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Sustainable Stormwater Management: Infiltration vs. Surface Treatment Strategies

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SUSTAINABLE STORMWATER MANAGEMENT: INFILTRATION VS. SURFACE TREATMENT STRATEGIES

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ABSTRACT AND BENEFITS

Stormwater managers are increasingly faced with the need to address many potentially conflicting issues as part of their activities, ranging from flood prevention to protection of downstream habitat. New urban development philosophies, such as low impact development, conservation design, no adverse impact, water-sensitive urban drainage systems, etc., establish goals similar to other professions – Do No Harm. This is addressed often through criteria such as maintaining pre-development hydrology to the maximum extent practicable after development with treatment provided to reduce pollutants to their pre-development level. These new management plans incorporate both infiltration and surface treatment/discharge into the development.

A series of flowcharts were developed to aid stormwater managers through the process of selecting appropriate management/treatment technologies that meets both the low/no-impact goals and the regulatory requirements. These charts refer to the specific document sections that address the issues of concern that should be considered when selecting appropriate stormwater practices. Appendices were developed to provide supporting information for users not familiar with the terminology (Glossary in Appendix A) or the methods and supporting literature.

This work has been based on the literature and guidance documents developed around the world. Surface-treatment technologies such as detention and filtration have a long history with much literature published about them. They are better understood than the infiltration practices currently gaining favor. Therefore, several chapters are devoted to the concerns associated with selecting infiltration and bioretention. The desire to incorporate infiltration raises two potential concerns: 1) acceptance of small-scale infiltration devices, especially by the regulatory authorities, and 2) the potential for groundwater contamination. For the first concern, Appendix B summarizes several references on the issues raised by current stormwater management authorities regarding low impact development and infiltration devices dispersed throughout a watershed.

The second concern is that the potential for groundwater contamination is not well-known or documented. Pollutant removal in the subsurface has not been addressed regularly by researchers, although some historical reports provide information about a few pollutants. However, none of the older reports reviewed herein provide sufficient information on the soil chemistry to use the data in modeling efforts. Some of the newer research reports soil chemistry information for a few parameters but only a few groups are measuring both infiltration water quality and soil pollutant accumulation. While this project does perform research on this topic, it does highlight the soil chemistry issues to be considered when designing infiltration systems.

The third activity under this document development activity was to identify questions/data gaps in the selection and use of stormwater treatment devices, with a focus on infiltration. The following questions were raised.

1. How effective are current and proposed stormwater management techniques at protecting surface water quality and habitat, as well as protecting groundwater? Groundwater and

vadose zone water chemistry information from field studies is limited in the literature. Few studies have looked at transport of stormwater-borne pollutants in the vadose zone of non-engineered soils. What soil and water chemistry data should be collected to improve the understanding of pollutant transport?

2. Would using water and wastewater treatment theory provide a better foundation in the models that predict BMP performance and reduce the uncertainty that has to be associated with every stormwater pollutant removal calculation? Water and wastewater theory has been applied successfully to the design of sedimentation devices, but it has not been as successful at predicting pollutant removal in filtration or infiltration devices.
3. How do the chemicals secreted by microorganisms affect pollutant mitigation in the surface and subsurface environment? What role does the local microbiological flora and fauna play in the trapping of pollutants and in the release of previously-trapped pollutants?
4. If infiltration is selected as a stormwater management technique, what issues of concern must be addressed outside of the pollutant transport? Issues to be addressed during treatment device selection include, but are not limited to, the following: groundwater mounding (and localized basement flooding), pollutant transport through the subsurface to the groundwater, increased maintenance of the infiltration basins, interference with septic tanks and leach fields, soil stability problems due to longer periods where the soil is 'wet', legal issues of increased flooding and/or reduced slope stability.
5. How can small-scale treatment technologies be incorporated on a watershed scale to provide sustainable stormwater management that protects ecological resources, human safety and health, and groundwater?

Benefits:

- ◆ Includes flow charts and checklists to guide users through the process of determining regulatory requirements, calculating the amount of stormwater runoff, and selecting the best array of treatment devices to promote mimicking of pre-development hydrology.
- ◆ Includes flowcharts and checklists to guide stormwater planners step-by-step through the process of stormwater management, documenting decisions throughout.
- ◆ Includes two levels of modeling to predict whether a site is appropriate for infiltration are described.
- ◆ Provides guidance on soil chemistry issues to consider before determining whether a site can provide adequate treatment is provided.
- ◆ Includes appendices with references to additional materials, including literature case studies, are provided for users who require additional information.

Keywords: Urban stormwater management, stormwater guidance, infiltration, vadose zone pollutant migration, surface stormwater treatment, stormwater pollutant control, surface water discharge.

TABLE OF CONTENTS

Acknowledgments.....	iii
Abstract and Benefits.....	iv
List of Tables.....	x
List of Figures.....	xii
List of Acronyms.....	xiii
Executive Summary.....	ES-1
1.0 Planning for Sustainable Stormwater Management.....	1-1
1.1 Introduction.....	1-1
1.2 Constraints of the Urban Stormwater Manager.....	1-2
1.3 Development of the Flow Chart for Guiding Stormwater Management Decisions.....	1-2
2.0 The Regulatory Environment.....	2-1
2.1 Introduction.....	2-1
2.2 Federal/National Stormwater Regulations and Programs.....	2-1
2.2.1 Federal Government (United States).....	2-1
2.2.2 International Stormwater Management.....	2-5
2.3 State Agencies with Stormwater Management Authority.....	2-5
2.4 Local Agencies with Stormwater Management Authority.....	2-6
2.5 The Total Maximum Daily Load (TMDL) Program.....	2-6
2.6 High-Value Waters.....	2-6
2.7 Drinking Water Source Protection.....	2-7
2.8 Treatment Guidance in the Absences of Regulatory Requirements.....	2-7
3.0 Characterizing Stormwater Runoff Flow and Its Impacts.....	3-1
3.1 Introduction.....	3-1
3.2 Calculation of Site-Level Pre- and Post-Development Volumes and Flow Rates.....	3-1
3.2.1 Factors Affecting Runoff Generation.....	3-2
3.2.2 Calculating Runoff.....	3-7
3.2.3 Water Quality Volume and Local Design Equations.....	3-8
3.2.4 Limitations and Local Requirements for Calculating Runoff.....	3-9
3.3 Long-term Monitoring and Evaluation of Impacts.....	3-10
3.4 Urbanization Effects on Soils and Resultant Water Transport.....	3-12
4.0 Characterizing Stormwater Runoff Pollution and Its Impacts.....	4-1
4.1 Introduction.....	4-1
4.2 Estimation of Stormwater Runoff Quality from Databases or Large Studies.....	4-7
4.2.1 Nationwide Stormwater Runoff Program.....	4-8
4.2.2 National Stormwater Quality Database.....	4-8
4.3 Monitoring Stormwater Runoff Quality.....	4-9

