFCD does not specify minimum onsite treatment requirements when regional/subregional facilities are used, some local governments (e.g., Arapahoe County) have specific requirements related to the minimum measures that must be implemented to minimize directly connected impervious area.

Chapter 2 provides a BMP selection tool to help planners and engineers determine whether onsite, subregional or regional strategies are best suited to the given watershed conditions.

6.0 Conclusion

Urban stormwater runoff can have a variety of chemical, biological, and physical effects on receiving waters. As a result, local governments must comply with federal, state and local requirements to minimize adverse impacts both during and following construction. UDFCD criteria are based on a Four Step Process focused on reducing runoff volumes, treating the remaining WQCV, stabilizing receiving drainageways and providing targeted source controls for post-construction operations at a site. Stormwater management requirements and objectives should be considered early in the site development process, taking into account a variety of factors, including the effectiveness of the BMP, long-term maintenance requirements, cost and a variety of site-specific conditions. The remainder of this manual provides guidance for selecting, designing, constructing and maintaining stormwater BMPs.

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Chapter 2
BMP Selection

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1.0 BMP Selection

This chapter provides guidance on factors that should be considered when selecting BMPs for new development or redevelopment projects. This guidance is particularly useful in the planning phase of a project. BMP selection involves many factors such as physical site characteristics, treatment objectives, aesthetics, safety, maintenance requirements, and cost. Typically, there is not a single answer to the question of which BMP (or BMPs) should be selected for a site; there are usually multiple solutions ranging from stand alone BMPs to treatment trains that combine multiple BMPs to achieve the water quality objectives. Factors that should be considered when selecting BMPs are the focus of this chapter.

1.1 Physical Site Characteristics

The first step in BMP selection is identification of physical characteristics of a site including topography, soils, contributing drainage area, groundwater, baseflows, wetlands, existing drainageways, and development conditions in the tributary watershed (e.g., construction activity). A fundamental concept of Low Impact Development (LID) is preservation and protection of site features including wetlands, drainageways, soils that are conducive to infiltration, tree canopy, etc., that provide water quality and other benefits. LID stormwater treatment systems are also designed to take advantage of these natural resources. For example, if a portion of a site is known to have soils with high permeability, this area may be well-suited for rain gardens or permeable pavement. Areas of existing wetlands, which would be difficult to develop from a Section 404 permitting perspective, could be considered for polishing of runoff following BMP treatment, providing additional water quality treatment for the site, while at the same time enhancing the existing wetlands with additional water supply in the form of treated runoff.

Some physical site characteristics that provide opportunities for BMPs or constrain BMP selection include:

- **Soils:** Soils with good permeability, most typically associated with Hydrologic Soil Groups (HSGs) A and B provide opportunities for infiltration of runoff and are well-suited for infiltration-based BMPs such as rain gardens, permeable pavement systems, sand filter, grass swales, and buffers, often without the need for an underdrain system. Even when soil permeability is low, these types of BMPs may be feasible if soils are amended to increase permeability or if an underdrain system is used. In some cases, however, soils restrict the use of infiltration based BMPs. When soils with moderate to high swell potential are present, infiltration should be avoided to minimize damage to adjacent structures due to water-induced swelling. In some cases, infiltration based designs can still be used if an impermeable liner and underdrain system are included in the design; however, when the risk of damage to adjacent infrastructure is high, infiltration based BMPs may not be appropriate. In all cases, consult with a geotechnical engineer when designing infiltration BMPs near structures. Consultation with a geotechnical engineer is necessary for evaluating the suitability of soils for different BMP types and establishing minimum distances between infiltration BMPs and structures.

- **Watershed Size**: The contributing drainage area is an important consideration both on the site level and at the regional level. On the site level, there is a practical minimum size for certain BMPs, largely related to the ability to drain the WQCV over the required drain time. For example, it is technically possible to size the WQCV for an extended detention basin for a half-acre site; however, designing a functional outlet to release the WQCV over a 40-hour drain time is practically impossible due to the very small orifices that would be required. For this size watershed, a filtering BMP, such as a rain garden, would be more appropriate. At the other end of the spectrum, there must be a limit on the maximum drainage area for a regional facility to assure adequate treatment of rainfall events that may produce runoff from only a portion of the area draining to the BMP. If the overall drainage area is too large, events that produce runoff from only a portion of the contributing area will pass through the BMP outlet (sized for the full drainage area) without adequate residence time in the BMP. As a practical limit, the maximum drainage area contributing to a water quality facility should be no larger than one square mile.

- **Groundwater**: Shallow groundwater on a site presents challenges for BMPs that rely on infiltration and for BMPs that are intended to be dry between storm events. Shallow groundwater may limit the ability to infiltrate runoff or result in unwanted groundwater storage in areas intended for storage of the WQCV (e.g., porous sub-base of a permeable pavement system or in the bottom of an otherwise dry facility such as an extended detention basin). Conversely, for some types of BMPs such as wetland channels or constructed wetland basins, groundwater can be beneficial by providing saturation of the root zone and/or a source of baseflow. Groundwater quality protection is an issue that should be considered for infiltration-based BMPs. Infiltration BMPs may not be appropriate for land uses that involve storage or use of materials that have the potential to contaminate groundwater underlying a site (i.e., "hot spot" runoff from fueling stations, materials storage areas, etc.). If groundwater or soil contamination exists on a site and it will not be remediated or removed as a part of construction, it may be necessary to avoid infiltration-based BMPs or use a durable liner to prevent infiltration into contaminated areas.

- **Base Flows**: Base flows are necessary for the success of some BMPs such as constructed wetland ponds, retention ponds and wetland channels. Without baseflows, these BMPs will become dry and unable to support wetland vegetation. For these BMPs, a hydrologic budget should be evaluated. Water rights are also required for these types of BMPs in Colorado.

- **Watershed Development Activities (or otherwise erosive conditions)**: When development in the watershed is phased or when erosive conditions such as steep slopes, sparse vegetation, and sandy soils exist in the watershed, a treatment train approach may be appropriate. BMPs that utilize filtration should follow other measures to collect sediment loads (e.g., a forebay). For phased developments, these measures must be in place until the watershed is completely stabilized. When naturally erosive conditions exist in the watershed, these measures should be permanent. The designer should consider existing, interim and future conditions to select the most appropriate BMPs.

1.2 Space Constraints

Space constraints are frequently cited as feasibility issues for BMPs, especially for high-density, lot-line-to-lot-line development and redevelopment sites. In some cases, constraints due to space limitations arise because adequate spaces for BMPs are not considered early enough in the planning process. This is most common when a site plan for roads, structures, etc., is developed and BMPs are squeezed into the remaining spaces. The most effective and integrated BMP designs begin by determining areas of a site that are best suited for BMPs (e.g., natural low areas, areas with well-drained soils) and then designing the layout of roads, buildings, and other site features around the existing drainage and water quality resources of the site. Allocating a small amount of land to water quality infrastructure during early planning stages will result in better integration of water quality facilities with other site features.

1.3 Targeted Pollutants and BMP Processes

BMPs have the ability to remove pollutants from runoff through a variety of physical, chemical and biological processes. The processes associated with a BMP dictate which pollutants the BMP will be effective at controlling. Primary processes include peak attenuation, sedimentation, filtration, straining, adsorption/absorption, biological uptake and hydrologic processes including infiltration and evapotranspiration. Table 2-1 lists processes that are associated with BMPs in this manual. For many sites, a primary goal of BMPs is to remove gross solids, suspended sediment and associated particulate fractions of pollutants from runoff. Processes including straining, sedimentation, and infiltration/filtration are effective for addressing these pollutants. When dissolved pollutants are targeted, other processes including adsorption/absorption and biological uptake are necessary. These processes are generally sensitive to media composition and contact time, oxidation/reduction potential, pH and other factors. In addition to pollutant removal capabilities, many BMPs offer channel stability benefits in the form of reduced runoff volume and/or reduced peak flow rates for frequently occurring events. Brief descriptions of several key processes, generally categorized according to hydrologic and pollutant removal functions are listed below:

Hydrologic Processes

1. **Flow Attenuation**: BMPs that capture and slowly release the WQCV help to reduce peak discharges. In addition to slowing runoff, volume reduction may also be provided to varying extents in BMPs providing the WQCV.

2. **Infiltration:** BMPs that infiltrate runoff reduce both runoff peaks and surface runoff volumes. The extent to which runoff volumes are reduced depends on a variety of factors such as whether the BMP is equipped with an underdrain and the characteristics and long-term condition of the infiltrating media. Examples of infiltrating BMPs include (unlined) sand filters, bioretention and permeable pavements. Water quality treatment processes associated with infiltration can include filtration and sorption.

3. **Evapotranspiration**: Runoff volumes can be reduced through the combined effects of evaporation and transpiration in vegetated BMPs. Plants extract water from soils in the root zone and transpire it to the atmosphere. Evapotranspiration is the hydrologic process provided by vegetated BMPs, whereas biological uptake may help to reduce pollutants in runoff.

Pollutant Removal/Treatment Processes

1. **Sedimentation:** Gravitational separation of particulates from urban runoff, or sedimentation, is a key treatment process by BMPs that capture and slowly release runoff. Settling velocities are a function of characteristics such as particle size, shape, density, fluid density, and viscosity. Smaller particles under 60 microns in size (fine silts and clays) (Stahre and Urbonas, 1990) can account for approximately 80% of the metals in stormwater attached or adsorbed along with other contaminants and can require long periods of time to settle out of suspension. Extended detention allows smaller particles to agglomerate into larger ones (Randall et al, 1982), and for some of the dissolved and liquid state pollutants to adsorb to suspended particles, thus removing a larger proportion of them through sedimentation. Sedimentation is the primary pollutant removal mechanism for many treatment BMPs including extended detention basins, retention ponds, and constructed wetland basins.

2. **Straining**: Straining is physical removal or retention of particulates from runoff as it passes through a BMP. For example, grass swales and grass buffers provide straining of sediment and coarse solids in runoff. Straining can be characterized as coarse filtration.

3. **Filtration**: Filtration removes particles as water flows through media (often sand or engineered soils). A wide variety of physical and chemical mechanisms may occur along with filtration, depending on the filter media. Metcalf and Eddy (2003) describe processes associated with filtration as including straining, sedimentation, impaction, interception, adhesion, flocculation, chemical adsorption, physical adsorption, and biological growth. Filtration is a primary treatment process

provided by infiltration BMPs. Particulates are removed at the ground surface and upper soil horizon by filtration, while soluble constituents can be absorbed into the soil, at least in part, as the runoff infiltrates into the ground. Site-specific soil characteristics, such as permeability, cation exchange potential, and depth to groundwater or bedrock are important characteristics to consider for filtration (and infiltration) BMPs. Examples of filtering BMPs include sand filters, bioretention, and permeable pavements with a sand filter layer.

4. **Adsorption/Absorption**: In the context of BMPs, sorption processes describe the interaction of waterborne constituents with surrounding materials (e.g., soil, water). Absorption is the incorporation of a substance in one state into another of a different state (e.g., liquids being absorbed by a solid). Adsorption is the physical adherence or bonding of ions and molecules onto the surface of another molecule. Many factors such as pH, temperature and ionic state affect the chemical equilibrium in BMPs and the extent to which these processes provide pollutant removal. Sorption processes often play primary roles in BMPs such as constructed wetland basins, retention ponds, and bioretention systems. Opportunities may exist to optimize performance of BMPs through the use of engineered media or chemical addition to enhance sorption processes.

5. **Biological Uptake:** Biological uptake and storage processes include the assimilation of organic and inorganic constituents by plants and microbes. Plants and microbes require soluble and dissolved constituents such as nutrients and minerals for growth. These constituents are ingested or taken up from the water column or growing medium (soil) and concentrated through bacterial action, phytoplankton growth, and other biochemical processes. In some instances, plants can be harvested to remove the constituents permanently. In addition, certain biological activities can reduce toxicity of some pollutants and/or possible adverse effects on higher aquatic species. Unfortunately, not much is understood yet about how biological uptake or activity interacts with stormwater during the relatively brief periods it is in contact with the biological media in most BMPs, with the possible exception of retention ponds between storm events (Hartigan, 1989). Bioretention, constructed wetlands, and retention ponds are all examples of BMPs that provide biological uptake.

When selecting BMPs, it is important to have realistic expectations of effluent pollutant concentrations. The International Stormwater BMP Database (www.bmpdatabase.org) provides BMP performance information that is updated periodically and summarized in Table 2-2. BMPs also provide varying degrees of volume reduction benefits. Both pollutant concentration reduction and volume reduction are key components in the whole life cycle cost tool *BMP-REALCOST.xls* (Roesner and Olson 2009) discussed later in this chapter.

It is critical to recognize that for BMPs to function effectively, meet performance expectations, and provide for public safety, BMPs must:

1. Be designed according to UDFCD criteria, taking into account site-specific conditions (e.g., high groundwater, expansive clays and long-term availability of water).

2. Be constructed as designed. This is important for all BMPs, but appears to be particularly critical for permeable pavements, rain gardens and infiltration-oriented facilities.

3. Be properly maintained to function as designed. Although all BMPs require maintenance, infiltration-oriented facilities are particularly susceptible to clogging without proper maintenance. Underground facilities can be vulnerable to maintenance neglect because maintenance needs are not evident from the surface without special tools and procedures for access. Maintenance is not only essential for proper functioning, but also for aesthetic and safety reasons. Inspection of facilities is an important step to identify and plan for needed maintenance.

Table 2-1. Primary, Secondary and Incidental Treatment Process Provided by BMPs

	Hydrologic Processes			**Treatment Processes**				
	Peak	Volume		Physical			Chemical	Biological
UDFCD BMP	Flow Attenuation	Infiltration	Evapo-transpiration	Sedimentation	Filtration	Straining	Adsorption/ Absorption	Biological Uptake
Grass Swale	I	S	I	S	S	P	S	S
Grass Buffer	I	S	I	S	S	P	S	S
Constructed Wetland Channel	I	N/A	P	P	S	P	S	P
Green Roof	P	S	P	N/A	P	N/A	I	P
Permeable Pavement Systems	P	P	N/A	S	P	N/A	N/A	N/A
Bioretention	P	P	S	P	P	S	S[1]	P
Extended Detention Basin	P	I	I	P	N/A	S	S	I
Sand Filter	P	P	I	P	P	N/A	S[1]	N/A
Constructed Wetland Pond	P	I	P	P	S	S	P	P
Retention Pond	P	I	P	P	N/A	N/A	P	S
Underground BMPs	Variable	N/A	N/A	Variable	Variable	Variable	Variable	N/A

Notes:

P = Primary; S = Secondary, I = Incidental; N/A = Not Applicable

[1] Depending on media

Table 2-2. BMP Effluent EMCs (Source: International Stormwater BMP Database, August

Solids and Nutrients (milligrams/liter)										
BMP Category	Sample Type	Total Suspended Solids	Total Dissolved Solids	Nitrogen, Total	Total Kjeldahl Nitrogen (TKN)	Nitrogen, Ammonia as N	Nitrogen, Nitrate (NO3) as N*	Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N*	Phosphorus as P, Total	Phosphorus, Orthophosphate as P
Bioretention (w/Underdrain)	Inflow	44.6 (41.8-53.3, n= 6)	NC	1.46 (1.24-1.63, n= 7)	1.22 (1.00-1.33, n= 8)	0.19 (0.16-0.23, n= 8)	NC	0.30 (0.25-0.38, n= 10)	0.13 (0.12-0.17, n= 12)	0.04 (0.01-0.10, n= 7)
	Outflow	12.9 (6.8-17.3, n= 6)	NC	1.15 (0.92-2.98, n= 7)	0.94 (0.60-2.09, n= 8)	0.06 (0.05-0.38, n= 8)	NC	0.21 (0.14-0.29, n= 10)	0.13 (0.08-0.19, n= 12)	0.06 (0.03-0.33, n= 7)
Grass Buffer	Inflow	52.3 (50.0-63.3, n= 14)	57.5 (32.0-89.3, n= 12)	NC	1.40 (1.15-2.10, n= 13)	0.38 (0.23-0.64, n= 10)	0.44 (0.42-0.92, n= 13)	NC	0.18 (0.09-0.25, n= 14)	0.04 (0.03-0.06, n= 10)
	Outflow	22.3 (15.0-28.3, n= 14)	88.0 (73.3-110.0, n= 12)	NC	1.20 (0.95-1.50, n= 13)	0.25 (0.13-0.36, n= 9)	0.33 (0.23-0.78, n= 13)	NC	0.30 (0.11-0.56, n= 14)	0.10 (0.05-0.29, n= 10)
Grass Swale	Inflow	54.5 (30.5-76.5, n= 15)	79.5 (64.2-100.1, n= 12)	NC	1.83 (1.40-2.11, n= 12)	0.06 (0.02-0.09, n= 4)	0.41 (0.23-0.78, n= 12)	0.25 (0.19-0.37, n= 4)	0.22 (0.13-0.29, n= 15)	0.04 (0.03-0.04, n= 3)
	Outflow	*18.0* (8.9-39.5, n= 19)	*71.0* (34.9-85.0, n= 10)	*0.60* (0.55-1.34, n= 6)	1.23 (0.41-1.48, n= 16)	*0.05* (0.03-0.06, n= 8)	0.29 (0.21-0.66, n= 15)	0.22 (0.18-0.31, n= 8)	0.23 (0.19-0.31, n= 19)	*0.10* (0.08-0.12, n= 7)
Detention Basin (aboveground extended det.)	Inflow	59.5 (17.8-83.8, n= 18)	88.5 (85.0-98.8, n= 6)	1.05 (1.04-1.25, n= 3)	1.32 (0.77-1.70, n= 10)	0.08 (0.04-0.10, n= 5)	0.45 (0.30-0.90, n= 8)	0.23 (0.17-0.50, n= 5)	0.20 (0.18-0.30, n= 17)	NC
	Outflow	22.0 (11.6-28.5, n= 20)	85.0 (54.3-113.5, n= 6)	2.54 (1.7-2.69, n= 3)	1.66 (0.86-1.95, n= 10)	0.09 (0.07-0.10, n= 5)	0.40 (0.27-0.85, n= 8)	0.17 (0.08-0.43, n= 6)	0.20 (0.13-0.26, n= 18)	NC
Media Filters (various types)	Inflow	44.0 (32.0-75.0, n= 21)	42.0 (28.4-59.0, n= 13)	1.51 (0.73-1.80, n= 5)	1.53 (0.87-2.00, n= 17)	0.34 (0.08-1.12, n= 11)	0.38 (0.23-0.57, n= 16)	0.33 (0.23-0.51, n= 6)	0.20 (0.13-0.33, n= 21)	0.02 (0.02-0.06, n= 7)
	Outflow	8.0 (5.0-17.0, n= 21)	55.0 (46.0-62.0, n= 13)	0.63 (0.43-1.41, n= 4)	0.80 (0.50-1.22, n= 17)	0.11 (0.04-0.15, n= 10)	0.66 (0.39-0.73, n= 16)	0.43 (0.05-1.00, n= 5)	0.11 (0.06-0.15, n= 21)	0.02 (0.02-0.06, n= 7)
Retention Pond (aboveground wet pond)	Inflow	44.5 (24.0-88.3, n= 40)	89.0 (59.3-127.5, n= 9)	1.71 (1.07-2.36, n= 19)	1.18 (0.77-1.42, n= 28)	0.09 (0.04-0.15, n= 23)	0.43 (0.32-0.69, n= 15)	0.27 (0.11-0.55, n= 24)	0.23 (0.14-0.39, n= 38)	0.09 (0.07-0.21, n= 26)
	Outflow	12.1 (7.9-19.7, n= 40)	151.3 (70.8-182.0, n= 9)	1.31 (1.01-1.54, n= 19)	0.99 (0.76-1.29, n= 30)	0.07 (0.04-0.17, n= 24)	0.19 (0.13-0.26, n= 15)	0.05 (0.02-0.20, n= 24)	0.11 (0.07-0.19, n= 40)	0.05 (0.02-0.08, n= 27)
Wetland Basin	Inflow	39.6 (24.0-56.8, n= 14)	NA	1.54 (1.07-2.16, n= 6)	1.10 (0.77-1.30, n= 4)	0.10 (0.04-0.13, n= 8)	0.32 (0.32-0.44, n= 5)	0.46 (0.11-0.63, n= 7)	0.12 (0.14-0.27, n= 11)	0.04 (0.07-0.13, n= 5)
	Outflow	12.0 (8.5-17.5, n= 16)	NC	1.16 (0.98-1.39, n= 6)	1.00 (0.90-1.14, n= 8)	0.06 (0.04-0.10, n= 8)	0.12 (0.10-0.16, n= 7)	0.17 (0.05-0.34, n= 7)	0.08 (0.05-0.14, n= 13)	0.06 (0.02-0.25, n= 7)
Permeable Pavement**	Inflow	23.5 (16.0-45.3, n = 5)	NA	NC	2.40 (1.80-3.30, n = 3)	NC	NC	0.59 (0.27-0.80, n = 5)	0.12 (0.10-0.13, n = 5)	NC
	Outflow	29.1 (16.3-34.0, n = 7)	NA	NC	1.05 (0.90-1.33, n = 7)	NC	NC	1.24 (1.21-1.39, n = 4)	0.13 (0.10-0.19, n = 5)	NC

*Some BMP studies include analyses for both NO2/NO3 and NO3; therefore, these analytes are reported separately, even though results are expected to be comparable in stormwater runoff.

Table Notes provided below part 2 of this table.