4.4	Predicting Receiving Water Health from the Literature, Databases and Models.....	4-10
4.4.1	Impervious Cover Model (ICM).....	4-10
4.4.2	Receiving Water Models	4-11
4.5	Monitoring Watershed and Receiving Water Health.....	4-11
4.5.1	Selection of Biological Endpoints for Monitoring.....	4-13
4.5.2	Selection of Chemical Endpoints for Monitoring.....	4-14
5.0	Selecting Appropriate Stormwater Control Practices	5-1
5.1	Introduction.....	5-1
5.2	Selecting Treatment Devices Based on Program Goals	5-3
5.3	Selecting Appropriate Stormwater Management Practices – Process Steps	5-3
5.3.1	Land Use	5-9
5.3.2	Physical Feasibility Factors	5-9
5.3.3	Watershed Factors Affecting Treatment Device Selection.....	5-9
5.3.4	Stormwater Management Capability	5-11
5.3.5	Community and Environmental Factors	5-11
5.4	Design and Performance Guidance.....	5-12
5.4.1	Design References	5-12
5.4.2	Performance References	5-14
6.0	Water Quantity Issues Related to Infiltration Design	6-1
6.1	Introduction.....	6-1
6.2	General Siting Considerations	6-3
6.2.1	Adequate Infiltration Surface Area and Media Depth	6-3
6.2.2	Site Slope	6-3
6.2.3	Depth to Groundwater.....	6-4
6.3	General Soils Considerations.....	6-4
6.3.1	Soil Characteristics that Affect Infiltration.....	6-5
6.3.2	Soil Infiltration Rates.....	6-7
6.3.3	Hydrologic Soil Group as an Indirect Measure of Infiltration Rate	6-8
6.3.4	Soil Media for Engineered Infiltration Devices.....	6-8
6.3.5	Restrictions in Specific Soil Types	6-9
6.3.6	Comparison of Guidance for Bioretention/Bioinfiltration and Infiltration Systems.....	6-9
6.4	Modeling of Water Transport beneath Infiltration Basins.....	6-12
6.5	Clogging and the Need for Pretreatment	6-13
6.5.1	Estimating the Lifespan of Infiltration Devices.....	6-13
6.5.2	Pretreatment	6-14
6.5.3	Use of Clogging Data to Size an Infiltration Device for a Given Lifespan.....	6-14
6.6	Maintenance.....	6-16
6.7	Climate Issues in Infiltration Design	6-16
6.7.1	Arid or Semi-Arid Climates.....	6-16
6.7.2	Cold Climates.....	6-16

7.0	Water Quality Issues Relation to Infiltration Design	7-1
7.1	Introduction.....	7-1
7.2	Treatment Ability of Stormwater Infiltration Devices.....	7-1
7.3	Soil Chemistry and Pollutant Removal and Retention	7-3
	7.3.1 Soil Horizon Impacts on Geochemistry.....	7-3
	7.3.2 Effects on Soil Chemistry of Pore Water and Infiltrating Stormwater	7-4
	7.3.3 Soil Chemical Properties Affecting Pollutant Transport	7-4
	7.3.4 Leaching/Release of Pollutants from Soil during Infiltration.....	7-8
7.4	Water Chemistry	7-8
	7.4.1 Water pH and Salinity.....	7-8
	7.4.2 Predictors of Organic Pollutant Removal	7-9
	7.4.3 Form of the Pollutants in Water.....	7-9
7.5	Groundwater Contamination Potential	7-9
	7.5.1 Simple Model to Predict Vadose Zone Treatability and Groundwater Contamination Potential.....	7-10
	7.5.2 Vadose Zone Computer Model for Predicting Groundwater Contamination Potential and Basin Lifespan.....	7-12
7.6	Predicting Lifespan Based on Soil Chemistry Changes	7-14
7.7	Selecting an Engineered Soil Media	7-17
	7.7.1 Properties that Affect Media Performance	7-17
	7.7.2 Tests Required for Complete Media Evaluation.....	7-18
8.0	Surface Treatment of Stormwater – Sedimentation and Filtration	8-1
8.1	Introduction.....	8-1
8.2	Known Stormwater Treatment Ability of Detention and Filtration Systems	8-1
8.3	Sedimentation	8-2
	8.3.1 Basic Design Guidance.....	8-2
	8.3.2 Design Fundamentals.....	8-3
	8.3.3 Short-Circuiting in Detention Ponds.....	8-5
	8.3.4 Enhancements to Sedimentation and Evaluations of Manufactured Treatment Devices	8-6
8.4	Filtration	8-6
	8.4.1 Properties that Affect Media Performance	8-7
	8.4.2 Characteristics of Media Previously Evaluated for Stormwater Treatment	8-7
	8.4.3 The Media as a Source of Pollutants.....	8-8
	8.4.4 Modeling the Pollutant Removal Ability of Stormwater Filters.....	8-9
8.5	Microorganism Removal in Sedimentation and Filtration.....	8-10
8.6	Vector Concerns in Surface Treatment Devices	8-12
9.0	Predicting the Effectiveness of Stormwater Management Practices	9-1
9.1	Introduction.....	9-1
9.2	Predicting the Performance of a Single Treatment Device.....	9-1
9.3	Predicting Treatment Performance for Devices Connected in Series.....	9-2
9.4	Predicting Treatment Performance for Devices Connected in Parallel	9-2
9.5	Predicting the Effectiveness of Multiple Devices on a Site.....	9-2

10.0	Predicting the Capital and Operations and Maintenance (O&M) Costs of Stormwater Management Practices	10-1
10.1	Introduction.....	10-1
10.2	Types of Costs and Methods of Predicting Costs	10-1
10.3	References on Costs of Stormwater Management	10-2
10.4	Life-Cycle Analysis of Stormwater Management Practices	10-3
11.0	Conclusions and Data Gaps	11-1
11.1	Conclusions.....	11-1
11.2	Data Gaps.....	11-2
	Appendix A: Glossary.....	A-1
	Appendix B: Constraints on the Urban Stormwater Manager	B-1
	Appendix C: Regulatory Environment	C-1
	Appendix D: Hydrology to Support the Design of Stormwater Control Practices.....	D-1
	Appendix E: Impacts of Compaction on Infiltration	E-1
	Appendix F: Impacts of Urban Runoff and Development on Receiving Waters	F-1
	Appendix G: Urban Runoff Pollution Sources	G-1
	Appendix H: Stormwater Monitoring Programs.....	H-1
	Appendix I: Soils and Infiltration	I-1
	Appendix J: Case Studies of Infiltration.....	J-1
	Appendix K: Literature Tables	K-1
	Appendix L: Checklists.....	L-1
	References.....	R-1

LIST OF TABLES

2-1	Documentation of Regulatory Requirements for Sustainable Site Stormwater Management	2-4
2-2	Stormwater Management Agencies	2-8
3-1	Checklist for Calculating Stormwater Volume, Peak Flow Rate, or Exceedence Storm.....	3-4
3-2	Soil Texture Classifications.....	3-5
3-3	Comparison of Common Bulk Densities.....	3-6
3-4	Acceptable Computation Methodologies for Stormwater Management Plans	3-10
3-5	Constraints on Using Recommended Hydrologic Models	3-10
3-6	Design Applications for Recommended Hydrologic Models.....	3-11
3-7	Signs of Compaction	3-12
3-8	Techniques for Solving Compaction Problems in New and Existing Planting Sites.....	3-13
4-1	Checklist for Evaluating Stormwater and Receiving Water Quality Compared to Standards.....	4-3
4-2	Parameters of Concern when Evaluating Different Receiving Water Uses	4-15
5-1	Appropriate Treatment Practices/BMPs Based on Management Goals	5-3
5-2	Checklist for Determining Whether to Use Infiltration, Surface Treatment, or a Combination.....	5-8
5-3	Land Use Selection Matrix	5-10
5-4	Physical Feasibility Matrix	5-12
5-5	Relationship between Watershed or Regional Selection Issues and Treatment Device Selection	5-13
5-6	Stormwater Device Performance Matrix.....	5-14
5-7	Community and Environmental Factors Matrix.....	5-14
5-8	Number of BMP Studies in the International BMP Database	5-16
6-1	Grain Size Limits by Various Classification Systems.....	6-6
6-2	Soil Porosities.....	6-6
6-3	Ranges of Intrinsic Permeabilities for Soils and Sediments.....	6-6
6-4	Hydrologic Soil Group Designations	6-8
6-5	Infiltration System Design Criteria by Representative Locality per Rainfall Region	6-10
6-6	Bioretention System Design Criteria by Representative Locality per Rainfall Region	6-11
6-7	Infiltration Methodologies in Stormwater Management Software	6-12
6-8	Volumetric Runoff Coefficients by Land Use.....	6-14
6-9	Suspended Solids Concentration by Land Use.....	6-15
6-10	Model Application Scenario.....	6-15
6-11	Typical Maintenance Activities for Infiltration Basins	6-17
7-1	Median Influent and Effluent Concentrations for Infiltration Treatment Devices	7-2
7-2	Orientation and Description of Soil Horizons	7-3
7-3	Clay Minerals and Surface Properties	7-5
7-4	Groundwater Contamination Potential for Stormwater Pollutants.....	7-11
7-5	Mobility Classes for Organic Contaminants	7-11
7-6	Metal Mobility Classes.....	7-12

7-7	Groundwater Contamination Potential for Stormwater Pollutants Post-Treatment	7-13
7-8	Typical Soil Properties for Different Soil Textures and Organic Amendments.....	7-15
7-9	Infiltration Rates and Saturated Hydraulic Conductivities for Amendment Mixtures...	7-15
7-10	Example Characteristics for Bioretention Mixtures	7-15
7-11	Example Total Cation Content Calculation for Stormwater	7-16
8-1	Median Influent and Effluent Concentrations of Stormwater Control Practices.....	8-1
8-2	Sieve Size Analysis of Non-Fibrous Media	8-7
8-3	Cation Exchange Capacity of Filtration Media	8-8
8-4	Summary of Potentially Leachable Compounds from Media	8-9
9-1	Predicting Effluent Quality from Stormwater Treatment Devices	9-2
9-2	Predicting Treatment Performance for Devices Installed in Series	9-3
9-3	Predicting Treatment Performance for Devices Installed in Parallel	9-4
9-4	Stormwater Modeling Programs and Design Tools	9-7
9-5	Potential Uses for Specific Models	9-8
9-6	Contaminants Included in the Model Predictions.....	9-8
9-7	Control Practices Addressed by the Models	9-9
10-1	Cost References	10-3

LIST OF FIGURES

1-1	Top-Level Flow Chart for Stormwater Management	1-3
2-1	Regulatory Environment for Sustainable Stormwater Management	2-2
3-1	Predicting Stormwater Quality Flow Chart	3-3
3-2	Soil Textural Triangle.....	3-6
4-1	Stormwater and Receiving Water Quality Evaluation Flowchart	4-2
4-2	Comparison of Pollutant Concentrations by Land Use (NURP).....	4-8
4-3	Impervious Cover Model.....	4-11
5-1	Separation of Cumulative Rainfall and Runoff Distributions into Treatment Objectives	5-4
5-2	FHWA Flow Chart for Selecting Appropriate Control Practices.....	5-5
5-3	Flowchart for Stormwater Runoff Quantity Treatment.....	5-6
5-4	Flowchart for Stormwater Runoff Quality Treatment.....	5-7
6-1	Examples of Installed Infiltration Practices.....	6-1
8-1	Critical Velocity and Pond Dimensions	8-4
8-2	Poorly Designed Detention Pond	8-6
8-3	Sieve Size Analysis of Granular Media.....	8-8
8-4	Capacity of Various Potential Stormwater Filtration Media	8-9
8-5	Ratios of Effluent to Influent Concentrations as a Function of Bed Volumes Treated for 10 Stormwater Media	8-11

LIST OF ACRONYMS

AEC	Anion exchange capacity
ANN	Artificial neural networks
APHA	American Public Health Association
ASCE	American Society of Civil Engineers
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BOD ₅	Biochemical oxygen demand
BMP	Best management practice
CALTRANS	California Department of Transportation
CEC	Cation exchange capacity
COD	Chemical oxygen demand
CSO	Combined sewer overflow
CWP	Center for Watershed Protection
DGGE	Denaturing gradient gel electrophoresis
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DOD	U.S. Department of Defense
DRC	Distributed runoff control
DURM	Delaware Urban Runoff Model
EEE	Eastern equine encephalitis
FHWA	Federal Highway Administration
GSA	General Services Administration
HRT	Hydraulic residence time
HSPF	Hydrologic Simulation Program-FORTRAN
HUS	Hemolytic uremic syndrome
IDF	Intensity-duration-frequency
IPPC	Integrated pollution prevention and control
ISC	Impervious surface cover
ISZ	Internal storage zone
LAC	La Crosse encephalitis
LEED	Leadership in Energy and Environmental Design
LID	Low impact development
LIFE™	Low-Impact Feasibility Evaluation
MCTT	Multi-chambered treatment train
MOP	Manual of Practice
MOUSE	Model of Urban Sewers
MS4	Municipal separate storm sewer system
MUSIC	Model for Urban Stormwater Improvement Conceptualization
NCHRP	National Cooperative Research Program
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRCS	National Resource Conservation Service (formerly SCS)
NSQD	National Stormwater Quality Database

NTU	Nephelometric turbidity unit
NURP	Nationwide Urban Runoff Program
ORP	Oxidation-reduction potential
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PCR	Polymerase chain reaction
PCGEMS	Graphical Exposure Modeling System for the PC
PFGE	Pulse field gel electrophoresis
PRMS	Precipitation-Runoff MOdelling Systems
PSH	Penn State Harrisburg
PUD	Planned use development
PURRS	Probabilistics Urban Rainfall and Wastewater Reuse Simulator
RAPD	Randomly amplified polymorphic DNA
RUNQUAL	Runoff Quality from Developed Sites
RWI	Recreational water illness
SAR	Sodium adsorption ratio
SCS	Soil Conservation Service (now NRCS)
SESOIL	Seasonal Soil (compartment model)
SLAMM	Source Loading and Management Model
SLE	St. Louis equine encephalitis
SLURP	Simple Lumped Reservoir Parametric
SOD	Sediment oxygen demand
SRM	Snowmelt Runoff Model
SS	Suspended solids
SSARR	Streamflow Synthesis and Reservoir Regulation
SSC	Suspended sediment concentration
SSO	Sanitary sewer overflow
SUDS	Sustainable urban drainage system
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
TCLP	Toxicity characteristic leaching procedure
TIA	Total impervious area
TIE	Toxicity identification evaluation
TKN	Total Kjeldahl nitrogen
TMDL	Total maximum daily load
TOC	Total organic carbon
TR	Technical Release
TRFLP	Terminal restriction fragment length polymorphism
TRI	Toxic Release Inventory
TSS	Total suspended solids
SUDS	Sustainable urban drainage systems
USDA	U.S. Department of Agriculture
U.S. EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UV	Ultra-violet (light)
UVQ	Urban Volume and Quantity
VBNC	Viable but non-culturable

VT/PSUHM	Virginia Tech-Penn State Urban Hydrology Model
WARMF	Watershed Analysis Risk Factor Model
WBM	Water Balance Model
WDNR	Wisconsin Department of Natural Resources
WEE	Western equine encephalitis
WEF	Water Environment Federation
WERF	Water Environment Research Foundation
WET	Whole effluent toxicity
WHO	World Health Organization
WQv	Water quality volume
WSUD	Water sensitive urban design
ZPC	Point of zero charge

EXECUTIVE SUMMARY

Urban stormwater runoff contributes to the degradation of receiving surface waters and groundwater. This degradation is caused both by the increased flows resulting from urbanization and conversion of infiltrating land to impervious area and by the pollutants (chemical and microbiological) contained within runoff. Stormwater management is a fundamental component of site development for new construction and often is required to the maximum extent practicable for redevelopment of urban/suburban lands to minimize/remediate the impacts of urbanization.

To meet the demands for stormwater management, many regulatory agencies have developed guidance documents to assist in the design of stormwater treatment devices. This manual is not intended to supplant those documents, but instead to supplement their content and to aid in the appropriate selection of stormwater treatment devices. Planning for sustainable stormwater management depends upon: the integration of information regarding the hydrology, chemistry, and biology of existing watershed conditions; the establishment the “ideal” watershed characteristics to minimize impacts; the identification of the causes of current and potential future watershed degradation; and the identification, implementation, and maintenance of appropriate stormwater control devices (often called by regulatory agencies as Best Management Practices (BMPs)) to correct existing problems and prevent future degradation. In addition, the outcomes from the planning process must be reassessed regularly and updated in light of changes in the watershed, changes in technology, and changes in laws and regulations governing urban stormwater management and control practices. In many cases, the advent and implementation of discharge limits through the total maximum daily load (TMDL) process are affecting the way that stormwater managers currently “do business.” The profession is moving away from only requiring strict implementation of treatment devices on a development site to the concept of load allocations in a watershed that then are assigned to individual sources/sites. These sources then must determine the best method practicable to address and control stormwater runoff loads to the required permit limits.