		Metals (micrograms/liter)													
BMP Category	Sample Type	Arsenic, Diss.	Arsenic, Total	Cadmium, Diss.	Cadmium, Total	Chromium, Diss.	Chromium, Total	Copper, Diss.	Copper, Total	Lead, Diss.	Lead, Total	Nickel, Diss.	Nickel, Total	Zinc, Diss.	Zinc, Total
Bioretention (w/Underdrain)	Inflow	NA	NC	NC	NC	NC	NC	NC	19.5 (15.3-35.8, n= 3)	NC	NC	NC	NC	NC	68.0 (51-68.5, n= 5)
	Outflow	NA	NC	NC	NC	NC	NC	NC	10.0 (7.3-16.8, n= 3)	NC	NC	NC	NC	NC	8.5 (5.0-35.0, n= 5)
Grass Buffer	Inflow	0.8 (0.5-1.2, n= 12)	1.1 (0.9-2.3, n= 12)	0.2 (0.1-0.2, n= 12)	0.4 (0.3-0.8, n= 12)	2.4 (1.1-4.5, n= 12)	4.9 (2.9-7.4, n= 13)	12.9 (6.8-17.3, n= 12)	21.2 (15.0-41.0, n= 13)	0.9 (0.5-2.0, n= 12)	11.0 (6-35, n= 13)	2.9 (1.1-3.2, n= 12)	4.8 (3.4-8.4, n= 12)	37.8 (12.8-70, n= 12)	100.5 (53.0-245.0, n= 13)
	Outflow	1.2 (0.5-2.4, n= 12)	2.0 (0.7-3.0, n= 12)	0.1 (0.1-0.2, n= 12)	0.2 (0.1-0.2, n= 12)	2.3 (1.0-3.8, n= 12)	2.9 (2.0-5.5, n= 13)	7.1 (4.8-11.6, n= 12)	8.3 (6.4-12.5, n= 13)	0.5 (0.5-1.3, n= 12)	3.2 (1.8-6.0, n= 13)	2.1 (2.0-2.3, n= 12)	2.6 (2.2-3.2, n= 12)	19.8 (10.7-24.3, n= 12)	25.5 (15.0-57.9, n= 13)
Grass Swale	Inflow	0.6 (0.5-2.2, n= 9)	1.7 (1.6-2.7, n= 9)	0.3 (0.1-0.4, n= 13)	0.5 (0.4-0.9, n= 14)	2.2 (1.1-3.3, n= 7)	6.1 (3.6-8.3, n= 7)	10.6 (8.1-15.0, n= 13)	33.0 (26-34, n= 13)	1.4 (0.6-6.7, n= 13)	21.6 (12.5-46.4, n= 14)	5.1 (4.5-6.6, n= 6)	8.7 (7-12.5, n= 6)	40.3 (35.3-109.0, n= 13)	149.5 (43.8-244.3, n= 15)
	Outflow	0.6 (0.6-1.2, n= 8)	1.2 (0.9-1.7, n= 8)	0.2 (0.1-0.2, n= 12)	0.3 (0.2-0.4, n= 13)	1.1 (1.0-3.0, n= 6)	3.5 (1.7-5.0, n= 6)	8.6 (5.5-9.7, n= 13)	14.0 (6.7-18.5, n= 17)	1.0 (0.5-4.1, n= 13)	10.5 (1.7-12.0, n= 18)	2.0 (2.0-2.3, n= 5)	4.0 (3.1-4.5, n= 5)	22.6 (20.1-33.2, n= 13)	55.0 (20.6-65.4, n= 19)
Detention Basin (aboveground extended det.)	Inflow	1.1 (0.9-1.2, n= 5)	2.1 (1.3-2.6, n= 6)	0.3 (0.2-0.4, n= 8)	0.6 (0.3-1.2, n= 11)	2.6 (2.0-3.2, n= 3)	5.6 (5.0-6.5, n= 6)	5.8 (2.6-11.8, n= 8)	10.0 (4.8-33.5, n= 11)	1.0 (0.5-1.4, n= 8)	10.0 (1.5-41.0, n= 11)	2.9 (1.9-3.9, n= 4)	6.3 (5-9.4, n= 5)	16.4 (6.1-53.5, n= 8)	125.0 (21.5-225.3, n= 11)
	Outflow	1.2 (0.9-1.2, n= 5)	1.7 (1.1-1.9, n= 6)	0.3 (0.2-0.4, n= 9)	0.4 (0.2-0.6, n= 12)	1.9 (1.7-3.0, n= 4)	2.9 (1.9-3.8, n= 6)	9.0 (3.0-13.0, n= 9)	11.0 (6.2-20.1, n= 12)	1.0 (0.5-1.3, n= 9)	9.5 (1.3-18.6, n= 12)	3.1 (2.0-3.2, n= 5)	4.3 (3.2-5.4, n= 6)	19.0 (7.8-54.0, n= 9)	48.5 (19.1-94.0, n= 13)
Media Filters (various types)	Inflow	0.7 (0.5-1.1, n= 12)	1.1 (0.6-1.6, n= 12)	0.2 (0.2-0.2, n= 14)	0.4 (0.2-1.0, n= 17)	1.0 (1.0-1.0, n= 13)	2.1 (1.4-4.0, n= 13)	6.2 (5.4-7.4, n= 13)	13.5 (8.8-16.4, n= 18)	1.1 (1.0-2.0, n= 14)	9.0 (5.3-22.0, n= 17)	2.0 (2.0-2.7, n= 13)	3.9 (3.3-4.8, n= 13)	42.7 (28.5-79.2, n= 14)	86.0 (51.8-106.0, n= 19)
	Outflow	0.7 (0.6-1.1, n= 12)	1.1 (0.7-1.6, n= 12)	0.2 (0.2-0.2, n= 13)	0.2 (0.1-0.7, n= 17)	1.0 (1.0-1.0, n= 13)	1.0 (1.0-1.9, n= 13)	5.8 (3.1-8.3, n= 13)	7.3 (4.3-9.6, n= 18)	1.0 (1.0-1.0, n= 13)	1.6 (1.0-4.4, n= 17)	2.0 (2.0-2.6, n= 13)	2.9 (2.0-3.9, n= 13)	12.5 (6.7-49.0, n= 13)	20.0 (8.6-35.0, n= 19)
Retention Pond (aboveground wet pond)	Inflow	NC	1.0 (1.0-1.4, n= 3)	0.2 (0.2-0.4, n= 3)	1.0 (0.3-2.6, n= 20)	5.9 (1.6-10.0, n= 4)	5.0 (3.0-7.4, n= 12)	7.0 (6.0-9.5, n= 7)	6.3 (4.3-10.6, n= 26)	2.0 (1.0-5.1.0, n= 11)	9.7 (4-28, n= 33)	10.0 (6.2-10.0, n= 3)	6.5 (3.6-9, n= 8)	30.0 (15.5-42.6, n= 8)	51.8 (43.9-78.1, n= 32)
	Outflow	NC	1.0 (0.8-1.0, n= 3)	0.2 (0.2-0.4, n= 3)	0.4 (0.2-2.5, n= 20)	5.5 (1.0-10.0, n= 4)	2.2 (1.4-5.3, n= 12)	5.0 (4.7-5.8, n= 7)	5.4 (3.0-6.2, n= 26)	1.2 (1.0-4.9, n= 12)	4.7 (1.6-10.0, n= 33)	10.0 (7.2-10.0, n= 3)	2.5 (2.0-5.5, n= 9)	12.5 (9.4-28.6, n= 8)	26.0 (12.0-37.0, n= 33)
Wetland Basin	Inflow	NA	NA	NC	0.3 (0.3-0.4, n= 3)	NA	NA	NC	10.5 (4.3-15.9, n= 4)	NC	16.0 (4.0-23.8, n= 4)	NA	NA	NC	51.0 (43.9-120.8, n= 7)
	Outflow	NA	NA	0.5 (0.3-0.5, n= 3)	0.3 (0.1-0.5, n= 5)	NA	NA	5.0 (5.0-5.7, n= 3)	4.5 (3.3-5.0, n= 6)	1.0 (0.8-1.0, n= 3)	1.0 (1.0-2.5, n= 6)	NA	NA	11.0 (11.0-13.1, n= 3)	15.0 (5.0-28.9, n= 9)
Permeable Pavement**	Inflow	NA	NC	NC	NA	NC	NC	5.0 (2.5-6.4, n =3)	7.0 (4.5-19.4, n = 3)	0.1 (0.03-0.3, n = 3)	2.5 (1.3-15.1, n = 3)	NC	NC	25.0 (19.0-27.5, n = 3)	50.0 (45.0-51.0, n = 5)
	Outflow	NA	NC	NC	0.3 (0.3-0.4, n =3)	NC	NC	6.2 (4.5-6.4, n =4)	9.0 (3.0-14.7, n = 5)	0.3 (0.04-0.5, n = 4)	2.5 (1.3-9.5, n = 7)	NC	NC	14.6 (13.5-16.0, n = 4)	22.0 (20.0-31.6, n = 7)

Table Key

Sample Type	Analyte	**Description**
Inflow	52.3	= Median inflow value
	(50-63.3, n= 14)	= Interquartile range, sample size
Outflow	22.3	= Median outflow value
	(15-28.3, n= 14)	= Interquartile range, sample size

NA = Not available; studies containing 3 or more storms not available.
NC = Not calculated because fewer than 3 BMP studies for this category.
Interquartile Range = 25th percentile to 75th percentile values, calculated in Excel, which uses linear interpolation to calculate percentiles. For small sample sizes (particularly n<5), interquartile values may vary depending on statistical package used.

Table Notes:

**Permeable pavement data should be used with caution due to limited numbers of BMP studies and small numbers of storm events typically monitored at these sites. "Inflow" values are typically outflows monitored at a reference conventional paving site.

Descriptive statistics calculated by weighting each BMP study equally. Each BMP study is represented by the median analyte value reported for all storms monitored at each BMP (i.e., "n" = number of BMP studies, as opposed to number of storm events). Depending on the analysis objectives, researchers may also choose to use a storm-weighted analysis approach, a unit treatment process-based grouping of studies, or other screening based on design parameters and site-specific characteristics.

Analysis based on August 2010 BMP Database, which contains substantial changes relative to the 2008 BMP Database. Multiple BMPs have been recategorized into new BMP categories; therefore, the 2008 and 2010 data analysis are not directly comparable for several BMP types.

This table contains descriptive statistics only. Values presented in this table should not be used to draw conclusions related to statistically significant differences in performance for BMP categories. (Hypothesis testing for BMP Categories is provided separately in other BMP Database summaries available at www.bmpdatabase.org.)

These descriptive statistics are based on different statistical measures than those used in the 2008 BMP Database tabular summary. Be aware that results will vary depending on whether a "BMP Weighted" (one median or average value represents each BMP) or "Storm Weighted" (all storms for all BMPs included in statistical calculations) approach is used, as well as whether the median or another measure of central tendency is used. Several BMP Database publications in 2010 have focused on the storm-weighted approach, which may result in some differences between this table and other published summaries.

Values below detection limits replaced with 1/2 of detection limit.

1.4 Storage-Based Versus Conveyance-Based

BMPs in this manual generally fall into two categories: 1) storage-based and 2) conveyance-based. Storage-based BMPs provide the WQCV and include bioretention/rain gardens, extended detention basins, sand filters, constructed wetland ponds, retention ponds, and permeable pavement systems. Conveyance-based BMPs include grass swales, grass buffers, constructed wetlands channels and other BMPs that improve quality and reduce volume but only provide incidental storage. Conveyance-based BMPs can be implemented to help achieve objectives in Step 1 of the Four Step Process. Although conveyance BMPs do not satisfy Step 2 (providing the WQCV), they can reduce the volume requirements of Step 2. Storage-based BMPs are critical for Step 2 of the Four Step Process. Site plans that use a combination of conveyance-based and storage-based BMPs can be used to better mimic pre-development hydrology.

1.5 Volume Reduction

BMPs that promote infiltration or that incorporate evapotranspiration have the potential to reduce the volume of runoff generated. Volume reduction is a fundamental objective of LID. Volume reduction has many benefits, both in terms of hydrology and pollution control. While stormwater regulations have traditionally focused on runoff peak flow rates, emerging stormwater regulations require BMPs to mimic the pre-development hydrologic budget to minimize effects of hydromodification. From a pollution perspective, decreased runoff volume translates to decreased pollutant loads. Volume reduction has economic benefits, including potential reductions in storage requirements for minor and major events, reduced extent and sizing of conveyance infrastructure, and cost reductions associated with addressing channel stability issues. UDFCD has developed a computational method for quantifying volume reduction. This is discussed in detail in Chapter 3.

Hydromodification

The term hydromodification refers to altered hydrology due to increased imperviousness combined with constructed of conveyance systems (e.g., pipes) that convey stormwater efficiently to receiving waters. Hydromodification produces increased peaks, volume, frequency, and duration of flows, all of which can result in stream degradation, including stream bed down cutting, bank erosion, enlarged channels, and disconnection of streams from the floodplain. These factors lead to loss of stream and riparian habitat, reduced aquatic diversity, and can adversely impact the beneficial uses of our waterways.

Infiltration-based BMPs can be designed with or without underdrains, depending on soil permeability and other site conditions. The most substantial volume reductions are generally associated with BMPs that have permeable sub-soils and allow infiltration to deeper soil strata and eventually groundwater. For BMPs that have underdrains, there is still potential for volume reduction although to a lesser degree. As runoff infiltrates through BMP soils to the underdrain, moisture is retained by soils. The moisture eventually evaporates, or is taken up by vegetation, resulting in volume reduction. Runoff that drains from these soils via gravity to the underdrain system behaves like interflow from a hydrologic perspective with a delayed response that reduces peak rates. Although the runoff collected in the underdrain system is ultimately discharged to the surface, on the time scale of a storm event, there are volume reduction benefits.

Although effects of evapotranspiration are inconsequential on the time scale of a storm event, on an annual basis, volume reduction due to evapotranspiration for vegetated BMPs such as retention and constructed wetland ponds can be an important component of the hydrologic budget. Between events, evapotranspiration lowers soil moisture content and permanent pool storage, providing additional storage capacity for subsequent events.

Other surface BMPs also provide volume reduction through a combination of infiltration, use by the vegetation and evaporation. Volume reduction provided by a particular BMP type will be influenced by site-specific conditions and BMP design features. National research is ongoing with regard to estimating volume reduction provided by various BMP types. Based on analysis of BMP studies contained in the International Stormwater BMP Database, Geosyntec and WWE (2010) reported that normally-dry vegetated BMPs (filter strips, vegetated swales, bioretention, and grass lined detention basins) appear to have substantial potential for volume reduction on a long-term basis, on the order of 30 percent for filter strips and grass-lined detention basins, 40 percent for grass swales, and greater than 50 percent for bioretention with underdrains. Bioretention facilities without underdrains would be expected to provide greater volume reduction.

1.6 Pretreatment

Design criteria in this manual recommend forebays for extended detention basins, constructed wetland basins, and retention ponds. The purpose of forebays is to settle out coarse sediment prior to reaching the main body of the facility. During construction, source control including good housekeeping can be more effective than pre-treatment. It is extremely important that high sediment loading be controlled for BMPs that rely on infiltration, including permeable pavement systems, rain gardens, and sand filter extended detention basins. These facilities should not be brought on-line until the end of the construction phase when the tributary drainage area has been stabilized with permanent surfaces and landscaping.

1.7 Treatment Train

The term "treatment train" refers to multiple BMPs in series (e.g., a disconnected roof downspout draining to a grass swale draining to a constructed wetland basin.) Engineering research over the past decade has demonstrated that treatment trains are one of the most effective methods for management of stormwater quality (WERF 2004). Advantages of treatment trains include:

- **Multiple processes for pollutant removal**: There is no "silver bullet" for a BMP that will address all pollutants of concern as a stand-alone practice. Treatment trains that link together complementary processes expand the range of pollutants that can be treated with a water quality system and increase the overall efficiency of the system for pollutant removal.

- **Redundancy**: Given the natural variability of the volume, rate and quality of stormwater runoff and the variability in BMP performance, using multiple practices in a treatment train can provide more consistent treatment of runoff than a single practice and provide redundancy in the event that one component of a treatment train is not functioning as intended.

- **Maintenance**: BMPs that remove trash, debris, coarse sediments and other gross solids are a common first stage of a treatment train. From a maintenance perspective, this is advantageous since this first stage creates a well-defined, relatively small area that can be cleaned out routinely. Downgradient components of the treatment train can be maintained less frequently and will benefit from reduced potential for clogging and accumulation of trash and debris.

1.8 Online Versus Offline Facility Locations

The location of WQCV facilities within a development site and watershed requires thought and planning. Ideally this decision-making occurs during a master planning process. Outfall system plans and other reports may depict a recommended approach for implementing WQCV on a watershed basis. Such reports may call for a few large regional WQCV facilities, smaller sub-regional facilities, or an onsite approach. Early in the development process, it is important to determine if a master planning study has been completed that addresses water quality and to attempt to follow the plan's recommendations.

When a master plan identifying the type and location of water quality facilities has not been completed, a key decision involves whether to locate a BMP online or offline. Online refers to locating a BMP such that all of the runoff from the upstream watershed is intercepted and treated by the BMP. A single online BMP should be designed to treat both site runoff and upstream (offsite) runoff. Locating BMPs offline requires that all onsite catchment areas flow though a BMP prior to combining with flows from the upstream (offsite) watershed. Be aware, when water quality BMPs are constructed in "Waters of the State" they must be accompanied by upstream treatment controls and source controls.

When water quality BMPs are constructed in "Waters of the State," they must be accompanied by upstream treatment and source controls.

Online WQCV facilities are only recommended if the offsite watershed has less impervious area than that of the onsite watershed. Nevertheless, online WQCV facilities must be sized to serve the entire upstream watershed based on future development conditions. This recommendation is true even if upstream developments have installed their own onsite WQCV facilities. The only exception to this criterion is when multiple online regional or sub-regional BMPs are constructed in series and a detailed hydrologic model is prepared to show appropriate sizing of each BMP. The maximum watershed recommended for a water quality facility is approximately one square mile. Larger watersheds can be associated with decreased water quality.

1.9 Integration with Flood Control

In addition to water quality, most projects will require detention for flood control, whether on-site, or in a sub-regional or regional facility. In many cases, it is efficient to combine facilities since the land requirements for a combined facility are lower than for two separate facilities. Wherever possible, it is recommended WQCV facilities be incorporated into flood control detention facilities.

Local jurisdictions in the Denver area use different approaches for sizing volumes within a combined water quality and quantity detention facility. This varies from requiring no more than the 100-year detention volume, even though the WQCV is incorporated within it, to requiring the 100-year detention volume plus the full WQCV. This manual does not stipulate or recommend which policy should be used. When a local policy has not been established, UDFCD suggests the following approach:

- **Water Quality**: The full WQCV is to be provided according to the design procedures documented in this manual.
- **Minor Storm (not EURV)**: The full WQCV, plus the full minor storm detention volume, is to be provided.

- **100-Year Storm**: One-half the WQCV plus the full 100-year storm event volume should be provided for volumes obtained using the empirical equations or the FAA Method. When the analysis is done using hydrograph routing methods, each level of controls needs to be accounted for and the resultant 100-year control volume used in final design.
- **100-Year Storm using Full Spectrum Detention**: The full 100-year storm event volume should be provided according to the design protocol provided in the *Storage* chapter of Volume 2.

The *Storage* chapter in Volume 2 provides design criteria for full spectrum detention, which shows more promise in controlling the peak flow rates in receiving waterways than the multi-stage designs described above. Full spectrum detention not only addresses the WQCV for controlling water quality and runoff from frequently occurring runoff events, but also extends that control for all return periods through the 100-year event and closely matches historic peak flows downstream.

Finally, designers should also be aware that water quality BMPs, especially those that promote infiltration, could result in volume reductions for flood storage. These volume reductions are most pronounced for frequently occurring events, but even in the major event, some reduction in detention storage volume can be achieved if volume-reduction BMPs are widely used on a site. Additional discussion on volume reduction benefits, including a methodology for quantifying effects on detention storage volumes, is provided in Chapter 3.

1.9.1 Sedimentation BMPs

Combination outlets are relatively straightforward for most BMPs in this manual. For BMPs that utilize sedimentation (e.g. EDBs, constructed wetland ponds, and retention ponds) see BMP Fact Sheet T-12. This Fact Sheet shows examples and details for combined quality/quantity outlet structures.

1.9.2 Infiltration/Filtration BMPs

For other types of BMPs (e.g. rain gardens, sand filters, permeable pavement systems, and other BMPs utilizing processes other than sedimentation), design of a combination outlet structure generally consists of multiple orifices to provide controlled release of WQCV as well as the minor and major storm event. Incorporation of full spectrum detention into these structures requires reservoir routing. The *UD-Detention* worksheet available at www.udfcd.org can be used for this design. When incorporating flood control into permeable pavement systems, the design can be simplified when a near 0% slope on the pavement surface can be achieved. The flatter the pavement the fewer structures required. This includes lateral barriers as well as outlet controls since each pavement cell typically requires its own outlet structure. When incorporating flood control into a rain garden, the flood control volume can be placed on top of or downstream of the rain garden. Locating the flood control volume downstream can reduce the total depth of the rain garden, which will result in a more attractive BMP, and also benefit the vegetation in the flood control area because inundation and associated sedimentation will be less frequent, limited to events exceeding the WQCV.

1.10 Land Use, Compatibility with Surroundings, and Safety

Stormwater quality areas can add interest and diversity to a site, serving multiple purposes in addition to providing water quality functions. Gardens, plazas, rooftops, and even parking lots can become amenities and provide visual interest while performing stormwater quality functions and reinforcing urban design goals for the neighborhood and community. The integration of BMPs and associated landforms, walls, landscape, and materials can reflect the standards and patterns of a neighborhood and help to create lively, safe, and pedestrian-oriented districts. The quality and appearance of stormwater quality facilities should reflect the surrounding land use type, the immediate context, and the proximity of the site to important civic spaces. Aesthetics will be a more critical factor in highly visible urban commercial and office areas than at a heavy industrial site. The standard of design and construction should maintain and enhance property values without compromising function (WWE et al. 2004).

Public access to BMPs should be considered from a safety perspective. The highest priority of engineers and public officials is to protect public health, safety, and welfare. Stormwater quality facilities must be designed and maintained in a manner that does not pose health or safety hazards to the public. As an example, steeply sloped and/or walled ponds should be avoided. Where this is not possible, emergency egress, lighting and other safety considerations should be incorporated. Facilities should be designed to reduce the likelihood and extent of shallow standing water that can result in mosquito breeding, which can be a nuisance and a public health concern (e.g., West Nile virus). The potential for nuisances, odors and prolonged soggy conditions should be evaluated for BMPs, especially in areas with high pedestrian traffic or visibility.

1.11 Maintenance and Sustainability

Maintenance should be considered early in the planning and design phase. Even when BMPs are thoughtfully designed and properly installed, they can become eyesores, breed mosquitoes, and cease to function if not properly maintained. BMPs can be more effectively maintained when they are designed to allow easy access for inspection and maintenance and to take into consideration factors such as property ownership, easements, visibility from easily accessible points, slope, vehicle access, and other factors. For example, fully consider how and with what equipment BMPs will be maintained in the future. Clear, legally-binding written agreements assigning maintenance responsibilities and committing adequate funds for maintenance are also critical (WWE et al. 2004). The MS4 permit holder may also require right of access to perform emergency repairs/maintenance should it become necessary.