This document seeks to aid in planning for sustainable stormwater management, with a focus on infiltration devices. This focus on infiltration as a treatment technology is not intended to discourage surface treatment of runoff prior to discharge to surface receiving waters. However, surface treatment has a longer history of study with many references written to support and explain the design of these devices. References are provided for surface-treatment devices and pertinent findings are summarized herein. Infiltration as a stormwater management tool with appropriate design guidance does not have this history of study and breadth of reference publications, although the body of literature on infiltration is increasing. In addition, many regulatory agencies, for reasons of encouraging groundwater recharge and minimizing receiving water impacts from urbanization, are requiring infiltration first before surface treatment, unless the soils or site are not suitable for infiltration.

This document follows the process of stormwater management, from the determination of the appropriate regulatory authorities, laws, and guidance, through calculation/estimating the volume and flow rates of water and pollutants needing treatment, to the final step of designing treatment devices. Flowcharts were developed to guide the user through the process. The first

flowchart (Figure ES-1) describes the logic behind this document's organization and divides the activities into the general categories described above.

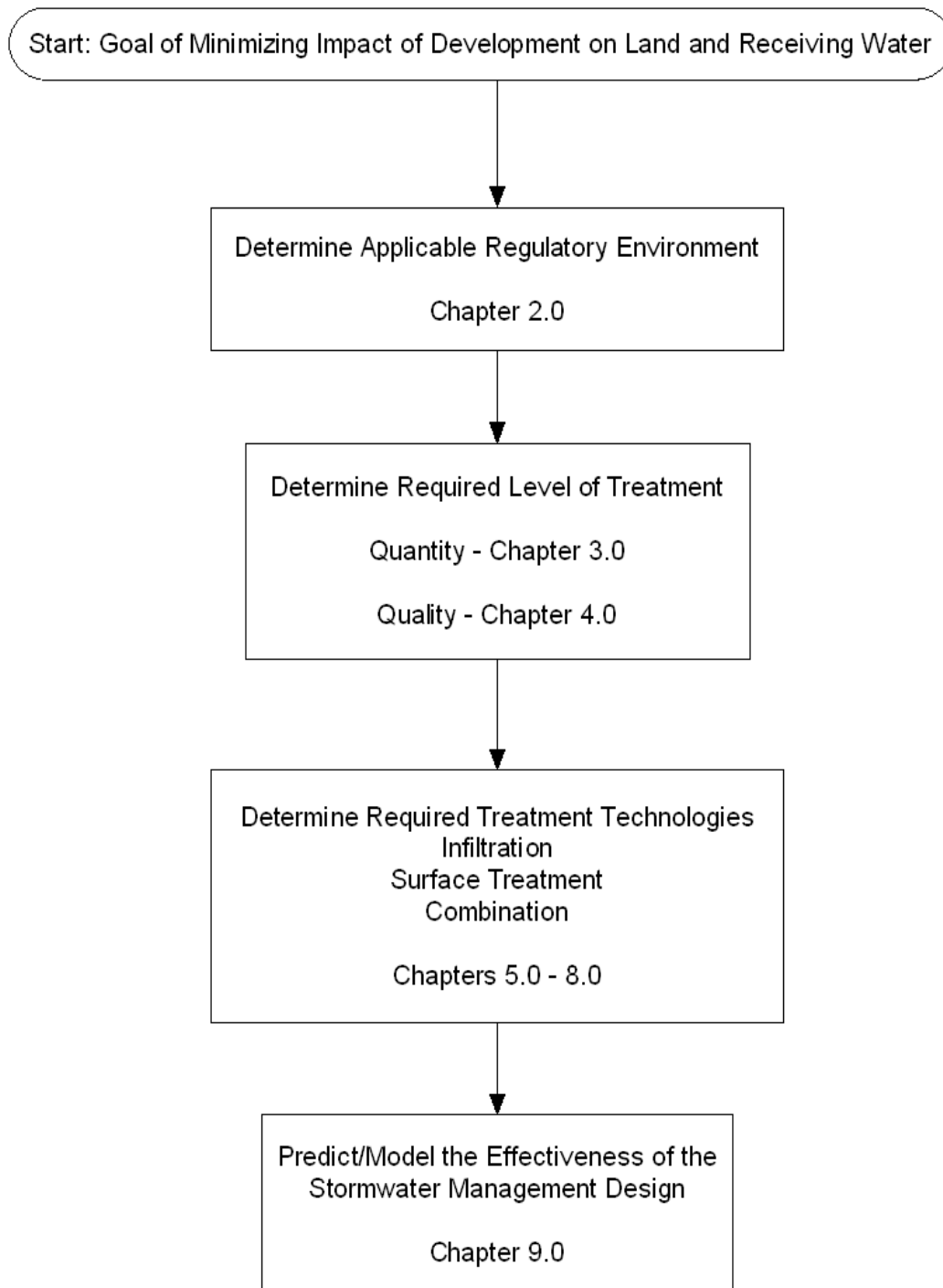


Figure ES-1. Organizational Flow Chart for the Stormwater Management Process.

For the steps outlined in Figure ES-1, flow charts were developed to guide the users through those individual processes. Checklists also were created so that the user could document the data used to support the decisions. These checklists, where applicable, contain not only the

field data but also document the source and provide space for regulatory limits to be entered. The side-by-side comparison of actual conditions to regulatory limits should enable the user and other reviewers to rapidly evaluate the selection of treatment practices. These flowcharts, Figures ES-2 through ES-6, describe the regulatory environment, the methods to characterize the watershed/receiving water and stormwater quantity, to characterize the receiving water and stormwater quality, to design treatment devices for stormwater quantity management, and to design devices for stormwater quality management, respectively.

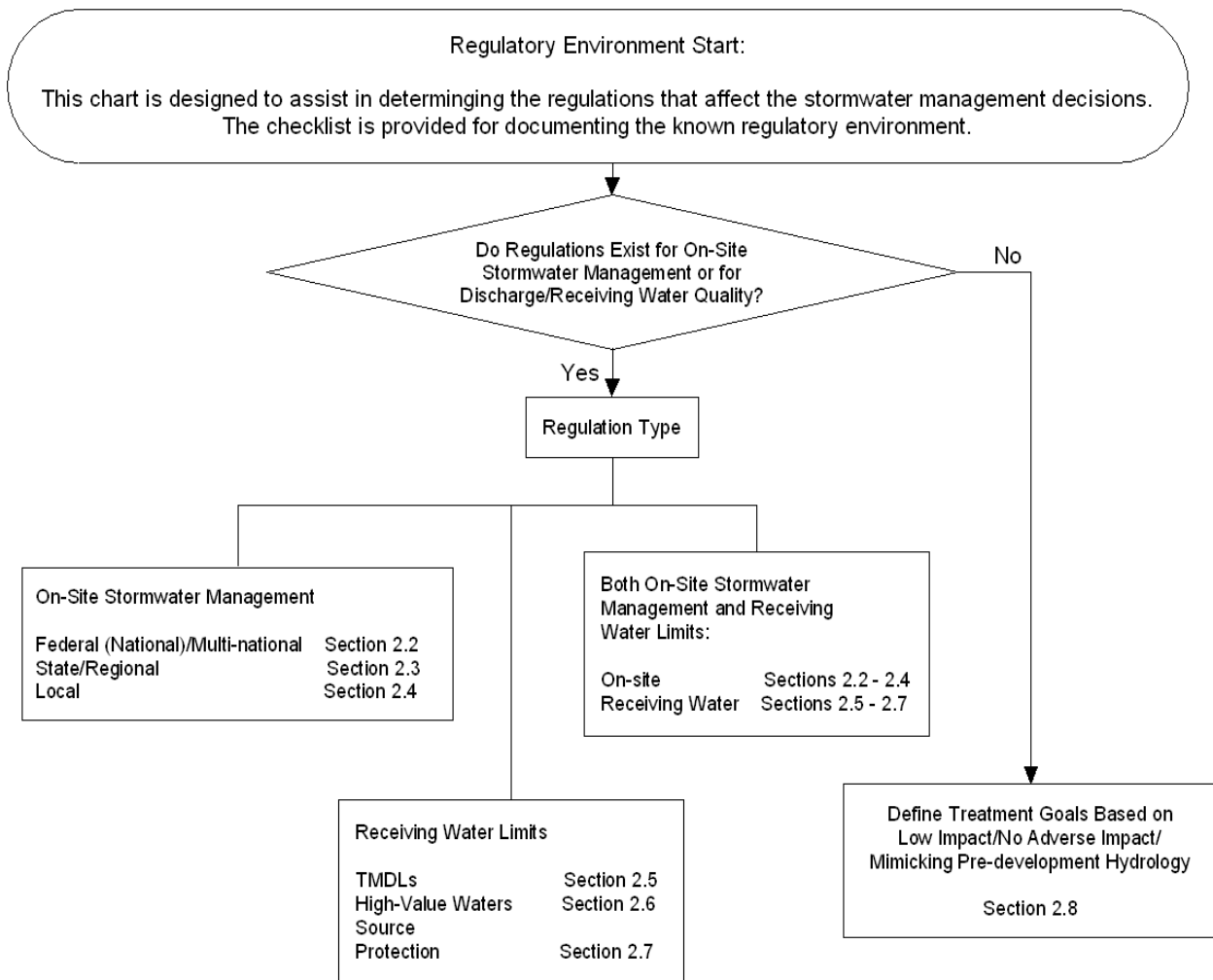


Figure ES-2. Flowchart for Characterizing the Regulatory Environment.

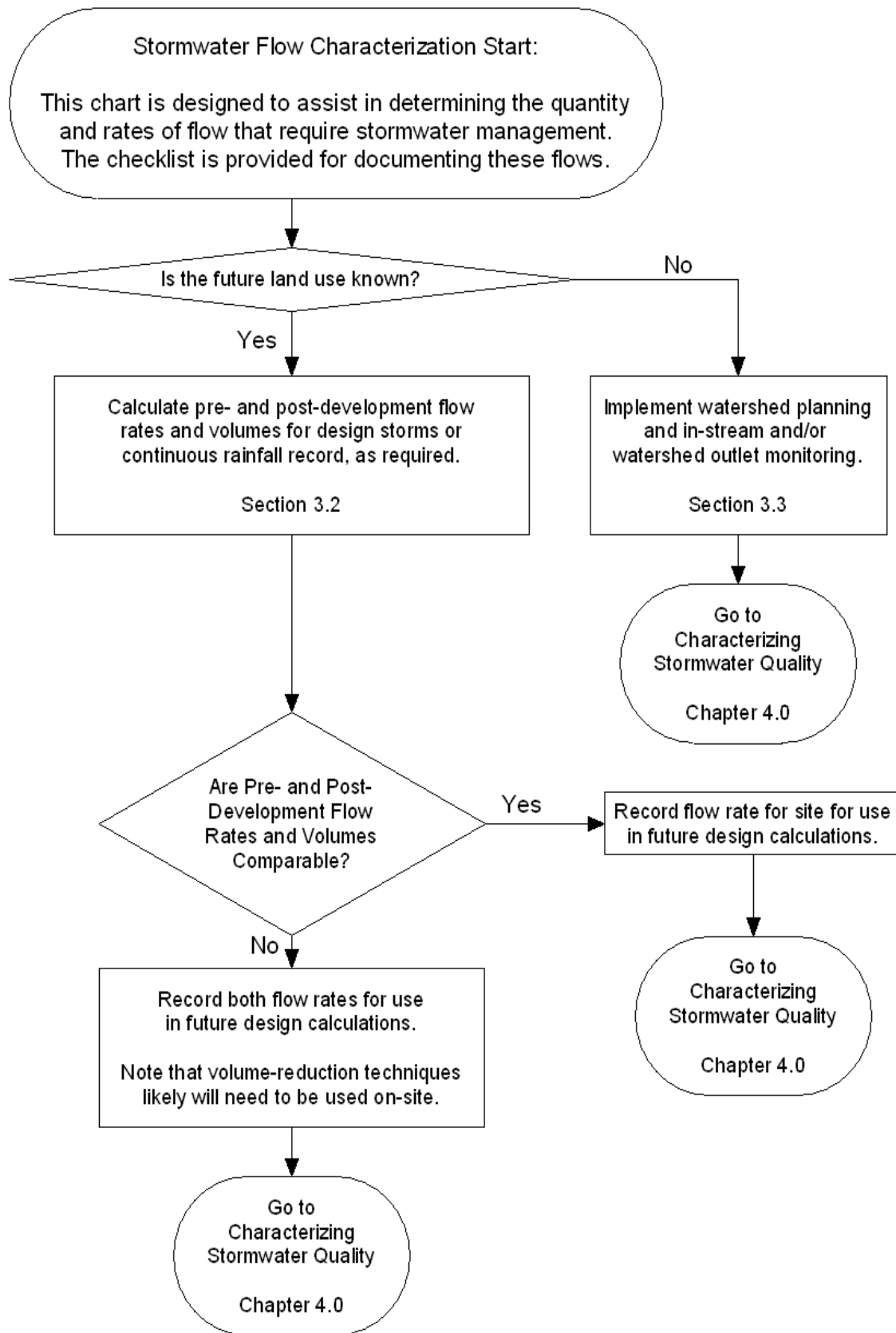


Figure ES-3. Flowchart for Characterizing Stormwater Quantity.

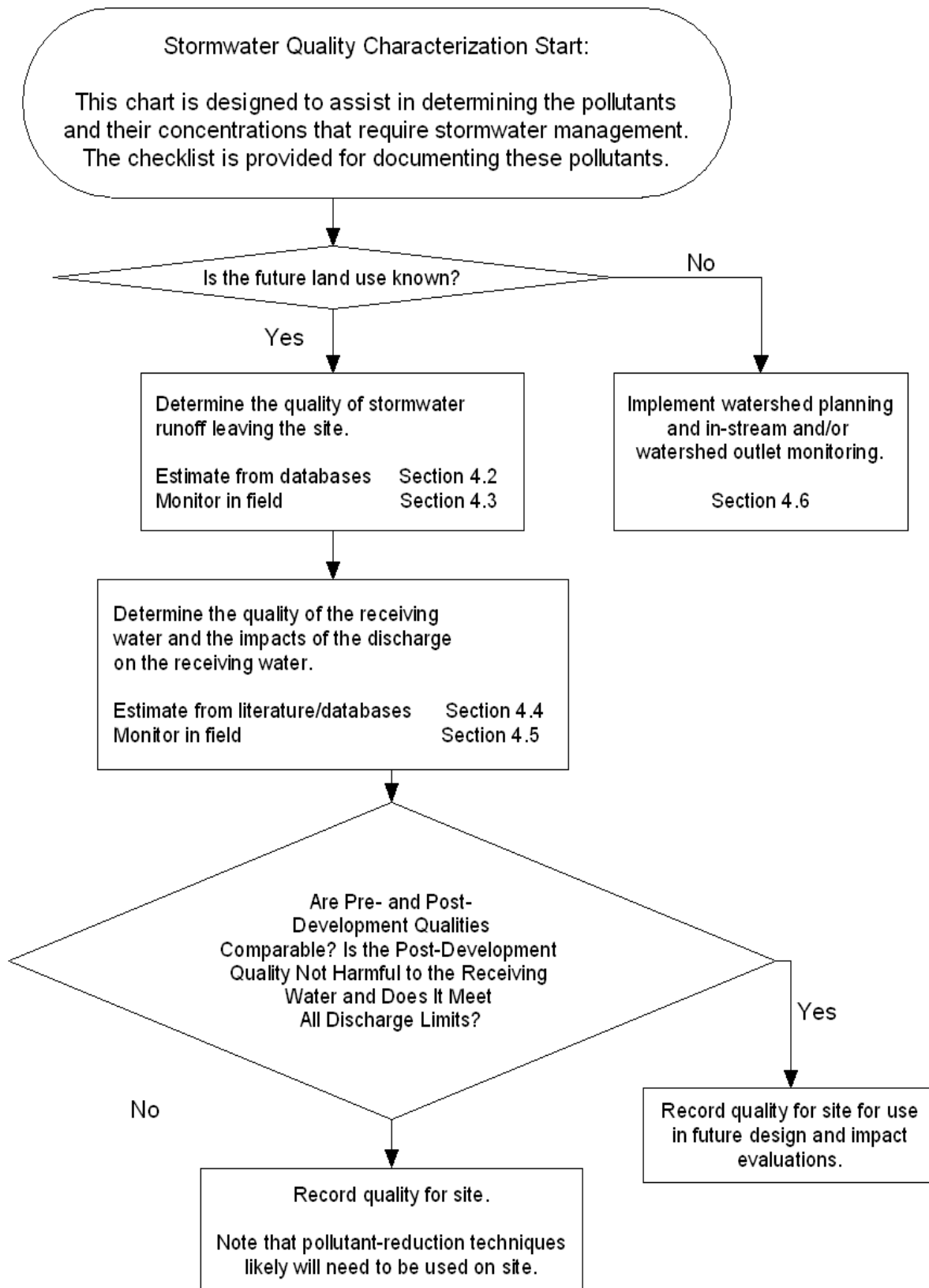


Figure ES-4. Flowchart for Characterizing Stormwater Quantity.