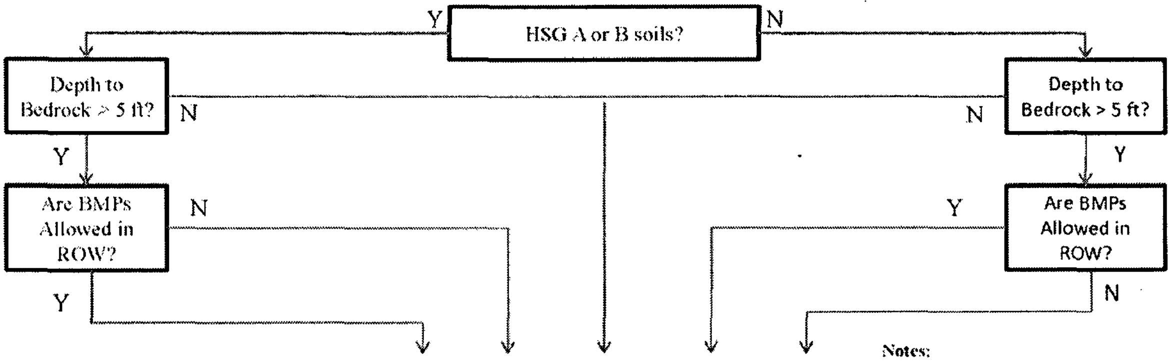
Sustainability of BMPs is based on a variety of considerations related to how the BMP will perform over time. For example, vegetation choices for BMPs determine the extent of supplemental irrigation required. Choosing native or drought-tolerant plants and seed mixes (as recommended in the *Revegetation* chapter of Volume 2) helps to minimize irrigation requirements following plant establishment. Other sustainability considerations include watershed conditions. For example, in watersheds with ongoing development, clogging of infiltration BMPs is a concern. In such cases, a decision must be made regarding either how to protect and maintain infiltration BMPs, or whether to allow use of infiltration practices under these conditions.

1.12 Costs

Costs are a fundamental consideration for BMP selection, but often the evaluation of costs during planning and design phases of a project focuses narrowly on up-front, capital costs. A more holistic evaluation of life-cycle costs including operation, maintenance and rehabilitation is prudent and is discussed in greater detail in Section 4 of this chapter. From a municipal perspective, cost considerations are even broader, involving costs associated with off-site infrastructure, channel stabilization and/or rehabilitation, and protection of community resources from effects of runoff from urban areas.

2.0 BMP Selection Tool

To aid in selection of BMPs, UDFCD has developed a BMP selection tool (*UD-BMP*) to guide users of this manual through many of the considerations identified above and to determine what types of BMPs are most appropriate for a site. This tool helps to screen BMPs at the planning stages of development and can be used in conjunction with the *BMP-REALCOST* tool described in Section 4. Simplified schematics of the factors considered in the *UD-BMP* tool are provided in Figures 2-1, 2-2, and 2-3, which correspond to highly urbanized settings, conventional developments, and linear construction in urbanized areas. Separate figures are provided because each setting or type of development presents unique constraints. Highly urbanized sites are often lot-line to lot-line developments or redevelopments with greater than 90 percent imperviousness with little room for BMPs. Linear construction typically refers to road and rail construction.



Step 1—Runoff Reduction Practices					
Permeable Pavement—Full Infiltration[4]	●	●			
Permeable Pavement—Partial or No Infiltration[4]			●	●	●
Green Roof	●	●[1]	●[1]	●[1]	●[1]
Step 2—Provide WQCV with Slow Release					
Permeable Pavement—Full Infiltration[4]	●	●			
Permeable Pavement --Partial or No Infiltration[4]			●	●	●
Bioretention—Full Infiltration[4]	●	●			
Bioretention—Partial or No Infiltration[4]			●	●	●
Green Roof with Full WQCV	●[1]	●[1]	●[1]	●[1]	●[1]
Underground BMPs with Full WQCV		●[2]			●[2]
Regional Water Quality Treatment	●[3]	●[3]	●[3]	●[3]	●[3]

Notes:

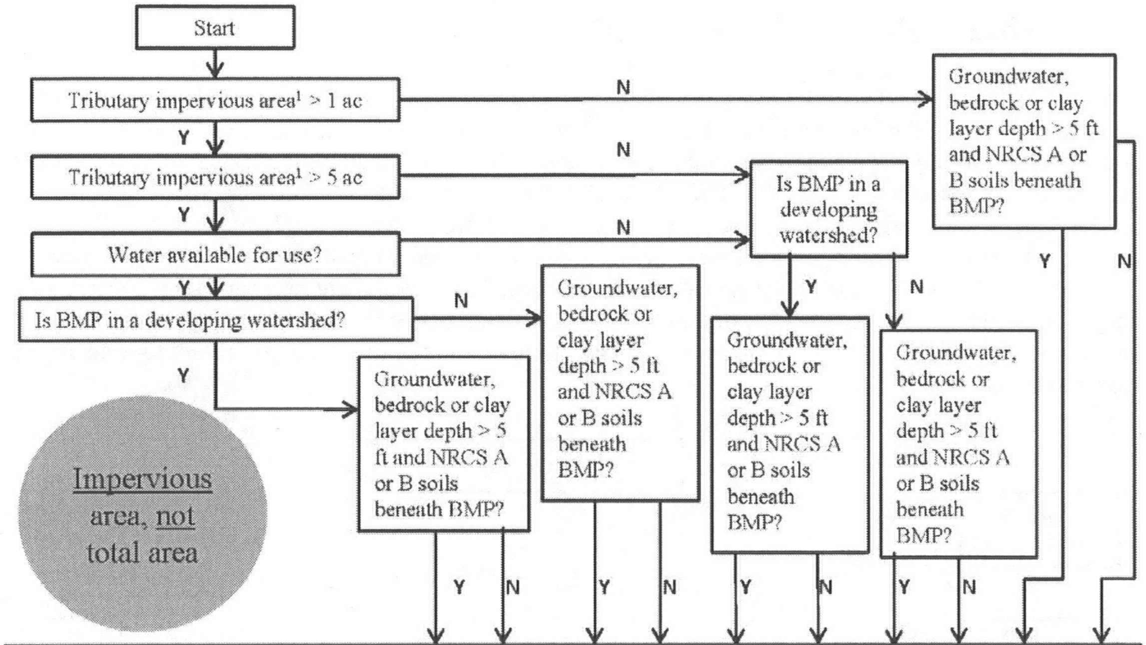
[1] In the Front Range of Colorado, irrigation, at least periodically in dry times, will be required to sustain a green roof.

[2] Underground BMPs should only be considered when surface-based BMPs are not practicable and only when approved by the local jurisdiction. See the Underground BMP Fact Sheet for additional restrictions on use.

[3] If a regional facility will be used to provide the WQCV, some degree of onsite treatment/MDCIA will still likely be required.

[4] No Infiltration = underdrain and liner
Partial Infiltration = underdrain and no liner
Full Infiltration = no underdrain and no liner

Figure 2-1. BMP Decision Tree for Highly Urbanized Sites



Step 1—Runoff Reduction Practices										
Grass Swale	●	●	●	●	●	●	●	●	●	●
Grass Buffer	●	●	●	●	●	●	●	●	●	●
Constructed Wetland Channel[2]	●[2]	●[2]	●[2]	●[2]						
Permeable Pavement—Full Infiltration[5]			●[6]				●[6]		●	
Permeable Pavement—No or Partial Infiltration[5]				●[6]				●[6]		●
Green Roof	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3]	●[3]
Step 2—Provide WQCV with Slow Release										
Permeable Pavement — Full Infiltration[5]			●[6]				●[6]		●	
Permeable Pavement – No or Partial Infiltration[5]				●[6]				●[6]		●
Bioretention—Full Infiltration[5]			●[6]				●[6]		●	
Bioretention—No or Partial Infiltration[5]				●[6]				●[6]		●
Extended Dry Detention Basin	●		●		●		●			
Constructed Wetland Basin[2]	●	●	●	●						
Retention Pond	●	●	●	●						
Sand Filter Extended Detention--Full Infiltration[5]			●				●		●	
Sand Filter Extended Detention--No or Partial Infiltration[5]				●				●		●
Green Roof	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3,6]	●[3]	●[3]
Regional Water Quality Treatment	●[4]	●[4]	●[4]	●[4]	●[4]	●[4]	●[4]	●[4]	●[4]	●[4]

Notes: [1] "Tributary impervious area" refers to the impervious area draining to the BMP, **not** the total area of the project site.

[2] For a successful wetland channel or basin, a water source (groundwater or baseflow) will be required.

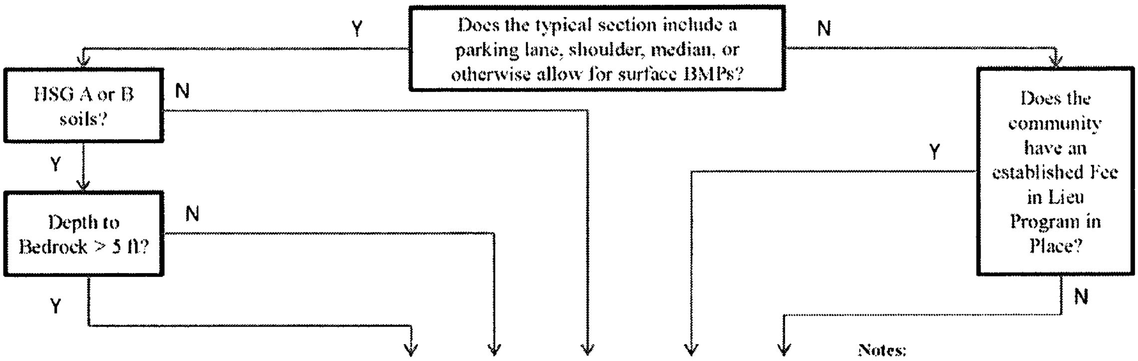
[3] In the Front Range of Colorado, irrigation, at least periodically in dry times, will be required to sustain a green roof.

[4] If a regional facility will be used to provide the WQCV, some degree of onsite treatment/MDCIA will still likely be required.

[5] No Infiltration = underdrain and liner, Partial Infiltration = underdrain and no liner, Full Infiltration = no underdrain and no liner.

[6] Consider this BMP for a portion of your site. It's best suited for impervious tributary areas of approximately one acre or less.

Figure 2-2. BMP Decision Tree for Conventional Development Sites



Step 1—Runoff Reduction Practices					
Permeable Pavement—Full Infiltration[3]	●				
Permeable Pavement—Partial or No Infiltration[3]		●	●		
Biofiltration Tree Planter	●	●	●	●	●
Step 2—Provide WQCV with Slow Release					
Permeable Pavement—Full Infiltration[3]	●				
Permeable Pavement—Partial or No Infiltration[3]		●	●		
Bioretention—Full Infiltration[3]	●				
Bioretention—Partial or No Infiltration[4]		●	●		
Fee in Lieu/Offsite Mitigation				●[4]	
Underground BMPs with Full WQCV				●[1]	●[1]
Regional Water Quality Treatment	●[2]	●[2]	●[2]	●[2]	●[2]

Notes:

[1] Underground BMPs should only be considered when surface-based BMPs are not practicable and only when approved by the local jusisdiction. See the Underground BMP Fact Sheet for additional restrictions on use.

[2] If a regional facility will be used to provide the WQCV, some degree of onsite treatment/MDCIA will still likely be required.

[3] No Infiltration = underdrain and liner
Partial Infiltration = underdrain and no liner
Full Infiltration = no underdrain and no liner

[4] Only recommended when the community has an established program for "Fee in Lieu"

Figure 2-3. BMP Decision Tree for Linear Construction in Urbanized Areas

3.0 Life Cycle Cost and BMP Performance Tool

The importance of cost effective BMP planning and selection is gaining recognition as agencies responsible for stormwater management programs continue to face stricter regulations and leaner budgets. The goal of the *BMP-REALCOST* tool is to help select BMPs that meet the project objectives at the lowest unit cost, where the project objectives are quantifiable measures such as reducing pollutant loads or runoff volumes to a receiving water. To do so, UDFCD has developed an approach that provides estimates for both the whole life costs and performance of BMPs. The approach was developed to be most effective at the large-scale, planning phase; however, it can also be applied to smaller scales during the design phase, perhaps with minor loss of accuracy. The *BMP-REALCOST* spreadsheet tool incorporates this approach and requires minimal user inputs in order to enhance its applicability to planning level evaluations. An overview of the general concepts providing the underlying basis of the tool follows.

3.1 BMP Whole Life Costs

Whole life costs (also known as life cycle costs) refer to all costs that occur during the economic life of a project. This method of cost estimating has gained popularity in the construction and engineering fields over the past few decades and the American Society of Civil Engineers (ASCE) encourages its use for all civil engineering projects. Generally, the components of the whole life cost for a constructed facility include construction, engineering and permitting, contingency, land acquisition, routine operation and maintenance, and major rehabilitation costs minus salvage value. In addition, UDFCD recommends the cost of administering a stormwater management program also be included as a long-term cost for BMPs. Reporting whole life costs in terms of net present value (NPV) is an effective method for comparing mutually exclusive alternatives (Newnan 1996).

To understand the value of using whole life cost estimating, one must first realize how the various costs of projects are generally divided amongst several stakeholders. For example, a developer is typically responsible for paying for the "up front" costs of construction, design, and land acquisition; while a homeowners' association or stormwater management agency becomes responsible for all costs that occur after construction. Many times, the ratios of these costs are skewed one way or another, with BMPs that are less expensive to design and construct having greater long-term costs, and vice versa. This promotes a bias, depending on who is evaluating the BMP cost effectiveness. Whole life cost estimating removes this bias; however, successful implementation of the concept requires a cost-sharing approach where the whole life costs are equitably divided amongst all stakeholders.

The methods incorporated into the *BMP-REALCOST* tool for estimating whole life costs are briefly described below. All cost estimates are considered "order-of-magnitude" approximations, hence UDFCD's recommendation of using this concept primarily at the planning level.

- **Construction Costs:** Construction costs are estimated using a parametric equation that relates costs to a physical parameter of a BMP; total storage volume (for storage-based BMPs), peak flow capacity (for flow-based or conveyance BMPs) or surface area (for permeable pavements).
- **Contingency/Engineering/Administration Costs:** The additional costs of designing and permitting a new BMP are estimated as a percentage of the total construction costs. For Denver-area projects, a value of 40% is recommended if no other information is available.
- **Land Costs:** The cost of purchasing land for a BMP is estimated using a derived equation that incorporates the number of impervious acres draining to the BMP and the land use designation in which the BMP will be constructed.

- **Maintenance Costs:** Maintenance costs are estimated using a derived equation that relates average annual costs to a physical parameter of the BMP.
- **Administration Costs:** The costs of administering a stormwater management program are estimated as percentage of the average annual maintenance costs of a BMP. For Denver-area projects, a value of 12% is recommended if no other information is available.
- **Rehabilitation/Replacement Costs:** After some period of time in operation, a BMP will require "major" rehabilitation. The costs of these activities (including any salvage costs or value) are estimated as a percentage of the original construction costs and applied near the end of the facility's design life. The percentages and design lives vary according to BMP.

3.2 BMP Performance

The performance of structural BMPs can be measured as the reduction in stormwater pollutant loading, runoff volume and runoff peak flows to the receiving water. It is generally acknowledged that estimating BMP performance on a storm-by-storm basis is unreliable, given the inherent variability of stormwater hydrologic and pollutant build-up/wash off processes. Even if the methods to predict event-based BMP performance were available, the data and computing requirements to do so would likely not be feasible at the planning level. Instead, UDFCD recommends an approach that is expected to predict long-term (i.e. average annual) BMP pollutant removal and runoff volume reduction with reasonable accuracy, using BMP performance data reported in the International Stormwater BMP Database (as discussed in Section 1.3).

3.3 Cost Effectiveness

The primary outputs of the *BMP-REALCOST* tool include net present value (NPV) of the whole life costs of the BMP(s) implemented, the average annual mass of pollutant removed (P_R, lbs/year) and the average annual volume of surface runoff reduced (R_R, ft^3/year). These reported values can then be used to compute a unit cost per lb of pollutant (C_P) or cubic feet of runoff (C_R) removed over the economic life (n, years) of the BMP using Equations 2-1 and 2-2, respectively.

$$C_P = \frac{NPV}{nP_R} \qquad \text{Equation 2-1}$$

$$C_R = \frac{NPV}{nR_R} \qquad \text{Equation 2-2}$$

4.0 Conclusion

A variety of factors should be considered when selecting stormwater management approaches for developments. When these factors are considered early in the design process, significant opportunities exist to tailor stormwater management approaches to site conditions. Two worksheets are available at www.udfcd.org for the purpose of aiding in the owner or engineer in the proper selection of treatment BMPs. The *UD-BMP* tool provides a list of BMPs for consideration based on site-specific conditions. *BMP-REALCOST* provides a comparison of whole life cycle costs associated with various BMPs based on land use, watershed size, imperviousness, and other factors.

5.0 References

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Chapter 3
Calculating the WQCV and Volume Reduction

Contents

Figures

Tables

1.0 Introduction

This chapter presents the hydrologic basis and calculations for the Water Quality Capture Volume (WQCV) and discusses the benefits of attenuating this volume or that of the Excess Urban Runoff Volume (EURV). This chapter also describes various methods for quantifying volume reduction when using LID practices. Use of these methods should begin during the planning phase for preliminary sizing and development of the site layout. The calculations and procedures in this chapter allow the engineer to determine effective impervious area, calculate the WQCV, and more accurately quantify potential volume reduction benefits of BMPs.

2.0 Hydrologic Basis of the WQCV

2.1 Development of the WQCV

The purpose of designing BMPs based on the WQCV is to improve runoff water quality and reduce hydromodification and the associated impacts on receiving waters. (These impacts are described in Chapter 1.) Although some BMPs can remove pollutants and achieve modest reductions in runoff volumes for frequently occurring events in a "flow through" mode (e.g., grass swales, grass buffers or wetland channels), to address hydrologic effects of urbanization, a BMP must be designed to control the volume of runoff, either through storage, infiltration, evapotranspiration or a combination of these processes (e.g., rain gardens, extended detention basins or other storage-based BMPs). This section provides a brief background on the development of the WQCV.

The WQCV is based on an analysis of rainfall and runoff characteristics for 36 years of record at the Denver Stapleton Rain Gage (1948-1984) conducted by Urbonas, Guo, and Tucker (1989) and documented in *Sizing a Capture Volume for Stormwater Quality Enhancement* (available at www.udfcd.org). This analysis showed that the average storm for the Denver area, based on a 6-hour separation period, has duration of 11 hours and an average time interval between storms of 11.5 days.

Using WQCV and Flood Control Hydrology

Channels are typically designed for an event that is large and infrequent, such as the 100-year event. A common misconception is that these large events are also responsible for most of the erosion within the drainageway. Instead, the *effective discharge*, by definition, is the discharge that transports the most bedload on an annual basis and this is, therefore, a good estimate of the *channel-forming flow* or the discharge that shapes the drainageway through sediment transport and erosion. The effective discharge does not correlate with a specific return period, but typically is characterized as a magnitude between the annual event and the 5-year peak, depending on reach-specific characteristics.

The typical flood control facility design may include peak reduction of the 5- or 10-year storm event as well as the 100-year event. Widespread use of this practice reduces flooding of streets and flooding along major drainageways. However, this practice does little to limit the frequency of channel-forming flows in drainageways. UDFCD recommends *Full Spectrum Detention,* a concept developed to replicate historic peak flows more closely for a broad spectrum of storm events. Widespread use of Full Spectrum Detention would, in theory, improve channel stability and reduce erosion; however, implementation of Full Spectrum Detention may not be feasible on all sites. Therefore, this manual provides a variety of storage-based BMPs that provide the WQCV and address hydrologic effects of urbanization through storage, infiltration, and/or evapotranspiration.

However, the great majority of storms are less than 11 hours in duration (i.e., median duration is less than average duration). The average is skewed by a small number of storms with long durations. Table 3-1 summarizes the relationship between total storm depth and the annual number of storms. As the table shows, 61% of the 75 storm events that occur on an average annual basis have less than 0.1 inches of precipitation. These storms produce practically no runoff and therefore have little influence in the development of the WQCV. Storm events between 0.1 and 0.5 inches produce runoff and account for 76% of the remaining storm events (22 of the 29 events that would typically produce runoff on an average annual basis). Urbonas et al. (1989) identified the runoff produced from a precipitation event of 0.6 inches as the target for the WQCV, corresponding to the 80th percentile storm event. The WQCV for a given watershed will vary depending on the imperviousness and the drain time of the BMP, but assuming 0.1 inches of depression storage for impervious areas, the maximum capture volume required is approximately 0.5 inches over the area of the watershed. Urbonas et al. (1989) concluded that if the volume of runoff produced from impervious areas from these storms can be effectively treated and detained, water quality can be significantly improved.

For application of this concept at a national level, analysis by Driscoll et al. (1989), as shown in Figure 3-1, regarding average runoff producing events in the U.S. can be used to adjust the WQCV.

Table 3-1. Number of Rainfall Events in the Denver Area
(Adapted from Urbonas et al. 1989)

Total Rainfall Depth (inches)	**Average Annual Number of Storm Events**	**Percent of Total Storm Events**	**Percentile of Runoff-producing Storms**
0.0 to 0.1	46	61.07%	0.00%
0.1 to 0.5	22	29.21%	75.04%
≤ 0.6	**69**	**91.61%**	**80.00%**
0.5 to 1.0	4.7	6.24%	91.07%
1.0 to 1.5	1.5	1.99%	96.19%
1.5 to 2.0	0.6	0.80%	98.23%
2.0 to 3.0	0.3	0.40%	99.26%
3.0 to 4.0	0.19	0.25%	99.90%
4.0 to 5.0	0.028	0.04%	100.00%
> 5.0	0	0.00%	100.00%
TOTAL:	**75**	**100%**	**100%**

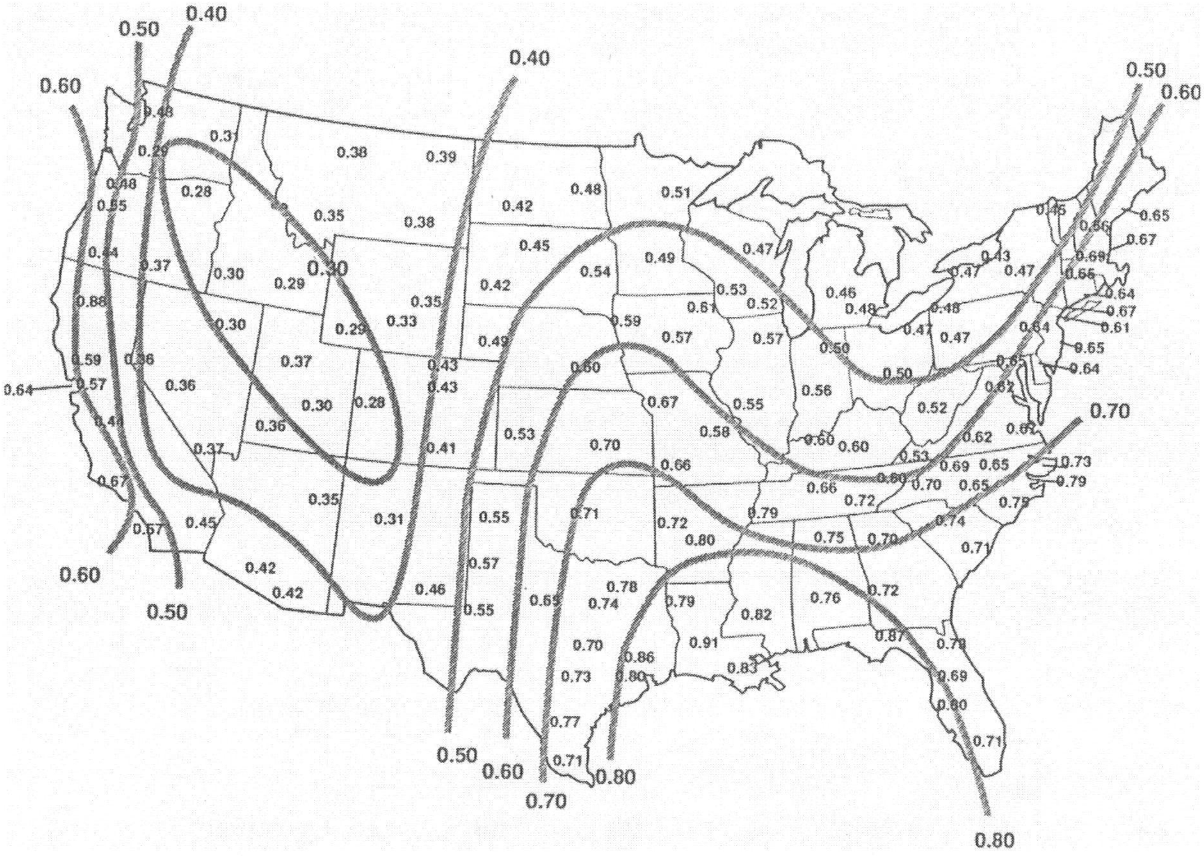

Figure 3-1. **Map of the Average Runoff Producing Storm's Precipitation Depth in the United States In Inches**
(Source: Driscoll et.al., 1989)

2.2 Optimizing the Capture Volume

Optimizing the capture volume is critical. If the capture volume is too small, the effectiveness of the BMP will be reduced due to the frequency of storms exceeding the capacity of the facility and allowing some volume of runoff to bypass treatment. On the other hand, if the capture volume for a BMP that provides treatment through sedimentation is too large, the smaller runoff events may pass too quickly through the facility, without the residence time needed to provide treatment.

Small, frequently occurring storms account for the predominant number of events that result in stormwater runoff from urban catchments. Consequently, these frequent storms also account for a significant portion of the annual pollutant loads. Capture and treatment of the stormwater from these small and frequently occurring storms is the recommended design approach for water quality enhancement, as opposed to flood control facility designs that focus on less frequent, larger events.

The analysis of precipitation data at the Denver Stapleton Rain Gage revealed a relationship between the percent imperviousness of a watershed and the capture volume needed to significantly reduce stormwater pollutants (Urbonas, Guo, and Tucker, 1990). Subsequent studies (Guo and Urbonas, 1996 and Urbonas, Roesner, and Guo, 1996) of precipitation resulted in a recommendation by the Water Environment

Federation and American Society of Civil Engineers (1998) that stormwater quality treatment facilities (i.e., post-construction BMPs) be based on the capture and treatment of runoff from storms ranging in size from "mean" to "maximized[1]" storms. The "mean" and "maximized" storm events represent the 70th and 90th percentile storms, respectively. As a result of these studies, water quality facilities for the Colorado Front Range are recommended to capture and treat the 80th percentile runoff event. Capturing and properly treating this volume should remove between 80 and 90% of the annual TSS load, while doubling the capture volume was estimated to increase the removal rate by only 1 to 2%.

2.3 Attenuation of the WQCV (BMP Drain Time)

The WQCV must be released over an extended period to provide effective pollutant removal for post-construction BMPs that use sedimentation (i.e., extended detention basin, retention ponds and constructed wetland ponds). A field study of basins with extended detention in the Washington, D.C. area identified an average drain time of 24 hours to be effective for extended detention basins. This generally equates to a 40-hour drain time for the brim-full basin. Retention ponds and constructed wetland basins have reduced drain times (12 hours and 24 hours, respectively) because the hydraulic residence time of the effluent is essentially increased due to the mixing of the inflow with the permanent pool.

When pollutant removal is achieved primarily through filtration such as in a sand filter or rain garden BMP, an extended drain time is still recommended to promote stability of downstream drainageways, but it can be reduced because it is not needed for effective pollutant removal. In addition to counteracting hydromodification, attenuation in filtering BMPs can also improve pollutant removal by increasing contact time, which can aid adsorption/absorption processes depending on the media. The minimum recommended drain time for a post-construction BMP is 12 hours; however, this minimum value should only be used for BMPs that do not rely fully or partially on sedimentation for pollutant removal.

2.4 Excess Urban Runoff Volume (EURV) and Full Spectrum Detention

The EURV represents the difference between the developed and pre-developed runoff volume for the range of storms that produce runoff from pervious land surfaces (generally greater than the 2-year event). The EURV is relatively constant for a given imperviousness over a wide range of storm events. This is a companion concept to the WQCV. The EURV is a greater volume than the WQCV and is detained over a longer time. It typically allows for the recommended drain time of the WQCV and is used to better replicate peak discharge in receiving waters for runoff events exceeding the WQCV. The EURV is associated with Full Spectrum Detention, a simplified sizing method for both water quality and flood control detention. Designing a detention basin to capture the EURV and release it slowly (at a rate similar to WQCV release) results in storms smaller than the 2-year event being reduced to flow rates much less than the threshold value for erosion in most drainageways. In addition, by incorporating an outlet structure designed per the criteria in this manual including an orifice or weir that limits 100-year runoff to the allowable release rate, the storms greater than the 2-year event will be reduced to discharge rates and hydrograph shapes that approximate pre-developed conditions. This reduces the likelihood that runoff hydrographs from multiple basins will combine to produce greater discharges than pre-developed conditions.

For additional information on the EURV and Full Spectrum Detention, including calculation procedures, please refer to the *Storage* chapter of Volume 2.

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[1] The term "maximized storm" refers to the optimization of the storage volume of a BMP. The WQCV for the "maximized" storm represents the point of diminishing returns in terms of the number of storm events and volume of runoff fully treated versus the storage volume provided.

3.0 Calculation of the WQCV

The first step in estimating the magnitude of runoff from a site is to estimate the site's total imperviousness. The total imperviousness of a site is the weighted average of individual areas of like imperviousness. For instance, according to Table RO-3 in the *Runoff* chapter of Volume 1 of this manual, paved streets (and parking lots) have an imperviousness of 100%; drives, walks and roofs have an imperviousness of 90%; and lawn areas have an imperviousness of 0%. The total imperviousness of a site can be determined taking an area-weighted average of all of the impervious and pervious areas. When measures are implemented minimize directly connected impervious area (MDCIA), the imperviousness used to calculate the WQCV is the "effective imperviousness." Sections 4 and 5 of this chapter provide guidance and examples for calculating effective imperviousness and adjusting the WQCV to reflect decreases in effective imperviousness.

The WQCV is calculated as a function of imperviousness and BMP drain time using Equation 3-1, and as shown in Figure 3-2:

$$\mathrm{WQCV} = a(0.91I^3 - 1.19I^2 + 0.78I) \qquad \text{Equation 3-1}$$

Where:

WQCV = Water Quality Capture Volume (watershed inches)

a = Coefficient corresponding to WQCV drain time (Table 3-2)

I = Imperviousness (%/100) (see Figures 3-3 through 3-5 [single family land use] and /or the *Runoff* chapter of Volume 1[other typical land uses])

Table 3-2. Drain Time Coefficients for WQCV Calculations

Drain Time (hrs)	**Coefficient, a**
12 hours	0.8
24 hours	0.9
40 hours	1.0

Figure 3-2, which illustrates the relationship between imperviousness and WQCV for various drain times, is appropriate for use in Colorado's high plains near the foothills. For other portions of Colorado or United States, the WQCV obtained from this figure can be adjusted using the following relationships:

$$\mathrm{WQCV}_{\mathrm{other}} = d_6\left(\frac{\mathrm{WQCV}}{0.43}\right) \qquad \text{Equation 3-2}$$

Where:

WQCV = WQCV calculated using Equation 3-1 or Figure 3-2 (watershed inches)

$\mathrm{WQCV}_{\mathrm{other}}$ = WQCV outside of Denver region (watershed inches)

d_6 = depth of average runoff producing storm from Figure 3-1 (watershed inches)

Once the WQCV in watershed inches is found from Figure 3-2 or using Equation 3-1 and/or 3-2, the required BMP storage volume in acre-feet can be calculated as follows:

$$V = \left(\frac{\text{WQCV}}{12}\right)A \qquad \text{Equation 3-3}$$

Where:

V = required storage volume (acre-ft)

A = tributary catchment area upstream (acres)

WQCV = Water Quality Capture Volume (watershed inches)

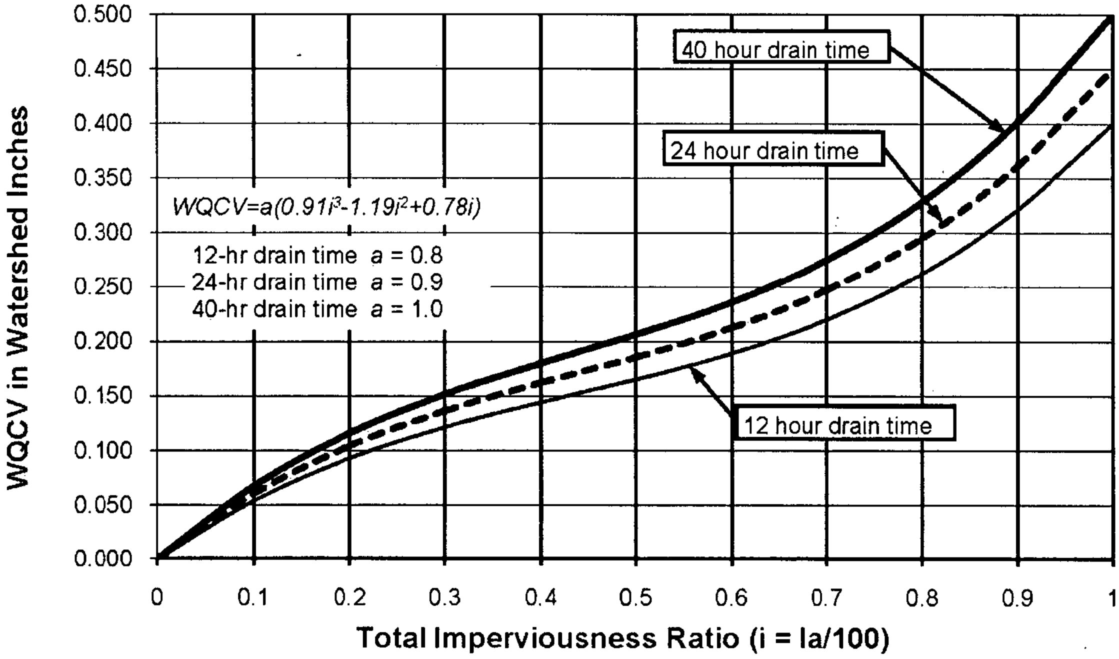

Figure 3-2. Water Quality Capture Volume (WQCV) Based on BMP Drain Time

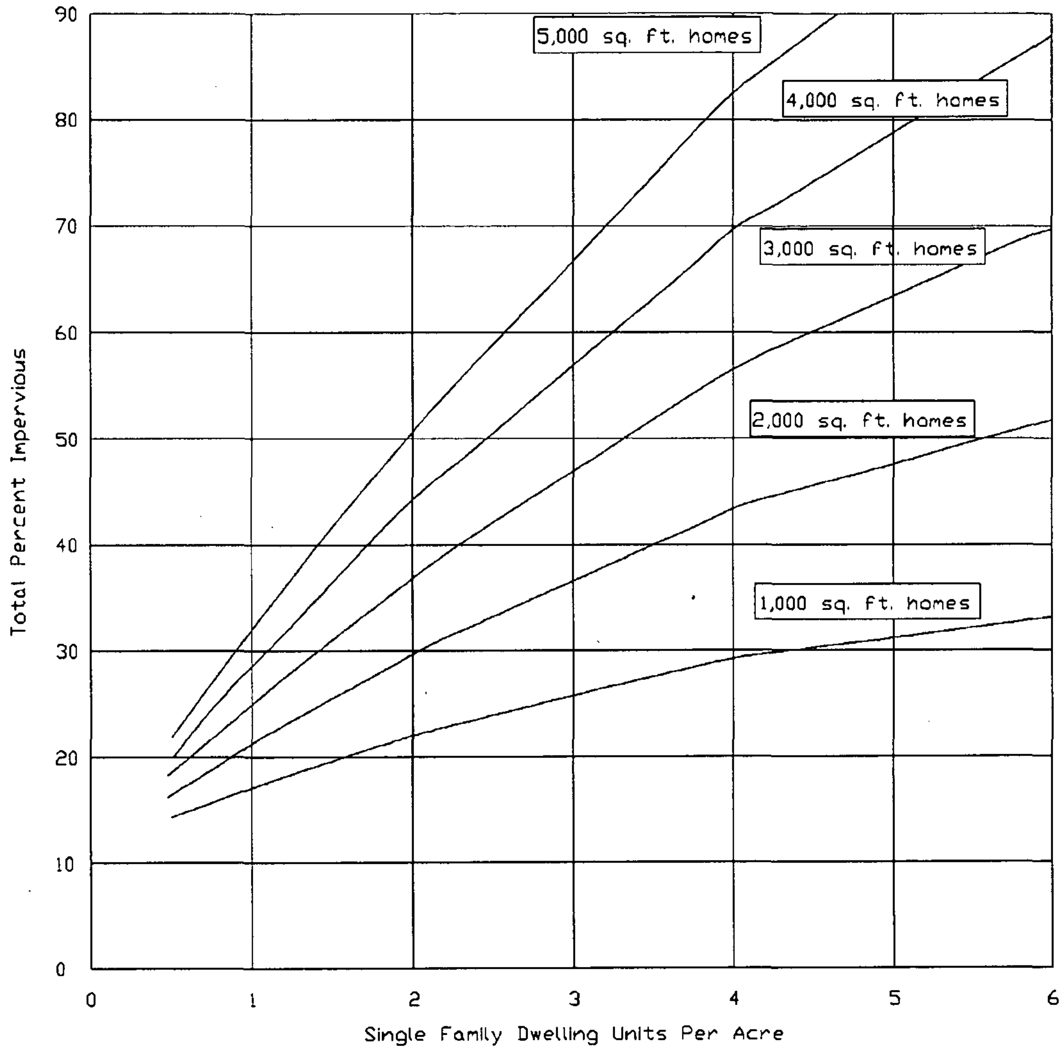

Figure 3-3. Watershed Imperviousness, Single Family Residential Ranch Style Houses

(Note: approximate area based on Tax Assessor's data, not actual "footprint" of homes.)

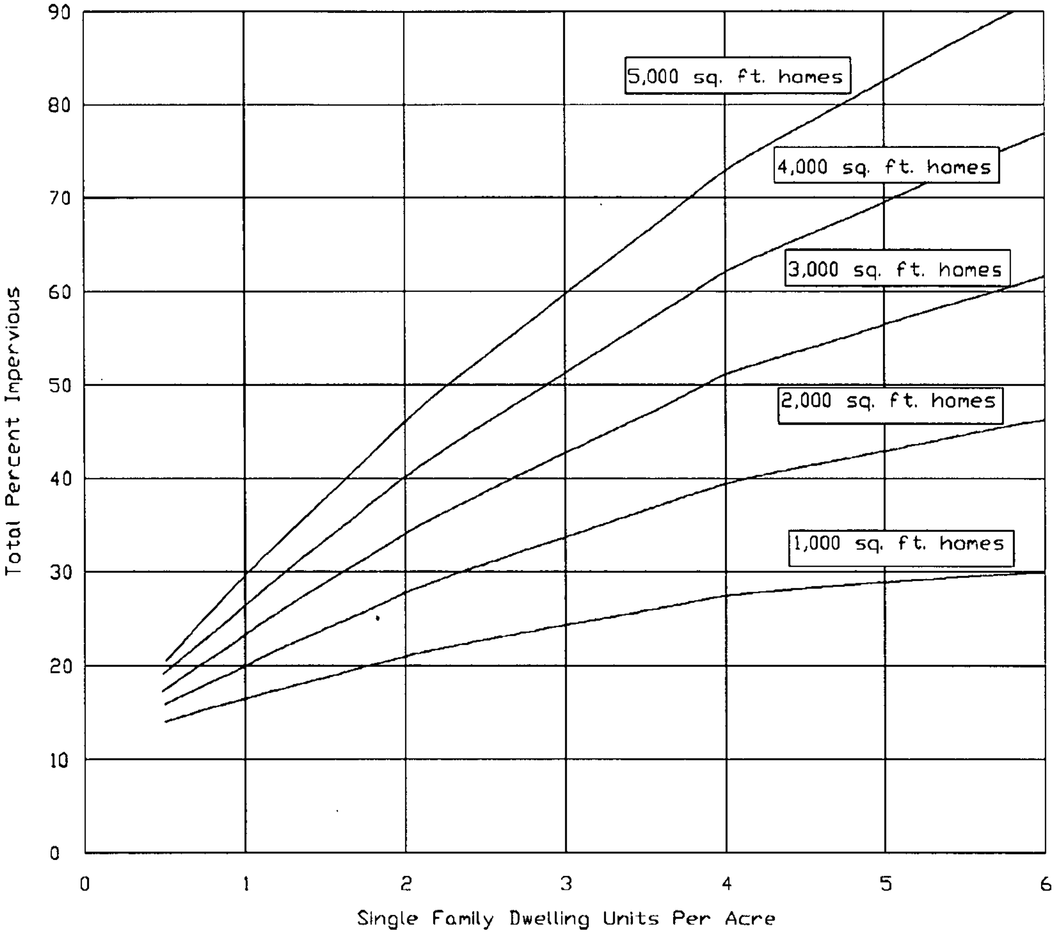

Figure 3-4. Watershed Imperviousness, Single Family Residential Split-Level Houses

(Note: approximate area based on Tax Assessor's data, not actual "footprint" of homes.)

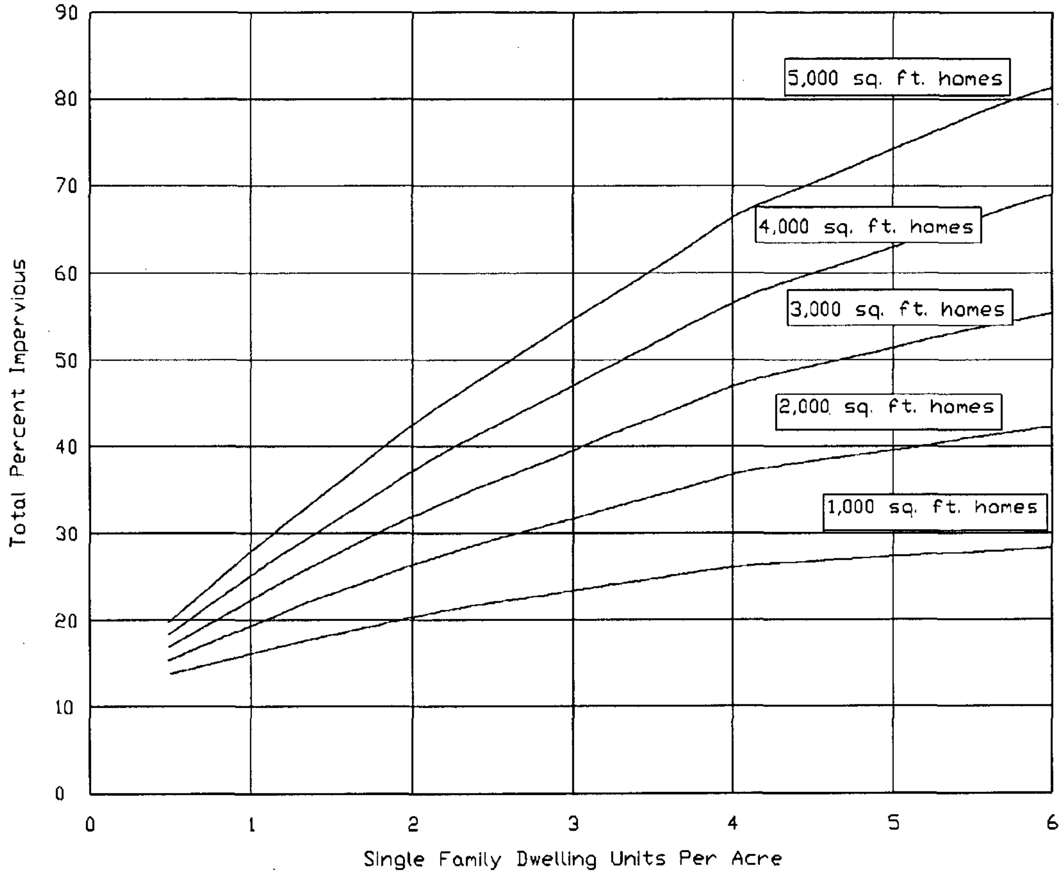

Figure 3-5. Watershed Imperviousness, Single Family Residential Two-Story Houses

(Note: approximate area based on Tax Assessor's data, not actual "footprint" of homes.)