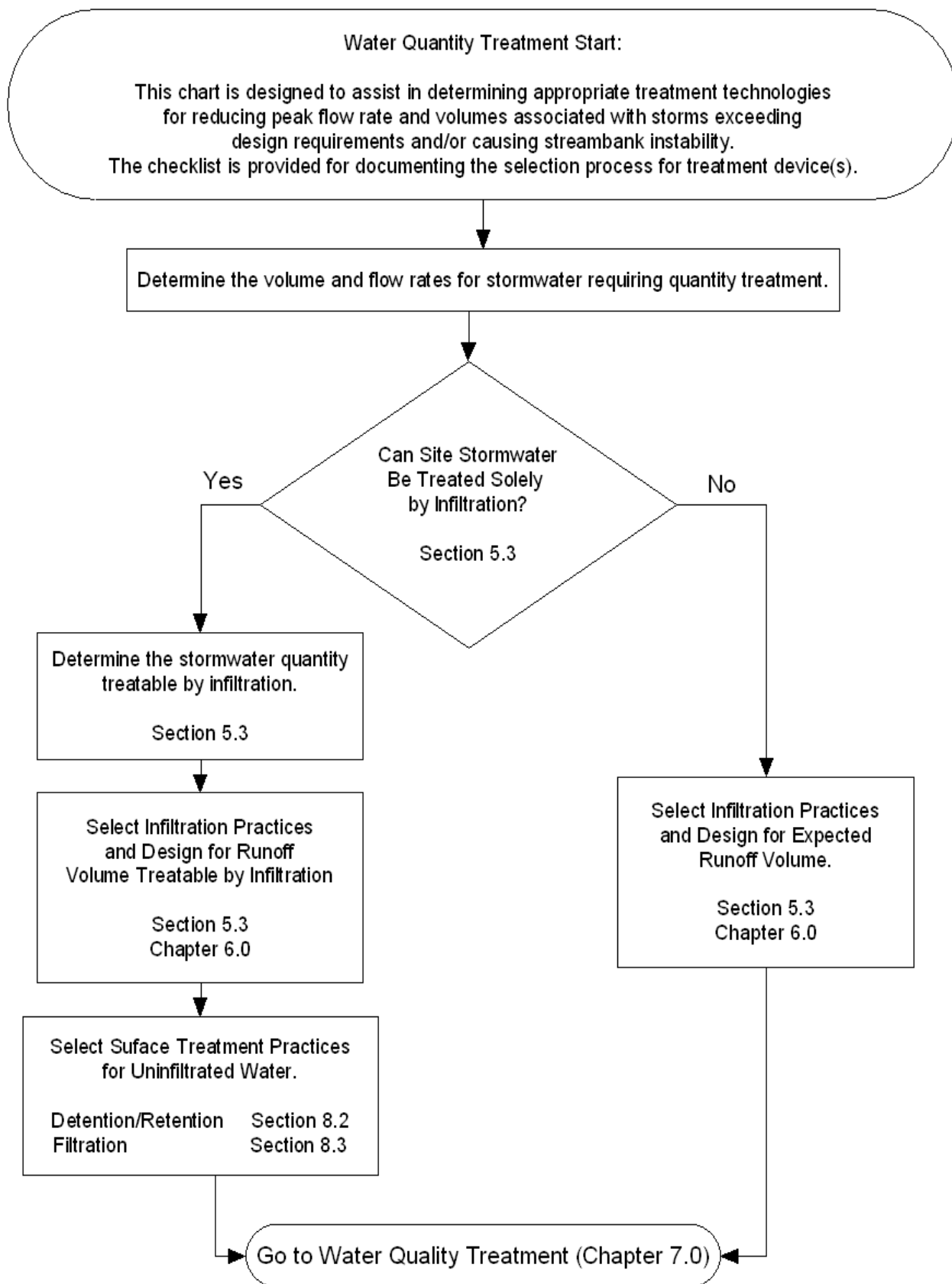


Figure ES-5. Flowchart for Determining Treatment for Stormwater Quantity Concerns.

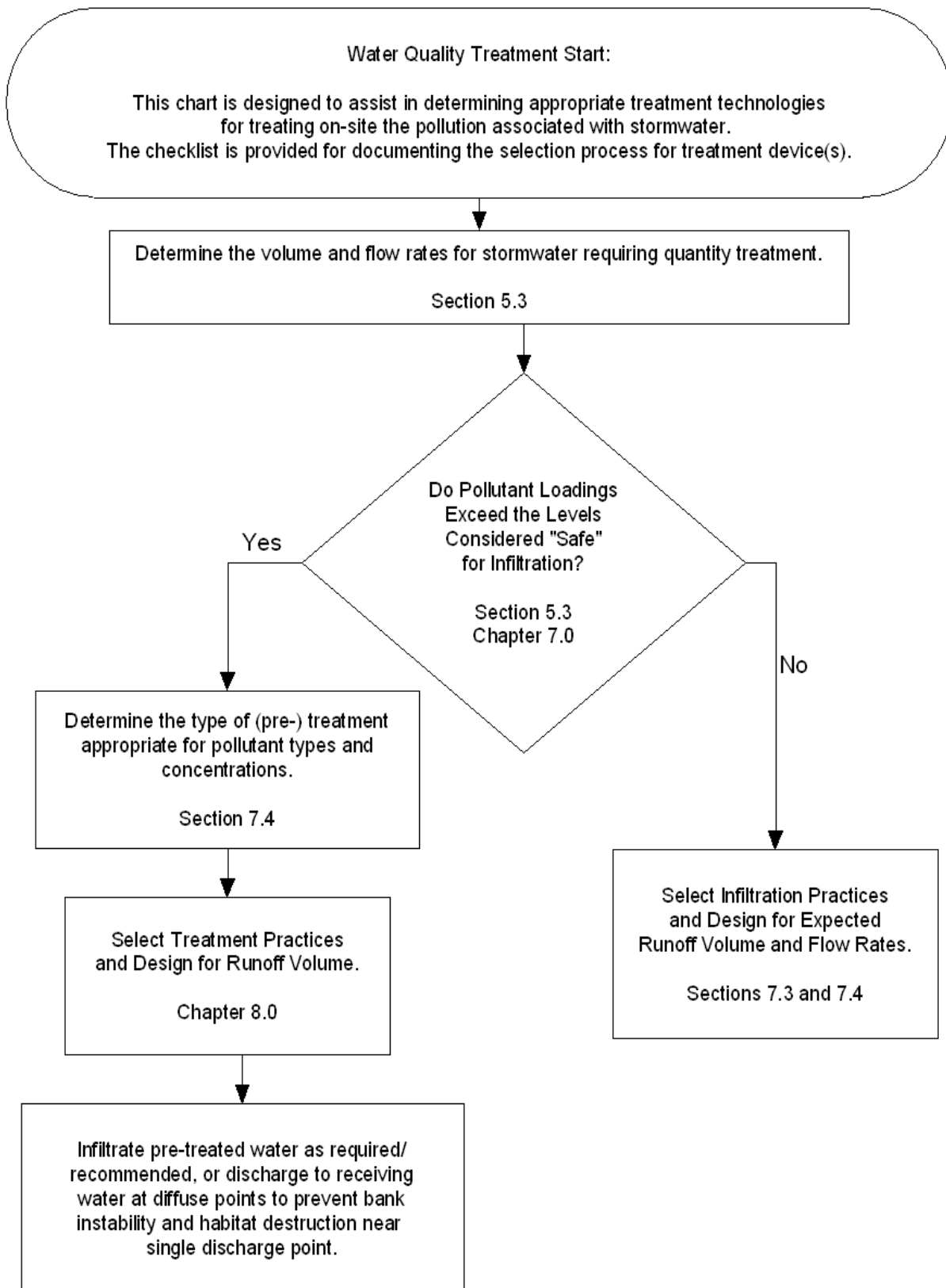


Figure ES-6. Flowchart for Determining Appropriate Treatment for Stormwater Quality Concerns.