4.0 Quantifying Volume Reduction

Volume reduction is an important part of the Four Step Process and is fundamental to effective stormwater management. Quantifying volume reduction associated with MDCIA, LID practices and other BMPs is important for watershed-level master planning and also for conceptual and final site design. It also allows the engineer to evaluate and compare the benefits of various volume reduction practices. This section describes the conceptual model for evaluating volume reduction and provides tools for quantifying volume reduction using three different approaches, depending on the size of the watershed, complexity of the design, and experience level of the user. In this section volume reduction is evaluated at the watershed level using CUHP and on the site level using SWMM or design curves and spreadsheets developed from SWMM analysis.

Defining Effective Imperviousness

The concepts discussed in this section are dependent on the concept of *effective imperviousness*. This term refers to impervious areas that contribute surface runoff to the drainage system. For the purposes of this manual, effective imperviousness includes directly connected impervious area and portions of the unconnected impervious area that also contribute to runoff from a site. For small, frequently occurring events, the effective imperviousness may be equivalent to directly connected impervious area since runoff from unconnected impervious areas may infiltrate into receiving pervious areas; however, for larger events, the effective imperviousness is increased to account for runoff from unconnected impervious areas that exceeds the infiltration capacity of the receiving pervious area. This means that the calculation of effective imperviousness is associated with a specific return period.

Note: Users should be aware that some national engineering literature defines *effective impervious* more narrowly to include only directly connected impervious area.

4.1 Conceptual Model for Volume Reduction BMPs—Cascading Planes

The hydrologic response of a watershed during a storm event is characterized by factors including shape, slope, area, imperviousness (connected and disconnected) and other factors (Guo 2006). As previously discussed, total imperviousness of a watershed can be determined by delineating roofs, drives, walks and other impervious areas within a watershed and dividing the sum of these impervious areas by the total watershed area. In the past, total imperviousness was often used for calculation of peak flow rates for design events and storage requirements for water quality and flood control purposes. This is a reasonable approach when much of the impervious area in a watershed is directly connected to the drainage system; however, when the unconnected impervious area in a catchment is significant, using total imperviousness will result in over-calculation of peak flow rates and storage requirements.

To evaluate the effects of MDCIA and other LID practices, UDFCD has performed modeling using SWMM to develop tools for planners and designers, both at the watershed/master planning level where site-specific details have not been well defined, and at the site level, where plans are at more advanced stages. Unlike many conventional stormwater models, SWMM allows for a relatively complex evaluation of flow paths through the on-site stormwater BMP layout. Conceptually, an urban watershed can be divided into four land use areas that drain to the common outfall point as shown in Figure 3-6, including:

Directly Connected Impervious Area (DCIA)

Unconnected Impervious Area (UIA)

Receiving Pervious Area (RPA)

Separate Pervious Area (SPA)

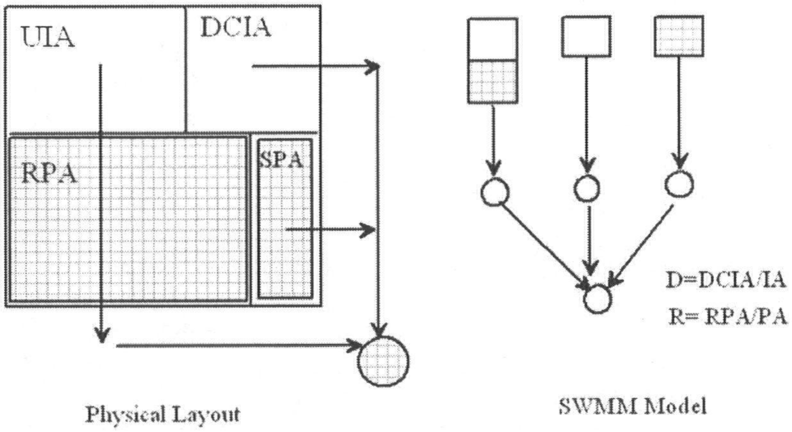

Figure 3-6. Four Component Land Use

A fundamental concept of LID is to route runoff generated from the UIA onto the RPA to increase infiltration losses. To model the stormwater flows through a LID site, it is necessary to link flows similarly to take into consideration additional depression storage and infiltration losses over the pervious landscape. One of the more recent upgrades to SWMM allows users to model overland flow draining from the upper impervious areas onto a downstream pervious area. As illustrated in Figure 3-6, the effective imperviousness is only associated with the cascading plane from UIA to RPA, while the other two areas, DCIA and SPA, are drained independently.

For a well-designed and properly constructed LID site, the effective imperviousness will be less than the total imperviousness. This difference will be greatest for smaller, more frequently occurring events and less for larger, less-frequent events. Aided by SWMM, effective imperviousness can be determined by a runoff-volume weighting method that accounts for losses along the selected flow paths. When designing a drainage system, design criteria that account for effective imperviousness can potentially reduce stormwater costs by reducing the size of infrastructure to convey and/or store the design stormwater flows and volumes. This chapter presents methods that allow the engineer to convert between total imperviousness and effective imperviousness at both the watershed and site scales.

4.2 Watershed/Master Planning-level Volume Reduction Method

For watershed-level assessments and master planning, CUHP provides options for users to model effects of LID through the "D" and "R" curves that are embedded in the model. The "D" curve relates the ratio of DCIA to total impervious area ($D = A_{DCIA}/A_{Imp}$). The "R" curve relates the ratio of RPA to total pervious area ($R = A_{RPA}/A_{Perv}$). Since site-level details (i.e., specific percentages of DCIA, UIA, RPA and SPA for a parcel or site-level drainage basin) are not generally known at the master planning level, UDFCD has developed default values for D and R in CUHP based on SWMM modeling and analysis of typical developments in the Denver metropolitan area. For any given value of total imperviousness, the CUHP model assigns values of D and R based on overall imperviousness and typical development patterns for two levels of LID implementation.[2]

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[2] In previous releases of Volume 3, these levels corresponded to the extent to which MDCIA is implemented as Levels 0, 1, and 2. The terminology (MDCIA) has been replaced with LID and additional return frequencies have been added to the MDCIA curves in Figures 3-7 and 3-8.

1. **Level 1.** The primary intent is to direct the runoff from impervious surfaces to flow over grass-covered areas and/or permeable pavement, and to provide sufficient travel time to facilitate the removal of suspended solids before runoff leaves the site, enters a curb and gutter system, or enters another stormwater collection system. Thus, at Level 1, to the extent practical, impervious surfaces are designed to drain over grass buffer strips or other pervious surfaces before reaching a stormwater conveyance system.

2. **Level 2.** As an enhancement to Level 1, Level 2 replaces solid street curb and gutter systems with no curb or slotted curbing, low-velocity grass-lined swales and pervious street shoulders, including pervious rock-lined swales. 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 storm sewer. The primary difference between Levels 1 and 2 is that for Level 2, a pervious conveyance system (i.e., swales) is provided rather than storm sewer. Disconnection of roof drains and other lot-level impervious areas is essentially the same for both Levels 1 and 2.

Figure 3-7 and Figure 3-8 can be used to estimate effective imperviousness for Level 1 and Level 2. Because rainfall intensity varies with return interval, the effective imperviousness also varies, as demonstrated by the separate curves for the 2-, 10- and 100-year return intervals (see Figure 3-7 and Figure 3-8). The effective imperviousness determined from Figure 3-7 and Figure 3-8 can be used as input for calculation of the WQCV, as the basis for looking up runoff coefficients based on imperviousness in the *Runoff* chapter in Volume 1 and for calculation of empirical storage volumes in accordance with the *Storage* chapter in Volume 2. Figure 3-7 and Figure 3-8 are intended for use at the planning level when specifics of the D and R relationships in CUHP are not yet well established.

It is notable that the reductions in effective imperviousness shown in Figure 3-7 and Figure 3-8 are relatively modest, ranging from little to no benefit for large events up to approximately 12% for Level 2 for a total imperviousness of roughly 50% (reduced to about 38% for the 2-year event). This is a function of the D and R relationships defined in CUHP. When site-level details are still in conceptual stages, the use of default D and R values for Levels 1 and 2 provides a tool for a master planning/watershed level assessment of effects of disconnected impervious area. At a more advanced stage of design, when site-specific disconnected areas, receiving pervious areas, flow paths, and other design details are available, the site-level methods in Section 4.3 can be used to better quantify volume reduction, and results will typically show greater reductions in effective imperviousness for aggressive LID implementation than reflected in the default D and R relationships used to create Figure 3-7 and Figure 3-8. Even so, it is unlikely that conveyance-based BMPs alone will provide adequate pollutant removal and volume reduction for most project sites, and a storage-based BMP (i.e., WQCV) will also be required.

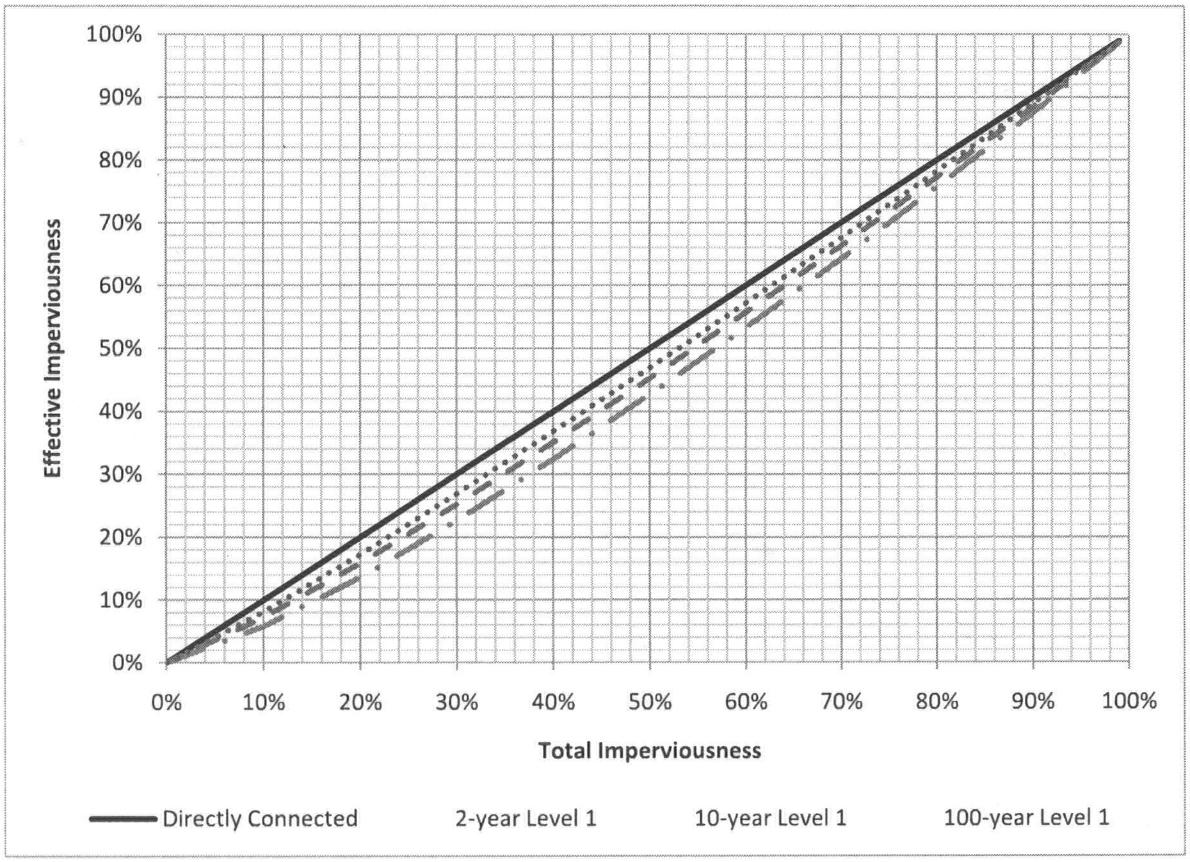


Figure 3-7. Effective Imperviousness Adjustments for Level 1 MDCIA

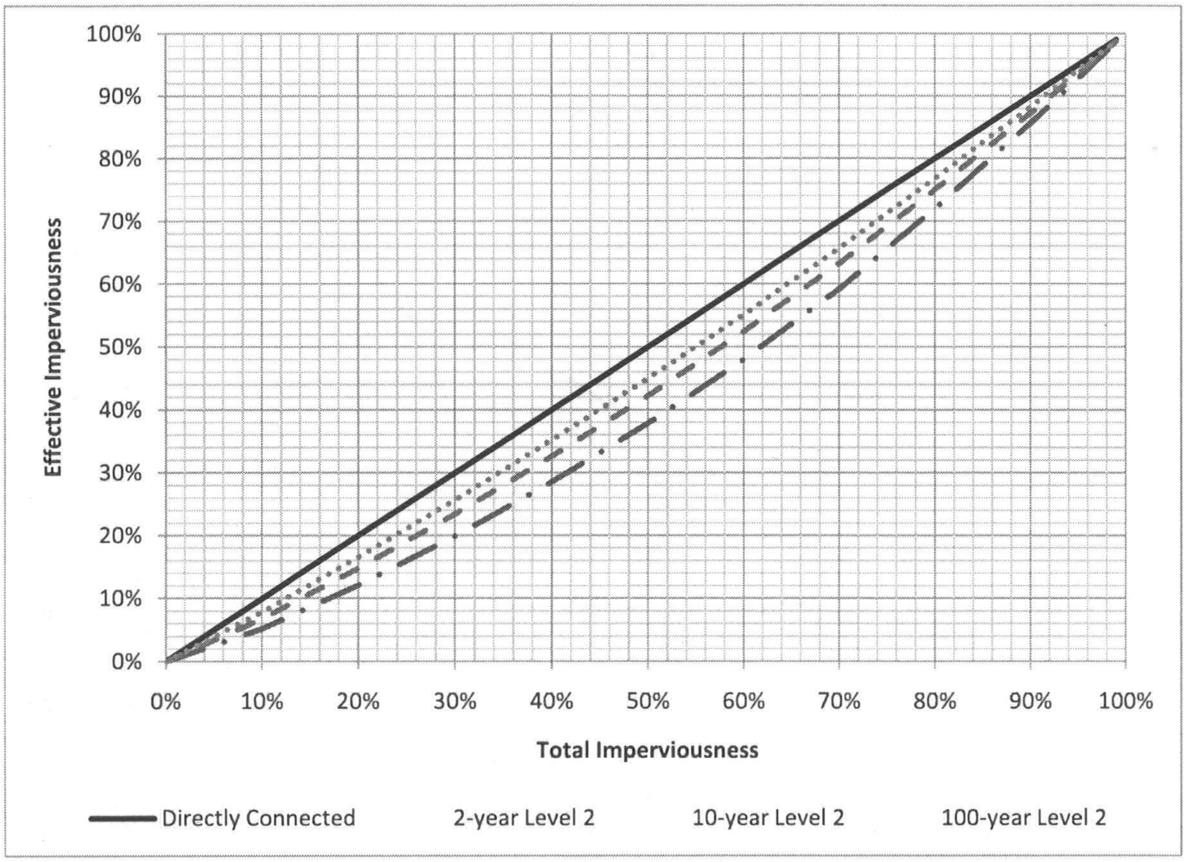


Figure 3-8. **Effective Imperviousness Adjustments for Level 2 MDCIA**

4.3 Site-level Volume Reduction Methods

For site-level planning, whether at a conceptual level or a more advanced stage of design, it is not necessary to use default D and R values if the various area fractions of a site (i.e., DCIA, UIA, RPA, and SPA) can be defined. Two options are available for quantification of volume reduction at the site level when these fractions have been identified:

1. SWMM modeling using the cascading plane approach, or
2. UDFCD Imperviousness Reduction Factor (IRF) charts and spreadsheet (located within the *UD-BMP* workbook available at www.udfcd.org)

The UDFCD IRF charts and spreadsheet were developed using a dimensionless SWMM modeling approach developed by Guo et al. (2010) that determines the effective imperviousness of a site based on the total area-weighted imperviousness and the ratio of the infiltration rate (average infiltration rate based on Green-Ampt), *f*, to the rainfall intensity, *I*. Because the IRF is based on cascading plane CUHP/SWMM modeling, it will yield results that are generally consistent with creation of a site-specific SWMM model.

To apply either of the above methods, a project site must first be divided into sub-watersheds based on topography and drainage patterns. For each sub-watershed, the areas of DCIA, UIA, RPA and SPA should be calculated. Sub-watersheds (and associated BMPs) will fall into one of two categories based on the types of BMPs used:

1. **Conveyance-based:** Conveyance-based BMPs include grass swales, vegetated buffers, and disconnection of roof drains and other impervious areas to drain to pervious areas (UDFCD 1999a). Conveyance based BMPs may have some incidental, short-term storage in the form of channel storage or shallow ponding but do not provide the WQCV, EURV or flood-control detention volume.

2. **Storage-based:** Storage-based BMPs include rain gardens, permeable pavement systems as detailed in this manual, extended detention basins and other BMPs in this manual that provide the WQCV, EURV or flood control detention volume.

4.3.1 SWMM Modeling Using Cascading Planes

Because of complexities of modeling LID and other BMPs using SWMM, the cascading planes alternative for site-level volume reduction analysis is recommended only for experienced users. Guidance for conveyance- and storage-based modeling includes these steps:

1. Each sub-watershed should be conceptualized as shown in Figure 3-6. Two approaches can be used in SWMM to achieve this:

    - Create two SWMM sub-catchments for each sub-watershed, one with UIA 100% routed to RPA and the other with DCIA and SPA independently routed to the outlet, or

    - Use a single SWMM sub-catchment to represent the sub-watershed and use the SWMM internal routing option to differentiate between DCIA and UIA. This option should only be used when a large portion of the pervious area on a site is RPA and there is very little SPA since the internal routing does not have the ability to differentiate between SPA and RPA (i.e., the UIA is routed to the entire pervious area, potentially overestimating infiltration losses).

2. Once the subwatershed is set up to represent UIA, DCIA, RPA and SPA in SWMM, the rainfall distribution should be directly input to SWMM. As an alternative, SWMM can be used only for routing with rainfall-runoff handled in CUHP using sub-watershed specific D and R values to define fractions of pervious and impervious areas.

3. Parameters for infiltration, depression storage and other input parameters should be selected in accordance with the guidance in the *Runoff* chapter of Volume 1.

4. For storage-based BMPs, there are two options for representing the WQCV:

    - The pervious area depression storage value for the RPA can be increased to represent the WQCV. This approach is generally applicable to storage-based BMPs that promote infiltration such as rain gardens, permeable pavement systems with storage or sand filters. This adjustment should not be used when a storage-based BMP has a well-defined outlet and a stage-storage-discharge relationship that can be entered into SWMM.

- The WQCV can be modeled as a storage unit with an outlet in SWMM. This option is preferred for storage-based BMPs with well defined stage-storage-discharge relationships such as extended detention basins.

These guidelines are applicable for EPA SWMM Version 5.0.018 and earlier versions going back to EPA SWMM 5.0. EPA is currently developing a version of EPA SWMM with enhanced LID modeling capabilities; however, this version had not been fully vetted at the time this manual was released.

4.3.2 IRF Charts and Spreadsheet

When UIA, DCIA, RPA, SPA and WQCV, if any, for a site have been defined, this method provides a relatively simple procedure for calculating effective imperviousness and volume reduction. Fundamentally, the IRF charts and spreadsheet are based on the following relationships.

For a conveyance-based approach:

$$K = \mathrm{Fct}\left(\frac{F_d}{P}, A_r\right) = \left(\mathrm{Fct}\frac{f}{I}, A_r\right)$$

For a storage-based approach:

$$K = \mathrm{Fct}\left(\frac{F_d}{P}, A_r, A_d\frac{\mathrm{WQCV}}{P}\right)$$

Where Fct designates a functional relationship and:

K = IRF (effective imperviousness/total imperviousness)

F_d = pervious area infiltration loss (in)

P = design rainfall depth (in)

A_r = RPA/UIA

f = pervious area average infiltration rate (in/hr)

I = rainfall intensity (in/hr)

A_d = RPA

WQCV = Water Quality Capture Volume (watershed inches)

A full derivation of equations based on these functional relationships can be found in Guo et al. (2010). The results of cascading plane modeling based on these relationships is shown in Figure 3-9 for the conveyance-based approach and Figure 3-10 for the storage-based approach.

Table 3-3 provides average infiltration rates that should be used for IRF calculations as a function of soil type and drain time.

Table 3-3. Infiltration Rates (*f*) for IRF Calculations

Soil Type	Conveyance-based[1]	Storage-based		
		12-hours	24-hours	40-hours
	(in/hr)	(in/hr)	(in/hr)	(in/hr)
Sand	5.85	5.04	4.91	4.85
Loamy Sand	1.92	1.40	1.31	1.27
Sandy Loam	1.04	0.64	0.56	0.52
Silt Loam	0.83	0.46	0.39	0.35
Loam	0.43	0.24	0.20	0.18
Sandy Clay Loam	0.34	0.16	0.13	0.11
Silty Clay Loam	0.27	0.13	0.10	0.08
Clay Loam	0.26	0.13	0.10	0.08
Silty Clay	0.18	0.08	0.06	0.05
Sandy Clay	0.16	0.08	0.06	0.05
Clay	0.12	0.05	0.04	0.03

[1] Values for conveyance-based BMPs are based on a 2-hour duration.

When using Figure 3-9 and Figure 3-10, it is important to understand that the curves are based on ratios of infiltration and precipitation ***rates***, not depths. Therefore the f/I = 2.0 curve could represent soils an average infiltration rate of 1 inch per hour and an event with a total precipitation of 0.5 inches in 1 hour (i.e., an event with a total depth that is roughly the same as the WQCV) or a longer event, such as 2.0 inches over 4 hours, which still would have a rainfall intensity of 0.5 inches per hour but that would have a total precipitation depth and overall runoff volume greater than the WQCV. Therefore, when using the storage-based curves in Figure 3-10 for small events, it is important to check the total precipitation depth as well as the f/I ratio. In cases where the total precipitation depth is less than 0.6 inches and the full WQCV is provided, the IRF, represented as *K*, can be set to 0 since all of the runoff will be captured by the storage-based BMP and released over an extended period, having minimal downstream effect on the timescale of an event. The *UD-BMP* worksheet approximates one-hour precipitation intensity as the one hour point precipitation depth and performs a check of the precipitation depth relative to the WQCV, assigning $K = 0$, when the precipitation depth is less than the WQCV for storage-based BMPs.