Chapter 10.0 addresses the literature available on life-cycle costs associated with stormwater treatment devices. The appendices provide supporting information for appropriate sections of this document. The appendix information was developed and included for the novice user, but was excluded from the main body of the document so that the experienced user did not have to read through it to use the remainder of the document.

This document has attempted to tie together what is known about stormwater treatment devices with the theory behind treatment process design and efficiency and behind surface and ground water movement. It addresses issues such as the impact of sediment accumulation in treatment devices, and the effects of soil and water chemistry on pollutant removal infiltration and filtration devices. This document was not designed to replace the regulatory and non-mandatory guidance documents provided for stormwater managers and designers by the appropriate regulatory authorities, but instead to outline the process logically and guide the user in determining the types of data needed to design devices that met the goal of stormwater management.

Data gaps also were identified. Most of the data gaps were in the areas of understanding infiltration/filtration pollutant removal at the concentrations and speciations of pollutants seen in stormwater. The rest were with modeling and understanding how the installation of multiple treatment devices in a watershed affect the outfall stormwater quantity and quality. The modeling is not yet able to use unit process theory to predict accurately the pollutant removal in these devices. The groups of data gaps are identified below.

Pollutants of Concern. Current research is focusing on identifying potential sources and predicting source loadings in order to improve modeling. However, much still remains unknown regarding microbiological pollution. While there have been a considerable number of studies published that examine the microbiological quality of recreational water, there is essentially no data beyond the California studies that directly address the relationship between urban stormwater runoff and recreational waterborne infections (RWIs). Instead, the information available seems to address the areas of RWIs and stormwater runoff as entirely separate issues.

There is ample evidence indicating an association between land-use patterns (degree of urbanization) and the presence of indicator organisms in receiving water. Even with these studies, there is very little information available concerning the source – urban stormwater runoff, CSO, SSO, wastewater discharge, etc. – of the indicator organisms. Rather, the relationships between wet-weather flows and higher concentrations of indicator organisms are used to infer a relationship between urban stormwater runoff and microbiological quality.

The second category of research has focused on the relationship between the presence of indicator organisms and adverse health outcomes. While statistically significant relationships have been documented in some studies, the majority of these studies also highlight the limitations of indicator organisms in monitoring recreational water quality.

Effects of Pollutants. As mentioned previously, data gaps exist in both effects of water quality on stream integrity as well as stream restoration. Some questions include: When does it become more than an episodic event, leaving a permanent mark on stream integrity? Does impervious surface (ISC) really worsen urban runoff and thus ruin the water quality in an urban stream. Is water quality ever bad without ISC and physical habitat modification? And when, in implementing these changes does it become a problem? Finally, what role does water quality

play in stream restoration? Do different streams (cold water versus warm water) need different restoration practices to achieve success? Future research should address these issues.

Design of Infiltration Facilities. In terms of infiltration, even using the quality-control-checked information in the International BMP database, no site provided complete information to confirm the use of SESOIL, or an equivalent model, and its predictive pollutant depth. Future research should use real data and calibrate a vadose zone that can predict pollutant migration depth. Monitoring of installed treatment devices for better prediction of performance given the theory is recommended.

Impacts on Downstream Health of Multiple Control Practices in a Watershed. The purpose of installing treatment devices on a site is to prevent post-development damage to downstream waters. However, the impact of multiple control practices in a watershed, if they are not planned correctly, may be minimal or negative. Research is needed on the cumulative impacts of multiple control practices in a watershed. This research should focus both on the impacts of water quality and quantity and should measure flow, and the parameters that characterize stream health.

Maintenance and Long-Term Performance of Stormwater Treatment Devices. Many of the regulatory agencies have begun to provide “mimicking pre-development hydrology” as the goal of stormwater management in their jurisdictions. Infiltration is seen as restoring groundwater recharge, while reducing the negative effects of increased stormwater runoff – increased pollutant loads, thermal effects, and stream instability due to increased energy delivered to the stream. However, only recently have datasets on the long-term performance and maintenance requirements of infiltration devices become available. A future research need will be to address the data gap of analyzing this data to determine general long-term performance trends and the factors that affect both the long-term performance and the need for maintenance on these devices.

Undertaking activities such as these will allow for refinement of models, which are the most effective way of predicting whether the water quality and quantity objectives can be met. As the models are improved, performance is better predicted and the uncertainties are then reduced to those inherent with the variability and frequency of rainfall.

CHAPTER 1.0

PLANNING FOR SUSTAINABLE STORMWATER MANAGEMENT

1.1 Introduction

Urban stormwater runoff contributes to the degradation of receiving surface waters and groundwater. This degradation is caused both by the increased flows resulting from urbanization and conversion of land where water freely infiltrated to impervious area and by the pollutants (chemical and microbiological) contained within runoff. The problems resulting from conventional stormwater management and the challenges associated with reducing the degradation associated with urban runoff are addressed in the National Research Council report entitled “Urban Stormwater Management in the United States” (National Research Council 2009). Stormwater management is a fundamental component of site development for new construction and often is required to the maximum extent practicable for redevelopment of urban/suburban lands to minimize/remediate the impacts of urbanization.

To meet the demands for stormwater management, many regulatory agencies have developed guidance documents to assist in the design of stormwater treatment devices. This manual is not intended to supplant those documents, but instead to supplement their content and to aid in the appropriate selection of stormwater treatment devices. Planning for sustainable stormwater management depends upon: the integration of information regarding the hydrology, chemistry, and biology of existing watershed conditions; the establishment of guidance defining the “ideal” watershed characteristics; the identification of the causes of current and potential future watershed degradation; and the identification, implementation, and maintenance of appropriate stormwater control devices (often called by regulatory agencies as Best Management Practices (BMPs)) to correct existing problems and prevent future degradation. In addition, this process must be reassessed regularly and updated in light of changes in the watershed, changes in technology, and changes in laws and regulations governing urban stormwater management and control practices. In many cases, the advent and implementation of discharge limits through the total maximum daily load (TMDL) process are affecting the way that stormwater managers currently “do business.” The land development profession is moving away from only requiring strict implementation of treatment devices on a development site to the concept of load allocations in a watershed that then are assigned to individual sources/sites. These sources then must determine the best method practicable to address and control stormwater runoff loads to the required permit limits.

This document has been developed to aid in planning for sustainable stormwater management, with a focus on infiltration devices. This focus on infiltration as a treatment device is not intended to discourage surface treatment of runoff prior to surface receiving waters. However, surface treatment has a longer history of study with many references written to support and explain the design of these devices. References are provided for surface-treatment devices and pertinent findings are summarized herein. Infiltration as a stormwater management tool with

appropriate design guidance does not have this history of study and breadth of reference publications, although the body of literature on infiltration is increasing.

1.2 Constraints of the Urban Stormwater Manager

It is imperative that the constraints faced by the municipality or stormwater authority be addressed as sustainable stormwater management strategies are evaluated. Over the past 40 to 50 years, several surveys of stormwater planners, engineers and regulatory authorities have been conducted to determine the state-of-the-practice at the time of the survey. Included in those surveys also have been questions regarding the impediments to the implementation of research results/newer techniques in the design of a modern stormwater plan. Appendix B summarizes the results of Pitt et al. (1999), Nowacek (2005), Clark et al. (2006), and KICP (2009). Each of these surveys of the impediments to implementation is limited in its size and/or scope. However, when examined together, they indicate that problems still exist in many areas with the acceptance of infiltration systems, especially small-scale systems, in the urban landscape. They can provide guidance as to where more public education is required and what the public and regulatory concerns are when selecting and presenting non-traditional development designs.