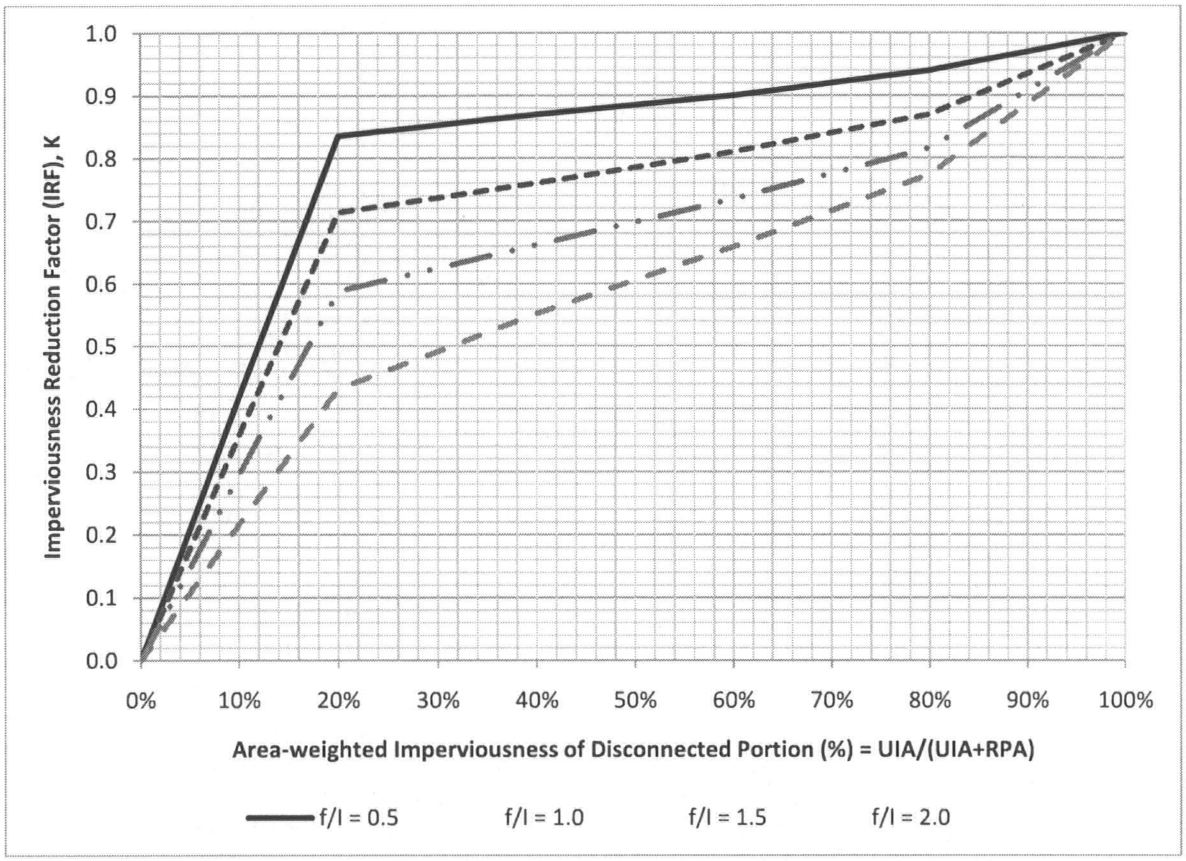


Figure 3-9. Conveyance-based Imperviousness Reduction Factor

Once *K* is known for a given storm event, the following equation can be used to calculate the effective imperviousness for that event:

$$I_{\text{Effective}}(\%) = \left(\frac{\text{DCIA} + (K \cdot \text{UIA})}{\text{DCIA} + \text{UIA} + \text{RPA} + \text{SPA}}\right) \cdot 100$$ Equation 3-4

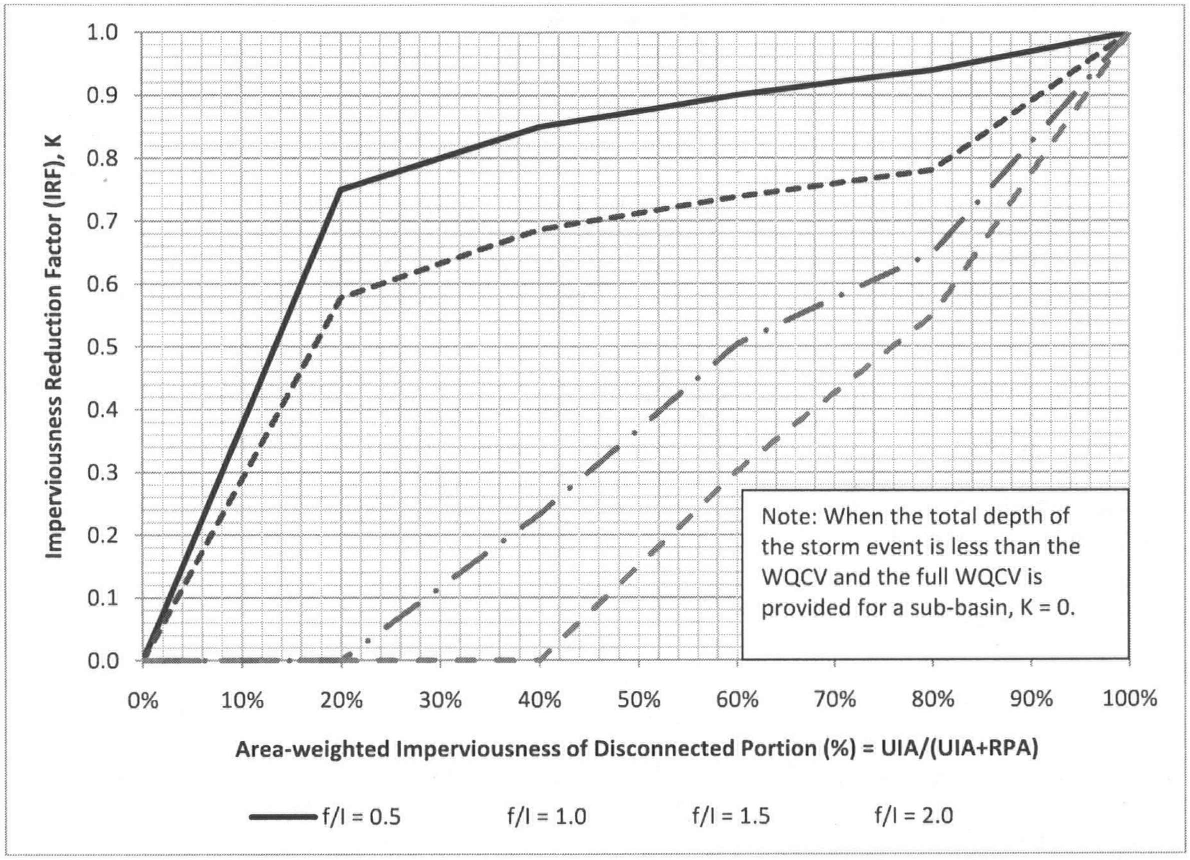
Where:

DCIA = directly connected impervious area

UIA = unconnected impervious area

RPA = receiving pervious area

SPA = separate pervious area



Note: When the total depth of the storm event is less than the WQCV and the full WQCV is provided for a sub-basin, K = 0.

Figure 3-10. Storage-based Imperviousness Reduction Factor

Four basic steps can be used to determine effective imperviousness when parameters including UIA, DCIA, RPA, SPA, WQCV, *f* and *I* are known. For clarity, these steps are accompanied by an example using a sub-watershed with a conveyance-based approach (i.e., no WQCV) with UIA = 0.25 acres, DCIA = 0.25 acres, RPA = 0.25 acres, SPA = 0.25 acres, *f* = 1.0 inch/hour and *I* = 0.5 inch/hour.

1. Calculate the area-weighted imperviousness of the disconnected portion. The disconnected portion of the sub-watershed consists of the UIA and the RPA. The area weighted imperviousness is calculated as UIA/(UIA+RPA).

   For the example, UIA + RPA = 0.25 + 0.25 = 0.50 acres. The area-weighted imperviousness of this area = 0.25/0.50 = 0.50 or 50%.

2. Calculate f/I based on the rainfall intensity for the design storm and the infiltration rate for the given RPA soil type. In this example, the 1-hour intensity is given as 0.5 inch/hour in the problem statement, and the infiltration rate is specified as 1 inch/hour. For this example, based on Table 3-3, the 1.0 inch/hour infiltration rate specified in the problem statement would roughly correspond to a sandy loam soil type for a conveyance-based BMP.

   For the example, *f/I* = 1.0/0.5 = 2.0.

For simplicity, the 1-hour rainfall intensity can be approximated as the 1-hour point precipitation depth for a given frequency. The 1-hour point precipitation values can be determined from Rainfall Depth-Duration-Frequency figures in the *Rainfall* chapter of Volume 1.

3. Using the appropriate figure (Figure 3-9 for the conveyance-based approach or Figure 3-10 for the storage-based approach), determine the Imperviousness Reduction Factor, *K*, corresponding to where the appropriate *f/I* line would be intersected by the x-axis value for area-weighted imperviousness. **Note: Figure 3-10 for the storage-based approach should only be used if the full WQCV is provided for the sub-watershed**. If quantification of volume reduction benefits of only a fraction of the WQCV (one-half for example) is required, Figure 3-10 is not applicable and SWMM modeling will be required.

   For the example, the *K* value corresponding to *f/I* = 2.0 and an area-weighted imperviousness of 50% using the conveyance-based chart, Figure 3-9, is 0.60. **It is very important to note that this *K* value applies only to the disconnected portion of the sub-watershed (i.e., UIA + RPA).**

4. Calculate the effective imperviousness of the sub-watershed. This calculation must factor in both connected and disconnected portions of the site:

$$I_{\text{Effective}}(\%) = \left(\frac{\text{DCIA} + (K \cdot \text{UIA})}{\text{DCIA} + \text{UIA} + \text{RPA} + \text{SPA}}\right) \cdot 100$$

   For the example, with DCIA = UIA = RPA = SPA = 0.25 acres and *K* = 0.60:

$$I_{\text{Effective}}(\%) = \left(\frac{0.25 + (0.60 \cdot 0.25)}{0.25 + 0.25 + 0.25 + 0.25}\right) \cdot 100 = 40\%$$

   This can be compared to the total area-weighted imperviousness for the sub-watershed = (DCIA + UIA)/ (DCIA + UIA + RPA + SPA) × 100% = 50%.

   To calculate volume reduction benefits associated with conveyance- or storage-based approaches, the effective imperviousness values determined according to this procedure (or using the spreadsheet tool *UD-BMP*) can be used in WQCV calculations and detention storage equations, such as the empirical storage equations in the *Storage* chapter of Volume 1. The WQCV and detention volume requirements calculated using the effective imperviousness can be compared with the same calculations using total sub-watershed imperviousness to determine potential volume reductions.

   Section 5.2 provides an example of the storage-based approach to complement the conveyance-based example above, as well as guidance for using the spreadsheet tool.

4.4 Other Types of Credits for Volume Reduction BMPs/LID

In addition to facility sizing reduction credits following the quantitative procedures in Section 4.3, communities can also consider other incentives to encourage volume reduction practices. Such incentives will depend on the policies and objectives of local governments. Representative examples that could be considered include:

- Stormwater utility fee credits.
- Lower stormwater system development fees when certain minimum criteria are met.

- Density bonuses that allow greater residential densities with the implementation of LID techniques.
- Variances for requirements such as number of required parking spaces or road widths.
- Flexibility in bulk, dimensional and height restrictions, allowing greater building heights and floor area ratios, reduced setbacks and others.
- Fast tracking the review process to provide priority status to LID projects with decreased time between receipt and review. If LID projects typically result in a longer review process, ensure equal status.
- Publicity such as providing recognition on websites, at Council meetings and in utility mailers.
- Opportunities for grant funding for large public projects serving as demonstration projects.
- LEED credits for those pursuing U.S. Green Building Council certification. Other green building credit programs such as those related to the Sustainable Sites Initiative may also be applicable.
- Flexibility with landscaping requirements (i.e. allowing vegetated BMPs to help satisfy landscape requirements or allowing BMPs to be located in the right-of-way.
- LEED credits for those pursuing U.S. Green Building Council certification. Other credit programs such those related to the Sustainable Sites Initiative may also be applicable.

5.0 Examples

5.1 Calculation of WQCV

Calculate the WQCV for a 1.0-acre sub-watershed with a total area-weighted imperviousness of 50% that drains to a rain garden (surface area of the rain garden is included in the 1.0 acre area):

1. Determine the appropriate drain time for the type of BMP. For a rain garden, the required drain time is 12 hours. The corresponding coefficient, *a*, from Table 3-2 is 0.8.
2. Either calculate or use Figure 3-2 to find the WQCV based on the drain time of 12 hours ($a = 0.8$) and total imperviousness = 50% ($I = 0.50$ in Equation 3-1):

$$\mathrm{WQCV} = 0.8(0.91(0.50)^3 - 1.19(0.50)^2 + 0.78(0.50))$$

$$\mathrm{WQCV} = 0.17 \text{ watershed inches}$$

3. Calculate the WQCV in cubic feet using the total area of the sub-watershed and appropriate unit conversions:

$$\mathrm{WQCV} = (0.17\ \mathrm{w.s.in.})(1\ \mathrm{ac})\left(\frac{1\mathrm{ft}}{12\ \mathrm{in}}\right)\left(\frac{43560\ \mathrm{ft}^2}{1\ \mathrm{ac}}\right) \approx 600\ \mathrm{ft}^3$$

Although this example calculated the WQCV using total area-weighted imperviousness, the same calculation can be repeated using effective imperviousness if LID BMPs are implemented to reduce runoff volume.

5.2 Volume Reduction Calculations for Storage-based Approach

Determine the effective imperviousness for a 1-acre sub-watershed with a total imperviousness of 50% that is served by a rain garden (storage-based BMP) for the water quality and 10-year events. Assume that the pervious area is equally-split between RPA and SPA with 0.25 acres for each and that the RPA is a rain garden with a sandy loam soil. Because a rain garden provides the WQCV, the curves for the storage-based approach can be used with UIA = 0.50 acres (1 acre · 50% impervious), RPA = 0.25 acres, SPA = 0.25 acres. There is no DCIA because everything drains to the rain garden in this example. To determine *f*, use Table 3-3 to look up the recommended infiltration rate for a sandy loam corresponding to a 12-hour drain time—the resulting infiltration rate is 0.64 inches/hour.

1. Calculate the area-weighted imperviousness of the disconnected portion. The disconnected portion of the sub-watershed consists of the UIA and the RPA. The area weighted imperviousness is calculated as UIA/(UIA+RPA).

   For the example, UIA + RPA = 0.50 + 0.25 = 0.75 acres. The area-weighted imperviousness of this area = 0.50/0.75 = 0.67 or 67%.

2. Determine rainfall intensities for calculation of *f/I* ratios. For the water quality event, which is roughly an 80th percentile event, there is no specified duration, so assume rainfall intensity based on a 1-hour duration, giving an intensity of approximately 0.6 inches/hour. For the water quality event, this is generally a conservative assumption since the runoff that enters the rain garden will have a mean residence time in the facility of much more than 1 hour. For the 10-year event, the 1-hour point rainfall depth from the *Rainfall* chapter, can be used to approximate the rainfall intensity for calculation of the *f/I* ratio. For this example, the 1-hour point precipitation for the 10-year event is approximately 1.55 inches, equating to an intensity of 1.55 inches/hour.

3. Calculate *f/I* based on the design rainfall intensity (0.6 inches/hour) and RPA infiltration rate from Table 3-3 (0.64 inches/hour).

   For the water quality event, *f/I* = 0.64/0.6 = 1.07.

   For the 10-year event, *f/I* = 0.64/1.55 = 0.41.

4. Using the appropriate figure (Figure 3-10 for the storage-based approach in this case), determine the Imperviousness Reduction Factor *K*, corresponding to where the appropriate *f/I* line would be intersected by the x-axis value for area-weighted imperviousness.

   For the water quality event, the *K* value corresponding to *f/I* = 1.07 and an area-weighted imperviousness of 50% using the storage-based chart, Figure 3-10, would be approximately 0.64; however, because the total depth of the water quality event is provided as the WQCV for the storage-based rain garden, *K* is reduced to 0 for the water quality event.

   For the 10-year event, the *K* value corresponding to *f/I* = 0.41 and an area-weighted imperviousness of 50% using the storage-based chart, Figure 3-10, is approximately 0.94.

   It is very important to note that these *K* value applies only to the disconnected portion of the sub-watershed (i.e., UIA + RPA). If this example included DCIA, the total imperviousness would be higher.

5. Calculate the effective imperviousness of the sub-watershed. This calculation must factor in both connected and disconnected portions of the site:

$$I_{\text{Effective}} = \left(\frac{\text{DCIA} + (K \cdot \text{UIA})}{\text{DCIA} + \text{UIA} + \text{RPA} + \text{SPA}}\right) \cdot 100$$

For the water quality event, with DCIA = 0 acres, UIA = 0.5 acres and RPA = SPA = 0.25 acres, with $K = 0$:

$$I_{\text{Effective}} = \left(\frac{0.00 + (0.0 \cdot 0.5)}{0.0 + 0.5 + 0.25 + 0.25}\right) \cdot 100 = 0\%$$

For the 10-year event, with DCIA = 0 acres, UIA = 0.5 acres and RPA = SPA = 0.25 acres, with $K = 0.94$:

$$I_{\text{Effective}} = \left(\frac{0.00 + (0.94 \cdot 0.5)}{0.0 + 0.5 + 0.25 + 0.25}\right) \cdot 100 = 47\%$$

These effective imperviousness values for the sub-watershed (0% for the water quality event and 47% for the 10-year event) can be compared to the total area-weighted imperviousness of 50%. These values can be used for sizing of conveyance and detention facilities.

5.3 Effective Imperviousness Spreadsheet

Because most sites will consist of multiple sub-watersheds, some using the conveyance-based approach and others using the storage-based approach, a spreadsheet capable of applying both approaches to multiple sub-watersheds to determine overall site effective imperviousness and volume reduction benefits is a useful tool. The *UD-BMP* workbook has this capability.

Spreadsheet inputs include the following for each sub-watershed:

Sub-watershed ID = Alphanumeric identifier for sub-watershed

Receiving Pervious Area Soil Type

Total Area (acres)

DCIA = directly connected impervious area (acres)

UIA = unconnected impervious area (acres)

RPA = receiving pervious area (acres)

SPA = separate pervious area (acres)

Infiltration rate, *f*, for RPA = RPA infiltration rate from Table 3-3 (based on soil type)

Sub-watershed type = conveyance-based "C" or volume-based "V"

Rainfall input = 1-hour point rainfall depths from Rainfall Depth-Duration-Frequency figures in the *Rainfall* chapter of Volume 1.

Calculated values include percentages of UIA, DCIA, RPA, and SPA; *f/I* values for design events; Imperviousness Reduction Factors (*K* values) for design events; effective imperviousness for design events for sub-watersheds and for the site as a whole; WQCV for total and effective imperviousness; and 10- and 100-year empirical detention storage volumes for total and effective imperviousness. Note that there may be slight differences in results between using the spreadsheet and the figures in this chapter due to interpolation to translate the figures into a format that can be more-easily implemented in the spreadsheet.

To demonstrate how the spreadsheet works, this section steps through two sub-basins from the Colorado Green development, shown in Figure 3-11. The Colorado Green development is a hypothetical LID development based on a real site plan. This example focuses on two sub-basins: (1) Sub-basin A which uses a volume-based approach and (2) Sub-basin E, which uses a conveyance-based LID approach. Note: For users working through this example using a calculator, to achieve results that closely agree with the spreadsheet entries, **do not** round interim results when used in subsequent equations.

Precipitation Input

Input data for precipitation include the following (see Figure 3-12).

1-hour point precipitation depth for the water quality event: The WQCV is relatively constant across the metropolitan Denver area, and is set at 0.60 inches. There is no specified duration for the WQCV, so for purposes of conservatively estimating the 1-hour point rainfall depth, the spreadsheet input assumes that the WQCV total precipitation depth occurs over a period of one hour. The spreadsheet input value for the 1-hour point rainfall depth for the water quality event should not change from the value in the example spreadsheet as long as the project is in the metropolitan Denver area.

10-year, 1-hour point rainfall depth: Determine the 10-year 1-hour point rainfall depths from Rainfall Depth-Duration-Frequency figures in the *Rainfall* chapter. For this example, the 10-year, 1-hour point rainfall depth is approximately 1.55 inches.

100-year, 1-hour point rainfall depth: Determine the 100-year 1-hour point rainfall depths from Rainfall Depth-Duration-Frequency figures in the *Rainfall* chapter. For this example, the 100-year, 1-hour point rainfall depth is approximately 2.60 inches.

Area and Infiltration Inputs

After precipitation data have been entered, the next step is to classify all areas of the site as UIA, RPA, DCIA, or SPA (see Figure 3-11) and to enter the areas into the spreadsheet in appropriate columns. Please note that blue bordered cells are designated for input, while black bordered cells are calculations performed by the spreadsheet. For the two sub-basins used in this example, A and E, inputs are:

Sub-basin A—DCIA = 0.00 ac, UIA = 0.56 ac, RPA =0.44 ac, SPA = 0.15 ac

Sub-basin E—DCIA = 0.00 ac, UIA = 0.11 ac, RPA =0.04 ac, SPA = 0.00 ac

The program calculates total area for each sub-basin as DCIA + UIA + RPA+ SPA and ensures that this value matches the user input value for total area:

Sub-basin A Total Area (ac) = 0.00 + 0.56 + 0.15 + 0.44 = 1.15 ac

Sub-basin E Total Area (ac) = 0.00 + 0.11 + 0.00 + 0.04 = 0.15 ac

The spreadsheet also calculates percentages of each of the types of areas by dividing the areas classified as DCIA, UIA, SPA and RPA by the total area of the sub-basin.

For each sub-basin, the user must enter the soil type and specify whether the RPA for each sub-basin is a conveyance-based ("C") or storage/volume-based ("V") BMP. The volume-based option should be selected only when the full WQCV is provided for the entire sub-basin. If the RPA is a volume-based BMP providing the full WQCV, the drain time must also be specified. Based on this input the spreadsheet will provide the infiltration rate. For sub-basins A and E in the example, the RPA is assumed to have sandy loam soils in the areas where BMPs will be installed. A rate of 0.64 inches per hour is used for Sub-basin A based on a sandy loam soil and a 12-hour drain time, and a rate of 1.04 inches/hour is used for Sub-basin E based on a sandy loam soil and a conveyance-based BMP type. Area and infiltration inputs are illustrated in Figure 3-13.

AR and f/I Calculations

After area and RPA infiltration parameters are input, the spreadsheet performs calculations of the A_R ratio and f/I parameters for design storm events including the water quality event and the 10- and 100-year events. Spreadsheet calculations are shown in Figure 3-14.

Calculations for **Sub-basin A** include the following:

$$A_R = \frac{\text{RPA}}{\text{UIA}} = \frac{0.44\text{ ac}}{0.56\text{ ac}} = 0.79$$

In general, the higher this ratio is, the greater the potential for infiltration and volume reduction.

$$I_{a\text{ Check}} = \frac{1}{1 + A_R} = \frac{1}{1 + 0.79} = 0.56$$

This is mathematically equivalent to UIA/(RPA+UIA) = 0.56/(0.44+0.56).

Next the spreadsheet calculates f/I parameters using the RPA infiltration rate and the 1-hour maximum intensity values for each event (values in the spreadsheet are rounded to the tenths place). Values for Sub-basin A include:

$$\frac{f}{I_{WQ}} = \frac{0.64\text{ in/hour}}{0.60\text{ in/hour}} = 1.1$$

$$\frac{f}{I_{10-yr}} = \frac{0.64\text{ in/hour}}{1.55\text{ in/hour}} = 0.4$$

$$\frac{f}{I_{100-yr}} = \frac{0.64\text{ in/hour}}{2.60\text{ in/hour}} = 0.2$$

Calculations for Sub-basin E include the following:

$$A_R = \frac{\text{RPA}}{\text{UIA}} = \frac{0.04\text{ ac}}{0.11\text{ ac}} = 0.36$$

$$I_{a\,Check} = \frac{1}{1 + A_R} = \frac{1}{1 + 0.36} = 0.73$$

This is mathematically equivalent to UIA/(RPA+UIA) = 0.11/(0.04+0.11).

f/I calculations for Sub-basin E include:

$$\frac{f}{I_{WQ}} = \frac{1.04\text{ in/hour}}{0.60\text{ in/hour}} = 1.7$$

$$\frac{f}{I_{10-yr}} = \frac{1.04\text{ in/hour}}{1.55\text{ in/hour}} = 0.7$$

$$\frac{f}{I_{100-yr}} = \frac{1.04\text{ in/hour}}{2.60\text{ in/hour}} = 0.4$$

IRF (K) and Effective Impervious Calculations

The next set of calculations determines the Impervious Reduction Factors (K values) for each design event and the effective imperviousness of the overall sub-basins.

Note: In the spreadsheet, the abbreviation "IRF" is used interchangeably with "K."

Calculation of the K value is based on a lookup table in the spreadsheet containing the data used to create Figures 3-9 and 3-10.

For the example, Sub-basin A is designated as "V-12" (volume-based BMP with a 12-hour drain time) and Sub-basin E is designated as "C" (conveyance-based). Calculations for IRF and effective imperviousness parameters provided below are shown in Figure 3-14.

Calculations for **Sub-basin A** include the following:

$$\text{IRF}_{\text{WQ}} = 0.00$$

$$\text{IRF}_{\text{10-yr}} = 0.92$$

$$\text{IRF}_{\text{100-yr}} = 0.96$$

The results from the lookup table can be compared against Figure 3-10 (volume-based curves) as a check. The K values can be read off Figure 3-10 using UIA/(RPA + UIA) = 0.56 (56%) and f/I = 1.1, 0.4 and 0.2 for the water quality, 10- and 100-year events respectively. Figure 3-15 illustrates the readings from the volume-based figure.

Calculations for **Sub-basin E** include the following:

$$\text{IRF}_{\text{WQ}} = 0.77$$

$$\text{IRF}_{\text{10-yr}} = 0.90$$

$$\text{IRF}_{\text{100-yr}} = 0.94$$

The results from the lookup table can be compared against Figure 3-9 (conveyance-based curves). The IRF values can be read off Figure 3-9 using UIA/(RPA + UIA) = 0.73 (73%) and f/I = 1.7, 0.7 and 0.4 for the water quality, 10- and 100-year events respectively. Figure 3-16 illustrates the readings from the conveyance-based figure.

The next step, illustrated in Figure 3-14, is to calculate the effective imperviousness for the water quality, 10- and 100-year events for the entire sub-basin. Note that the K value is only applied to the UIA and RPA portions of the sub-basins.

Calculations for **Sub-basin A** include the following:

$$I_{Total} = \frac{\text{DCIA} + \text{UIA}}{\text{Total Area}} = \frac{0.00\text{ ac} + 0.56\text{ ac}}{1.15\text{ ac}} = 49\%$$

$$I_{WQ} = 0$$

Note: Because the "V" option was selected in the spreadsheet, the effective imperviousness is set to 0.0 for the WQ event/WQCV (i.e., if the full WQCV is provided by a BMP and an event with less precipitation and runoff than the water quality design event occurs, the BMP will completely treat the runoff from the event, either infiltrating or releasing the runoff in a controlled manner, effectively making the imperviousness of the area on the timescale of the event approximately zero). **In order for I_{WQ} to be set to 0.0 for the water quality event, the full WQCV must be provided for the entire sub-basin.**

$$I_{10-yr} = \frac{\text{IRF}_{10-\text{yr}} \cdot \text{UIA} + \text{DCIA}}{\text{Total Area}} = \frac{0.92 \cdot 0.56\text{ ac} + 0.00\text{ ac}}{1.15\text{ ac}} = 45\%$$

$$I_{100-yr} = \frac{\text{IRF}_{100-\text{yr}} \cdot \text{UIA} + \text{DCIA}}{\text{Total Area}} = \frac{0.96 \cdot 0.56\text{ ac} + 0.00\text{ ac}}{1.15\text{ ac}} = 47\%$$

Calculations for **Sub-basin E** include the following:

$$I_{Total} = \frac{\text{DCIA} + \text{UIA}}{\text{Total Area}} = \frac{0.00\text{ ac} + 0.11\text{ ac}}{0.15\text{ ac}} = 73\%$$

$$I_{WQ} = \frac{\text{IRF}_{\text{WQ}} \cdot \text{UIA} + \text{DCIA}}{\text{Total Area}} = \frac{0.77 \cdot 0.11\text{ac} + 0.00\text{ ac}}{0.15\text{ ac}} = 56\%$$

$$I_{10-yr} = \frac{\text{IRF}_{10-\text{yr}} \cdot \text{UIA} + \text{DCIA}}{\text{Total Area}} = \frac{0.90 \cdot 0.11\text{ ac} + 0.00\text{ ac}}{0.15\text{ ac}} = 66\%$$

$$I_{100-yr} = \frac{\text{IRF}_{100-\text{yr}} \cdot \text{UIA} + \text{DCIA}}{\text{Total Area}} = \frac{0.94 \cdot 0.11\text{ ac} + 0.00\text{ ac}}{0.15\text{ ac}} = 69\%$$

Water Quality Capture Volume and 10- and 100-year Detention Volume Adjustments

Once the effective imperviousness values are calculated for the sub-basins, the adjusted, effective imperviousness values can be used in drainage calculations for conveyance and storage to quantify benefits of conveyance- and storage-based BMPs. Spreadsheet calculations are shown in Figure 3-14.

WQCV

To quantify the benefits of disconnected impervious area and other BMPs on the WQCV, the WQCV is calculated using both the total imperviousness and effective imperviousness of each sub-basin.

Calculations for **Sub-basin A** include the following:

$$\text{WQCV } I_{Total} = \left(0.91 \cdot I_{Total}^3 - 1.19 \cdot I_{Total}^2 + 0.78 \cdot I_{Total}\right) \cdot \text{Total Area} \cdot \frac{43560 \text{ ft}^2}{\text{ac}} \cdot \frac{1\text{ft}}{12 \text{ in}}$$

$$\text{WQCV } I_{Total} = (0.91 \cdot 0.49^3 - 1.19 \cdot 0.49^2 + 0.78 \cdot 0.49) \cdot 1.15 \text{ ac} \cdot \frac{43560 \text{ ft}^2}{\text{ac}} \cdot \frac{1\text{ft}}{12 \text{ in}} = 846 \text{ ft}^3$$

Since the volume-based option is specified for Sub-basin A, by definition, the entire WQCV (846 ft^3) is to be provided. Therefore, there is no need to calculate WQCV I_{WQ} for Sub-basin A. The spreadsheet returns the result "N/A." The effects of providing the WQCV for Sub-basin A lead to reductions in detention storage requirements for the 10- and 100-year events as demonstrated below.

Calculations for **Sub-basin E** include the following:

$$\text{WQCV } I_{Total} = \left(0.91 \cdot I_{Total}^3 - 1.19 \cdot I_{Total}^2 + 0.78 \cdot I_{Total}\right) \cdot \text{Total Area} \cdot \frac{43560 \text{ ft}^2}{\text{ac}} \cdot \frac{1\text{ft}}{12 \text{ in}}$$

$$\text{WQCV } I_{Total} = (0.91 \cdot 0.73^3 - 1.19 \cdot 0.73^2 + 0.78 \cdot 0.73) \cdot 0.15 \text{ ac} \cdot \frac{43560 \text{ ft}^2}{\text{ac}} \cdot \frac{1\text{ft}}{12 \text{ in}} = 158 \text{ ft}^3$$

Next the WQCV associated with I_{WQ} is calculated:

$$\text{WQCV } I_{WQ} = \left(0.91 \cdot I_{WQ}^3 - 1.19 \cdot I_{WQ}^2 + 0.78 \cdot I_{WQ}\right) \cdot \text{Total Area} \cdot \frac{43560 \text{ ft}^2}{\text{ac}} \cdot \frac{1\text{ft}}{12 \text{ in}}$$

$$\text{WQCV } I_{WQ} = (0.91 \cdot 0.56^3 - 1.19 \cdot 0.56^2 + 0.78 \cdot 0.56) \cdot 0.15 \text{ ac} \cdot \frac{43560 \text{ ft}^2}{\text{ac}} \cdot \frac{1\text{ft}}{12 \text{ in}} = 122 \text{ ft}^3$$

Therefore, the reduction in the required WQCV form the implementation of conveyance-based BMPs in Sub-basin E is approximately 158 ft^3 – 122 ft^3 = 36 ft^3, or approximately 23% relative to the WQCV based on total imperviousness.

10-Year Event

To evaluate effects of conveyance- and volume-based BMPs on 10-year detention storage volumes, the empirical equations from the *Storage* chapter of Volume 2 can be applied to the total impervious area and the effective imperviousness. The results of these calculations can be compared to determine the associated 10-year volume reduction.

Calculations for **Sub-basin A** include the following:

$$V_{10}\ I_{Total} = \frac{(0.95 \cdot \text{I}_{\text{Total}} - 1.90)}{1000} \cdot \text{Total Area} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}}$$

$$V_{10}\ I_{Total} = \frac{(0.95 \cdot 49\% - 1.90)}{1000} \cdot 1.15 \text{ ac} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}} = 2222 \text{ ft}^3$$

The same calculation is then performed using the effective imperviousness for the 10-year event:

$$V_{10}\ I_{10-yr\ Effective} = \frac{\left(0.95 \cdot I_{10-yr\ Effective} - 1.90\right)}{1000} \cdot \text{Total Area} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}}$$

$$V_{10}\ I_{Total} = \frac{(0.95 \cdot 45\% - 1.90)}{1000} \cdot 1.15\ \text{ac} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}} = 2046\ \text{ft}^3$$

The reduction in the 10-year storage volume as a result of the conveyance-based BMPs in Sub-basin A is, therefore, 2222 ft^3 – 2046 ft^3 = 176 ft^3, or approximately 8% relative to the 10-year storage volume based on total imperviousness.

Calculations for **Sub-basin E** include the following:

$$V_{10}\ I_{Total} = \frac{(0.95 \cdot I_{Total} - 1.90)}{1000} \cdot \text{Total Area} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}}$$

$$V_{10}\ I_{Total} = \frac{(0.95 \cdot 73\% - 1.90)}{1000} \cdot 0.15\ \text{ac} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}} = 443\ \text{ft}^3$$

The same calculation is then performed using the effective imperviousness for the 10-year event:

$$V_{10}\ I_{10-yr\ Effective} = \frac{\left(0.95 \cdot I_{10-yr\ Effective} - 1.90\right)}{1000} \cdot \text{Total Area} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}}$$

$$V_{10}\ I_{10-yr\ Effective} = \frac{(0.95 \cdot 66\% - 1.90)}{1000} \cdot 0.15\ \text{ac} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}} = 395\ \text{ft}^3$$

The reduction in the 10-year storage volume as a result of the conveyance-based BMPs in Sub-basin E is, therefore, 443 ft^3 – 395 ft^3 = 48 ft^3, or approximately 11% relative to the 10-year storage volume based on total imperviousness.

100-Year Event

To evaluate effects of conveyance- and volume-based BMPs on 100-year detention storage volumes, the empirical equations from the *Storage* chapter of Volume 2 can be applied to the total impervious area and the effective imperviousness. The results of these calculations can be compared to determine the associated 100-year volume reduction. Please note that there are two empirical equations for the 100-year detention storage volume in the *Storage* chapter, one for HSG A soils and the other for HSG B, C and D soils. The spreadsheet selects the appropriate equation based on the RPA infiltration rate that is input for the sub-basin. If the RPA infiltration rate is greater than or equal to 1 inch/hour, the HSG A equation is used. Otherwise, the HSG B, C and D equation is used.

Calculations for **Sub-basin A** include the following:

$$V_{100}\ I_{Total} = \frac{\left(-0.00005501 \cdot I_{Total}^2 + 0.030148 \cdot I_{Total} - 0.12\right)}{12} \cdot \text{Total Area} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}}$$

$$V_{100}\ I_{Total} = \frac{(-0.00005501 \cdot 49\%^2 + 0.030148 \cdot 49\% - 0.12)}{12} \cdot 1.15\ \text{ac} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}}$$
$$= 5083\ ft^3$$

The same calculation is then performed using the effective imperviousness for the 100-year event:

$$V_{100}\, I_{100-yr\ Effective} = \frac{\left(-0.00005501 \cdot I_{100-yr\ Effective}^{2} + 0.030148 \cdot I_{100-yr\ Effective} - 0.12\right)}{12} \cdot \text{Total Area} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}}$$

$$V_{100}\, I_{100-yr\ Effective} = \frac{(-0.00005501 \cdot 47\%^2 + 0.030148 \cdot 47\% - 0.12)}{12} \cdot 1.15\ \text{ac} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}} = 4865\ \text{ft}^3$$

The reduction in the 100-year storage volume, as a result of the conveyance-based BMPs in Sub-basin A, is 5083 ft^3 – 4865 ft^3 = 218 ft^3, a reduction of approximately 4.3%.

Calculations for **Sub-basin E** include the following:

$$V_{100}\, I_{Total} = \frac{\left(-0.00005501 \cdot I_{Total}^{2} + 0.030148 \cdot I_{Total} - 0.12\right)}{12} \cdot \text{Total Area} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}}$$

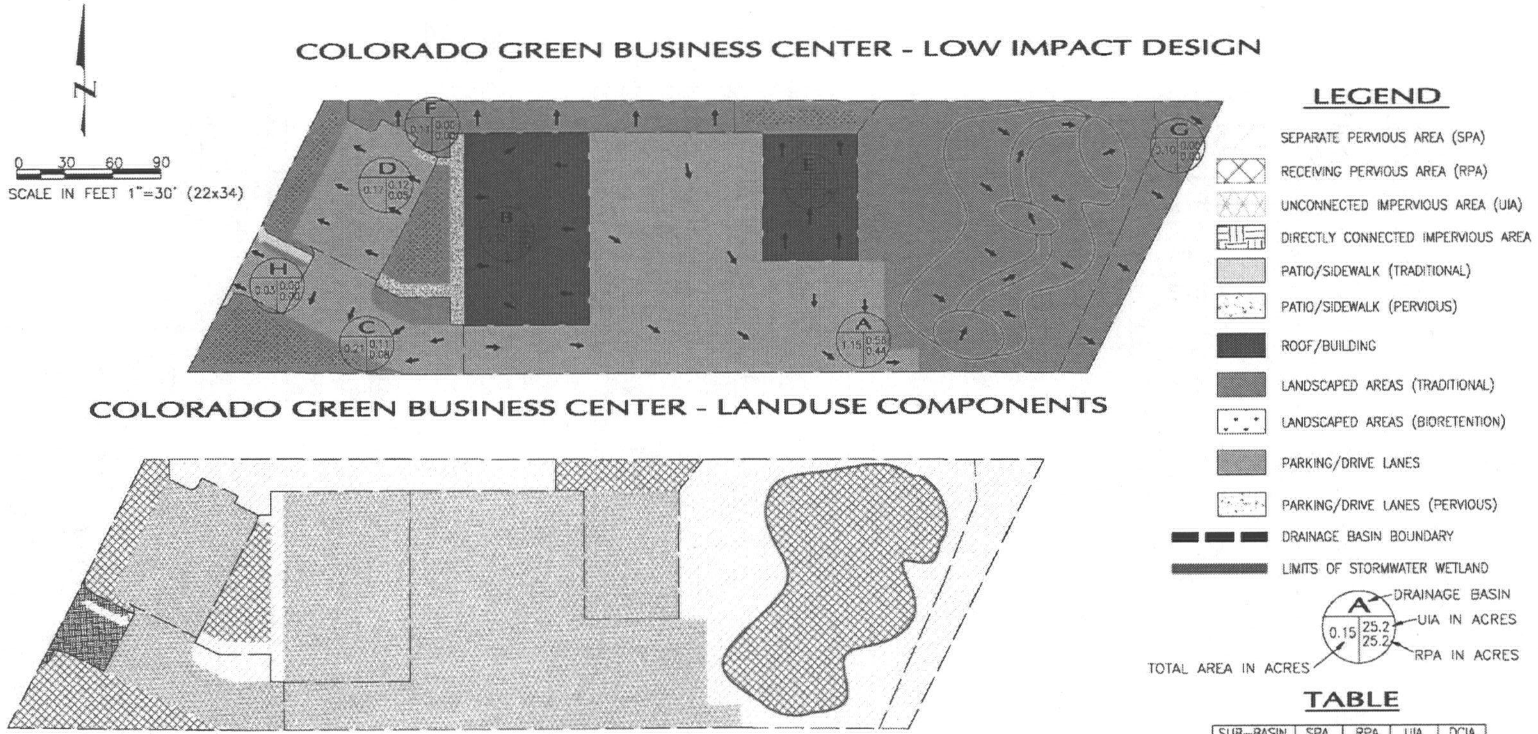
$$V_{100}\, I_{Total} = \frac{(-0.00005501 \cdot 73\%^2 + 0.030148 \cdot 73\% - 0.12)}{12} \cdot 0.15\ \text{ac} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}} = 977\ \text{ft}^3$$

The same calculation is then performed using the effective imperviousness for the 100-year event:

$$V_{100}\, I_{100-yr\ Effective} = \frac{\left(-0.00005501 \cdot I_{100-yr\ Effective}^{2} + 0.030148 \cdot I_{100-yr\ Effective} - 0.12\right)}{12} \cdot \text{Total Area} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}}$$

$$V_{100}\, I_{100-yr\ Effective} = \frac{(-0.00005501 \cdot 69\%^2 + 0.030148 \cdot 69\% - 0.12)}{12} \cdot 0.15\ \text{ac} \cdot 43560\ \frac{\text{ft}^3}{\text{ac} \cdot \text{ft}} = 927\ \text{ft}^3$$

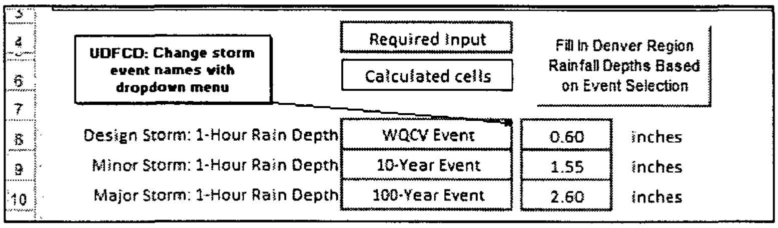
The reduction in the 100-year storage volume as a result of the volume-based BMPs in Sub-basin E is, therefore, 977ft^3 – 927 ft^3 = 50 ft^3, a reduction of approximately 5%.



TABLE

SUB-BASIN	SPA	RPA	UIA	DCIA
A	0.15	0.44	0.56	0.00
B	0.03	0.05	0.22	0.00
C	0.02	0.08	0.11	0.00
D	0.00	0.05	0.12	0.00
E	0.00	0.04	0.11	0.00
F	0.11	0.00	0.00	0.00
G	0.10	0.00	0.00	0.00
H	0.00	0.00	0.00	0.03
TOTALS	0.42	0.65	1.12	0.03

Figure 3-11. Colorado Green Development DCIA, UIA, RPA, and SPA



UDFCD: Change storm event names with dropdown menu

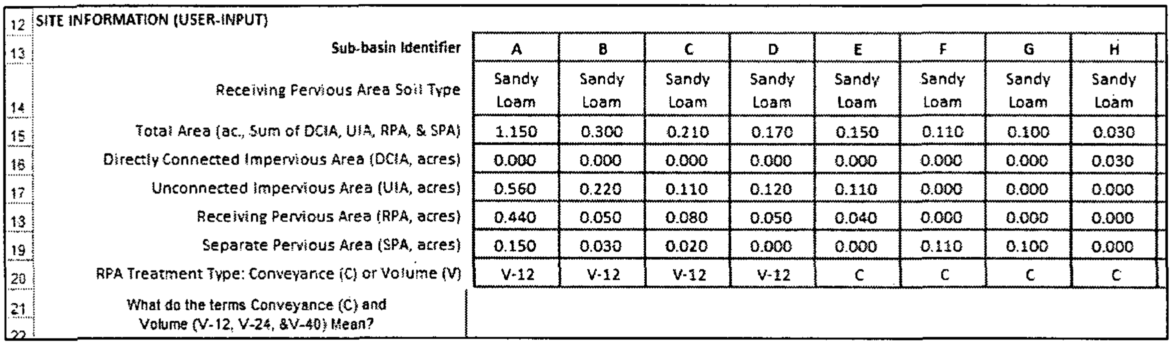
Required Input

Calculated cells

Fill In Denver Region Rainfall Depths Based on Event Selection

Design Storm: 1-Hour Rain Depth	WQCV Event	0.60	inches
Minor Storm: 1-Hour Rain Depth	10-Year Event	1.55	inches
Major Storm: 1-Hour Rain Depth	100-Year Event	2.60	inches

Figure 3-12. Colorado Green Precipitation Input Screen Shot

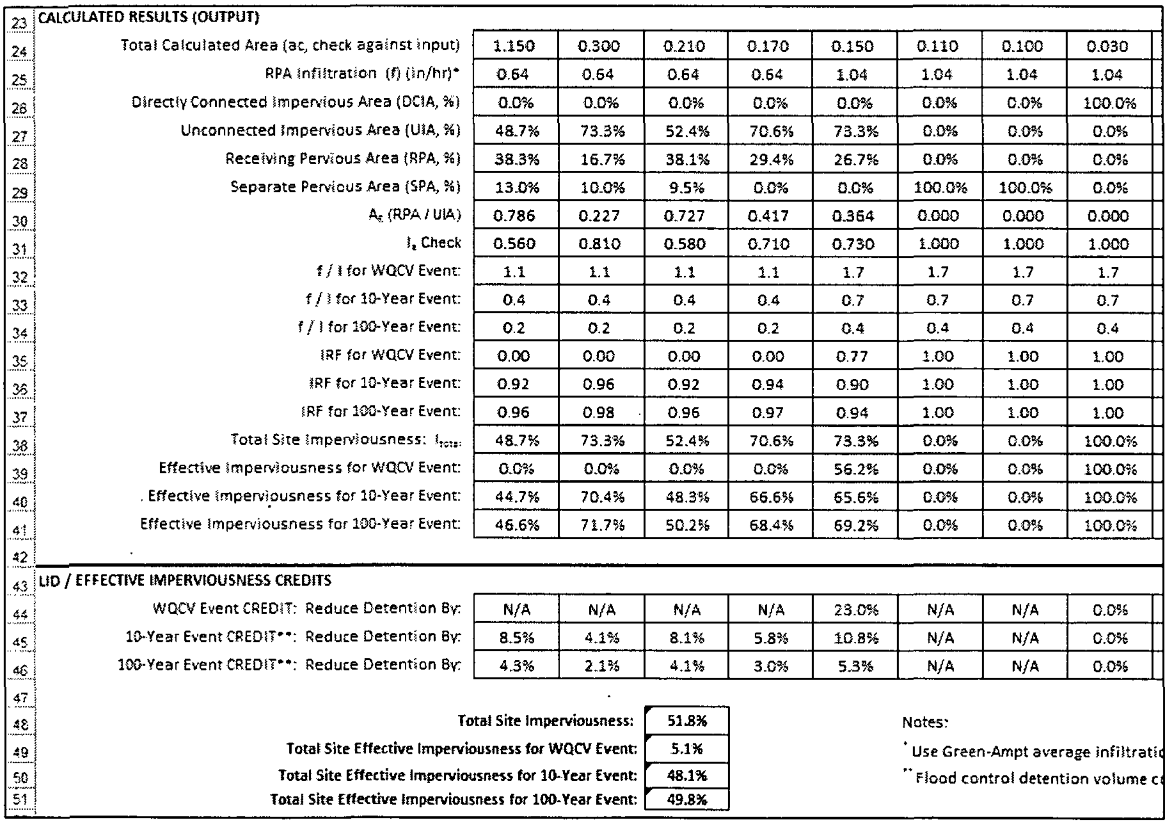


SITE INFORMATION (USER-INPUT)

Sub-basin Identifier	A	B	C	D	E	F	G	H
Receiving Pervious Area Soil Type	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
Total Area (ac., Sum of DCIA, UIA, RPA, & SPA)	1.150	0.300	0.210	0.170	0.150	0.110	0.100	0.030
Directly Connected Impervious Area (DCIA, acres)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030
Unconnected Impervious Area (UIA, acres)	0.560	0.220	0.110	0.120	0.110	0.000	0.000	0.000
Receiving Pervious Area (RPA, acres)	0.440	0.050	0.080	0.050	0.040	0.000	0.000	0.000
Separate Pervious Area (SPA, acres)	0.150	0.030	0.020	0.000	0.000	0.110	0.100	0.000
RPA Treatment Type: Conveyance (C) or Volume (V)	V-12	V-12	V-12	V-12	C	C	C	C

What do the terms Conveyance (C) and Volume (V-12, V-24, &V-40) Mean?

Figure 3-13. Colorado Green Area and Infiltration Input Screen Shot



CALCULATED RESULTS (OUTPUT)

Total Calculated Area (ac, check against input)	1.150	0.300	0.210	0.170	0.150	0.110	0.100	0.030
RPA Infiltration (f) (in/hr)*	0.64	0.64	0.64	0.64	1.04	1.04	1.04	1.04
Directly Connected Impervious Area (DCIA, %)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Unconnected Impervious Area (UIA, %)	48.7%	73.3%	52.4%	70.6%	73.3%	0.0%	0.0%	0.0%
Receiving Pervious Area (RPA, %)	38.3%	16.7%	38.1%	29.4%	26.7%	0.0%	0.0%	0.0%
Separate Pervious Area (SPA, %)	13.0%	10.0%	9.5%	0.0%	0.0%	100.0%	100.0%	0.0%
A_R (RPA / UIA)	0.786	0.227	0.727	0.417	0.364	0.000	0.000	0.000
I_a Check	0.560	0.810	0.580	0.710	0.730	1.000	1.000	1.000
f / I for WQCV Event:	1.1	1.1	1.1	1.1	1.7	1.7	1.7	1.7
f / I for 10-Year Event:	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7
f / I for 100-Year Event:	0.2	0.2	0.2	0.2	0.4	0.4	0.4	0.4
IRF for WQCV Event:	0.00	0.00	0.00	0.00	0.77	1.00	1.00	1.00
IRF for 10-Year Event:	0.92	0.96	0.92	0.94	0.90	1.00	1.00	1.00
IRF for 100-Year Event:	0.96	0.98	0.96	0.97	0.94	1.00	1.00	1.00
Total Site Imperviousness: I_{total}	48.7%	73.3%	52.4%	70.6%	73.3%	0.0%	0.0%	100.0%
Effective Imperviousness for WQCV Event:	0.0%	0.0%	0.0%	0.0%	56.2%	0.0%	0.0%	100.0%
Effective Imperviousness for 10-Year Event:	44.7%	70.4%	48.3%	66.6%	65.6%	0.0%	0.0%	100.0%
Effective Imperviousness for 100-Year Event:	46.6%	71.7%	50.2%	68.4%	69.2%	0.0%	0.0%	100.0%

LID / EFFECTIVE IMPERVIOUSNESS CREDITS

WQCV Event CREDIT: Reduce Detention By:	N/A	N/A	N/A	N/A	23.0%	N/A	N/A	0.0%
10-Year Event CREDIT**: Reduce Detention By:	8.5%	4.1%	8.1%	5.8%	10.8%	N/A	N/A	0.0%
100-Year Event CREDIT**: Reduce Detention By:	4.3%	2.1%	4.1%	3.0%	5.3%	N/A	N/A	0.0%

Total Site Imperviousness:	51.8%
Total Site Effective Imperviousness for WQCV Event:	5.1%
Total Site Effective Imperviousness for 10-Year Event:	48.1%
Total Site Effective Imperviousness for 100-Year Event:	49.8%

Notes:

* Use Green-Ampt average infiltratio

** Flood control detention volume c

Figure 3-14. Colorado Green Calculated Output Screen Shot

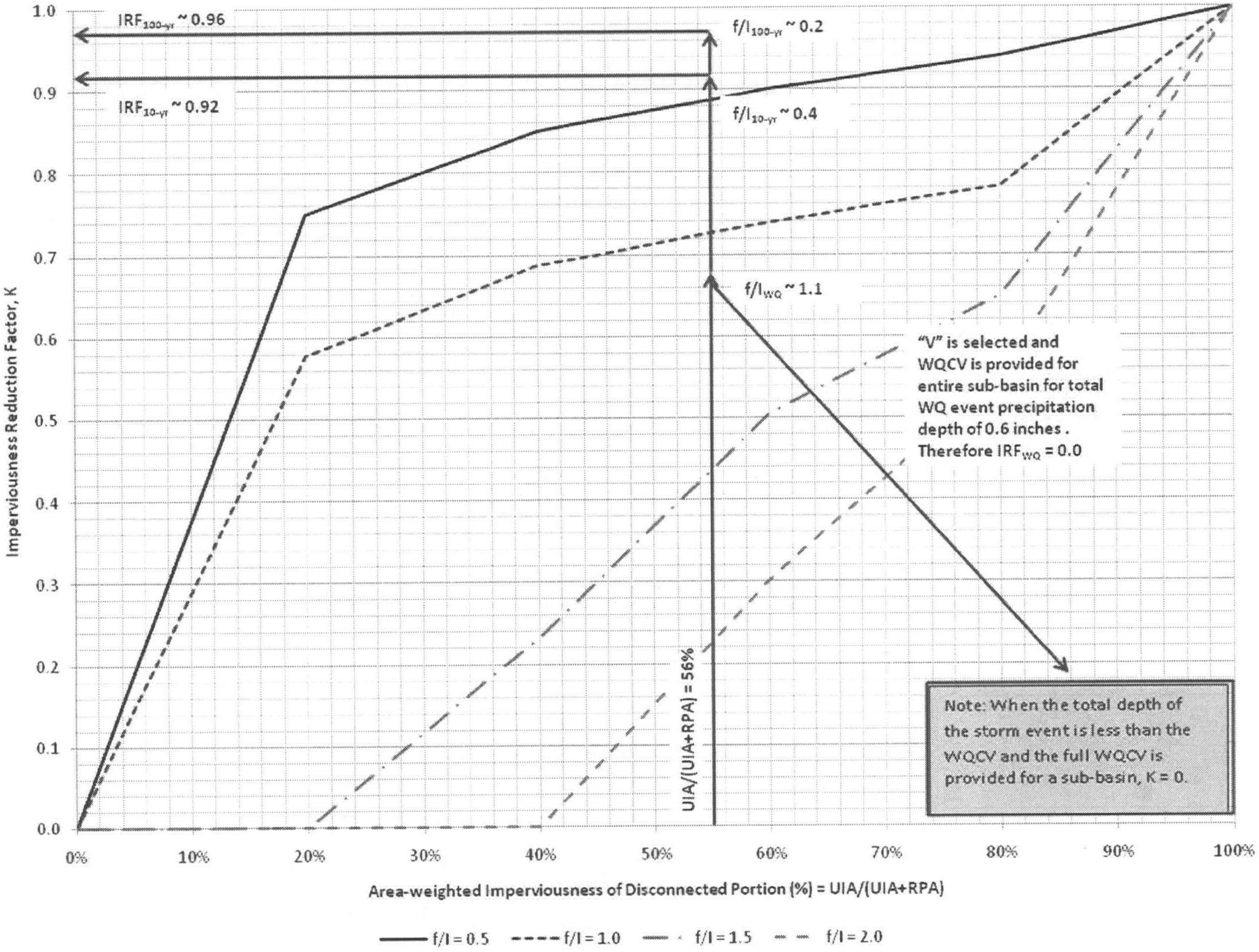


Figure 3-15. Colorado Green Imperviousness Reduction Factor Volume-based Lookup (Sub-basin A)

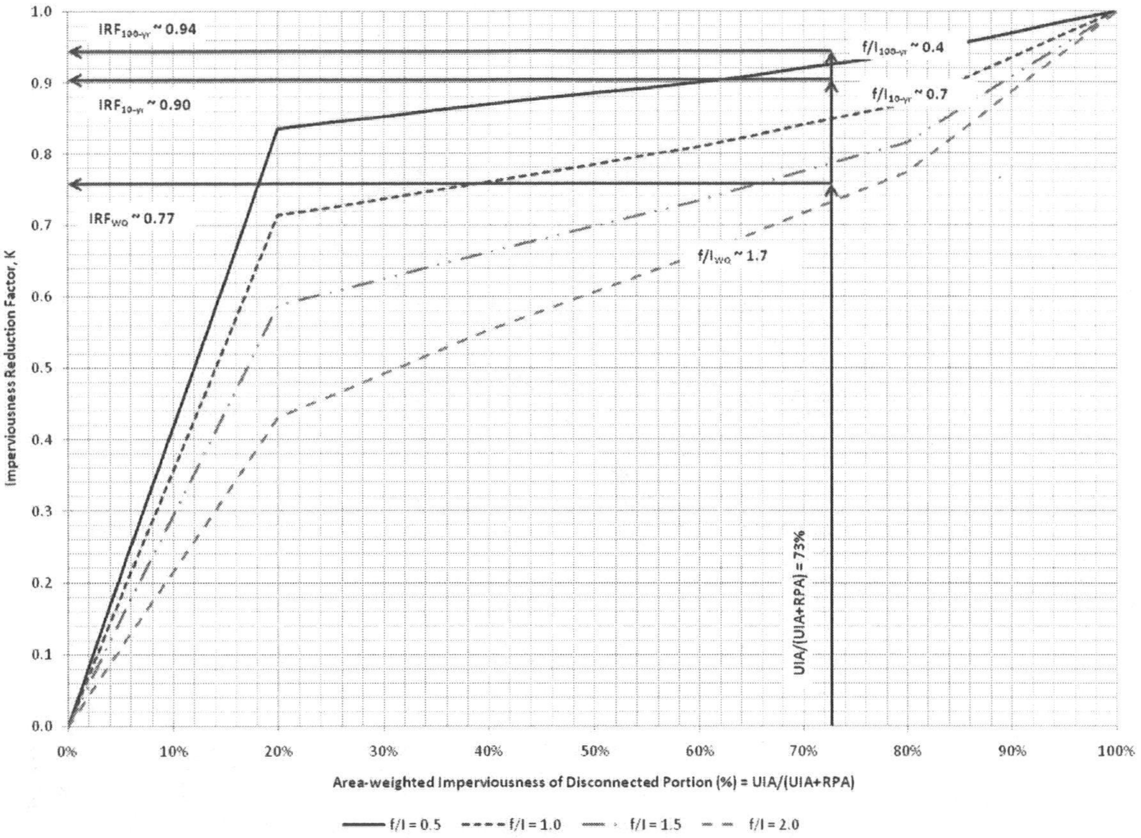


Figure 3-16. Colorado Green IRF Conveyance-based Lookup (Sub basin E)

6.0 Conclusion

This chapter provides the computational procedures necessary to calculate the WQCV and adjust imperviousness values used in these calculations due to implementation of LID/MDCIA in the tributary watershed. The resulting WQCV can then be combined with BMP specific design criteria in Chapter 4 to complete the BMP design(s).

7.0 References

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Chapter 4
Treatment BMPs

Contents

Treatment BMP Fact Sheets

Tables

1.0 Overview

Treatment BMPs in Volume 3

- Grass Swale
- Grass Buffer
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- Green Roof
- Extended Detention Basin
- Retention Pond
- Sand Filter Basin
- Constructed Wetland Pond
- Constructed Wetland Channel
- Permeable Pavement Systems
- Underground Practices

[1] *Also known as Porous Landscape Detention*

UDFCD has established design criteria, procedures, and details for a number of BMPs providing treatment of post-construction urban runoff. Additionally, general guidance has been developed and included for green roofs and underground BMPs. As discussed in Chapter 2, BMPs provide treatment through a variety of hydrologic, physical, biological, and chemical processes. The functions provided by BMPs may include volume reduction, treatment and slow release of the water quality capture volume (WQCV), and combined water quality/flood detention. Ideally, site designs will include a variety of source control and treatment BMPs combined in a "treatment train" that controls pollutants at their sources, reduces runoff volumes, and treats pollutants in runoff. Sites that are well designed for treatment of urban runoff will include all of the steps in the Four Step Process discussed in Chapter 1.

Building upon concepts and procedures introduced in Chapters 1 through 3, this chapter provides design procedures for treatment BMPs. Table 4-1 provides a qualitative overview of key aspects of the post-construction treatment BMPs included in this chapter. The table includes the degree to which the BMP is able to provide various functions, general effectiveness for treating targeted pollutants and other considerations such as life cycle costs. The table indicates which BMPs provide a conveyance function or a WQCV function. This distinction is important because not all treatment BMPs provide the WQCV. Wherever practical, combinations of BMPs in a treatment train approach are recommended. For example, BMPs that provide sedimentation functions can potentially improve the lifespan and reduce the maintenance frequency of filtration-oriented BMPs when the two BMPs are paired in series. Table 4-1 is based on best professional judgment from experiences in the Denver area along with data from the International Stormwater BMP Database (www.bmpdatabase.org) and is intended for general guidance only. Specific BMP designs and site-specific conditions may result in performance that differs from the general information provided in the table. In the case of underground and proprietary BMPs, wide variations in unit treatment processes make it difficult to provide generalized characterizations. Additionally, with regard to pollutant removal, in some cases, BMPs may be able to reduce pollutant concentrations, but this does not necessarily mean that the BMPs are able to treat runoff to numeric stream standards. For example, various studies have indicated that bioretention and retention pond BMPs may be able to reduce fecal indicator bacteria in urban runoff, but not necessarily meet instream primary contact recreational standards (WWE and Geosyntec 2010).

After reviewing physical site constraints, treatment objectives, master plans, and other factors, the designer can select the BMPs for implementation at the site and complete the engineering calculations and specifications for the selected BMPs. This chapter provides Fact Sheets for treatment BMPs that can be used in conjunction with the WQCV and volume reduction calculations in Chapter 3 in order to properly size and design the BMPs for the site. For new developments and significant redevelopments, designers should provide treatment of the WQCV with a slow release designed in accordance with criteria for the selected BMP. Additionally, sites that drain to impaired or sensitive receiving waters or that include onsite operations requiring additional treatment may need to implement measures that go beyond the minimum criteria provided in the Fact Sheets in this chapter.

2.0 Treatment BMP Fact Sheets

Fact sheets for each treatment BMP are provided as stand-alone sections of this chapter. The Fact Sheets are numbered with a "T" designation, indicating "Treatment" BMP. Fact Sheets typically include the following information:

- **Description**: Provides a basic description of the BMP.
- **Site Selection**: Identifies site-specific factors that affect the appropriateness of the BMP for the site.
- **Designing for Maintenance**: Identifies maintenance-related factors that should be considered during the BMP selection and design phase.
- **Design Procedure and Criteria:** Provides quantitative procedures and criteria for BMP design.
- **Construction Considerations**: Identifies construction-phase related factors that can affect long-term performance of the BMP.
- **Design Example**: Provides a design example corresponding to the UDFCD design spreadsheets accompanying this manual.

Designers should review each section of the Fact Sheet because successful long-term performance of the BMP includes all of these considerations, not simply the design procedure itself. Additionally, some Fact Sheets include call-out boxes with supplemental information providing design tips or other practical guidance that can enhance the benefits and performance of the BMP.

As part of the 2010 update of this manual, underground BMPs were added as treatment BMPs. UDFCD does not provide endorsement or approval of specific practices; instead, guidance is provided identifying when use of underground BMPs may be considered and the minimum criteria that should be met when site constraints do not enable aboveground treatment of runoff or when underground devices are used to provide pretreatment for site-specific or watershed-specific purposes.

Table 4-1. General Overview of Treatment BMPs Included in Volume 3

Overview	Grass Swale	Grass Buffer	Bioretention (Rain Garden)	Green Roof[5]	Extended Detention Basin	Sand Filter	Retention Pond	Constructed Wetland Pond	Constructed Wetland Channel	Permeable Pavement	Underground BMPs
Functions											
LID/Volume Red.	Yes	Yes	Yes	Yes	Somewhat	Yes	Somewhat	Somewhat	Somewhat	Yes	Variable
WQCV Capture	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Variable
WQCV+Flood Control	No	No	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Variable
Fact Sheet Includes EURV Guidance	No	No	No	No	Yes	No	Yes	Yes	No	No	No
Typical Effectiveness for Targeted Pollutants[3]											
Sediment/Solids	Good	Good	Very Good[1]	Unknown	Good	Very Good[1]	Very Good	Very Good	Unknown	Very Good[1]	Variable
Nutrients	Moderate	Moderate	Moderate	Unknown	Moderate	Good	Moderate	Moderate	Unknown	Good	Variable
Total Metals	Good	Good	Good	Unknown	Moderate	Good	Moderate	Good	Unknown	Good	Variable
Bacteria	Poor	Poor	Moderate	Unknown	Poor	Moderate	Moderate	Poor	Moderate	Unknown	Variable
Other Considerations											
Life-cycle Costs[4]	Low	Low	Moderate	Unknown	Moderate	Moderate	Moderate	Moderate	Low	High[2]	Moderate

[1] Not recomended for watersheds with high sediment yields (unless pretreatment is provided).

[2] Does not consider the life cycle cost of the conventional pavement that it replaces.

[3] Based primarily on data from the International Stormwater BMP Database (www.bmpdatabase.org).

[4] Based primarily on BMP-REALCOST available at www.udfcd.org. Analysis based on a single installation (not based on the maximum recommended watershed tributary to each BMP).

[5] Water quality data for green roofs are not yet robust enough to provide meaningful conclusions about pollutant removal. By reducing volume, green roofs have the de facto capability to reduce pollutant loads; however, on a concentration basis, more data is needed to better define effectiveness.

3.0 References

Wright Water Engineers and Geosyntec Consultants. 2010. *International Stormwater Best Management Practices Database Pollutant Category Summary: Fecal Indicator Bacteria.* Prepared for WERF, FHWA and EWRI-ASCE.