1.3 Development of Flow Charts for Guiding Stormwater Management Decisions

The purpose of the flow charts is to help the end user (the regulator, manager, and/or engineer) view stormwater management as a holistic process, where the improvement of the watershed condition is the primary goal. The flow chart in this chapter shows the organization of this document and focuses on the planning process and data assembly. A review of the holistic process lends itself to dividing the process into three parts: regulatory; evaluation of the impacts of development; and selection, design, and implementation of treatment practices to mitigate those impacts. The details of the planning and evaluation processes are in the appropriate chapters (references are cited in the action boxes). These actions typically involve gathering data and references to support and/or guide the following decision steps. Detailed flowcharts are included with the individual chapters to describe the steps and data requirements for that chapter's activities. They also reference the appropriate sections of each chapter where the specific concerns, questions and data requirements are addressed.

While the flow chart provides the logic for selecting stormwater management practices, documentation of the data collected at each step also is critical. For that reason, a checklist/worksheet has been developed for practical use and is incorporated into the appropriate chapters. The checklist summarizes the data collected for each action box on the flow chart. Its layout has been designed to allow for the comparisons of the site data with the regulatory standards and/or the guidance for healthy receiving waters. The checklist sections relating to each chapter is included in that chapter.

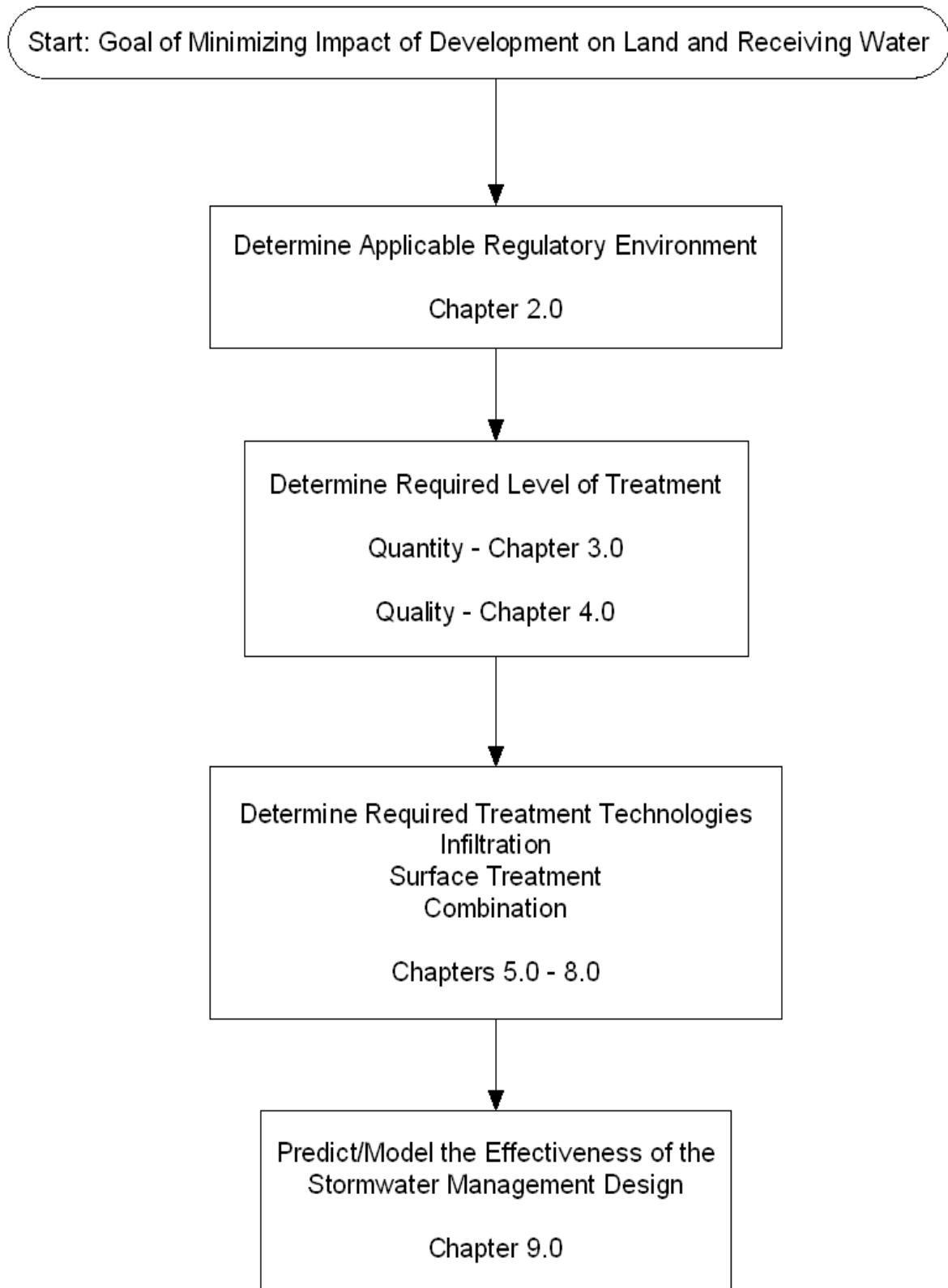


Figure 1-1. Top-Level Flow Chart for Stormwater Management.

CHAPTER 2.0

THE REGULATORY ENVIRONMENT

2.1 Introduction

This document has been developed to provide guidance to stormwater managers as they plan for sustainable stormwater management. However, users must remember that the regulatory environment of the site may dictate specific practices and design criteria. The user must consult all applicable regulations and guidance to determine the constraints for stormwater management for a site/watershed/local area.

Figure 2-1 is the flow chart for assisting in determining the regulatory requirements for a specific development/site/watershed. This chart addresses both the on-site and potential in-stream requirements. Additional information on the types of regulations and programs are located in the appropriate sections of this chapter (on-site stormwater management is addressed in Sections 2.2 through 2.4, while in-stream issues are addressed in Sections 2.5 through 2.7).

The checklists for recording specific regulatory information relating to water quantity and quality are contained in Chapters 3.0 and 4.0, depending on whether quantity or quality issues are being addressed. Table 2-1 contains the checklist for recording which regulatory requirements are appropriate for the site. They are included in those chapters because those chapters focus on gathering the needed site data. The completed checklist will encourage a line-by-line comparison of the site conditions with the regulatory requirements.

2.2 Federal/National Stormwater Regulations and Programs

2.2.1 Federal Government (United States)

The U.S. Environmental Protection Agency (U.S. EPA) has four programs (based on two acts and several sets of regulations) that affect stormwater management. The user is directed to other federal agencies, bureaus and offices as appropriate for federal projects. For example, the Energy Independence and Security Act of 2007 requires improvements in energy efficiency in federal buildings. The implementation, as reported by the General Accounting Office, is headed by the General Services Administration (GSA) because the GSA oversees the design, construction and maintenance of thousands of federal buildings. GSA is developing programs to ensure that new buildings achieve the U.S. Green Buildings Council's Leadership in Energy and Environmental Design (LEED) certification (a similar certification process, the Sustainable Sites Initiative, is being developed for site areas outside the building envelope). While the Act focuses on energy, its mandates may be applicable to the stormwater manager/designer of federal buildings. For example, stormwater and energy credits may be received for a green roof, which also may provide substantial mitigation of the quantity and quality of traditional roof runoff. This is only one example of why federal projects may have more regulations than are listed here. Other examples include highway projects and other development funded in whole or in part by the U.S. federal government. The four primary acts or programs that are managed by the U.S.

EPA and that affect stormwater management are the Clean Water Act, the Coastal Zone Reauthorization Act, the National Pollutant Discharge Elimination System (NPDES) permit program, and the Total Maximum Daily Load (TMDL) program. The TMDL program is discussed in Section 2.5 where receiving water limits are addressed.

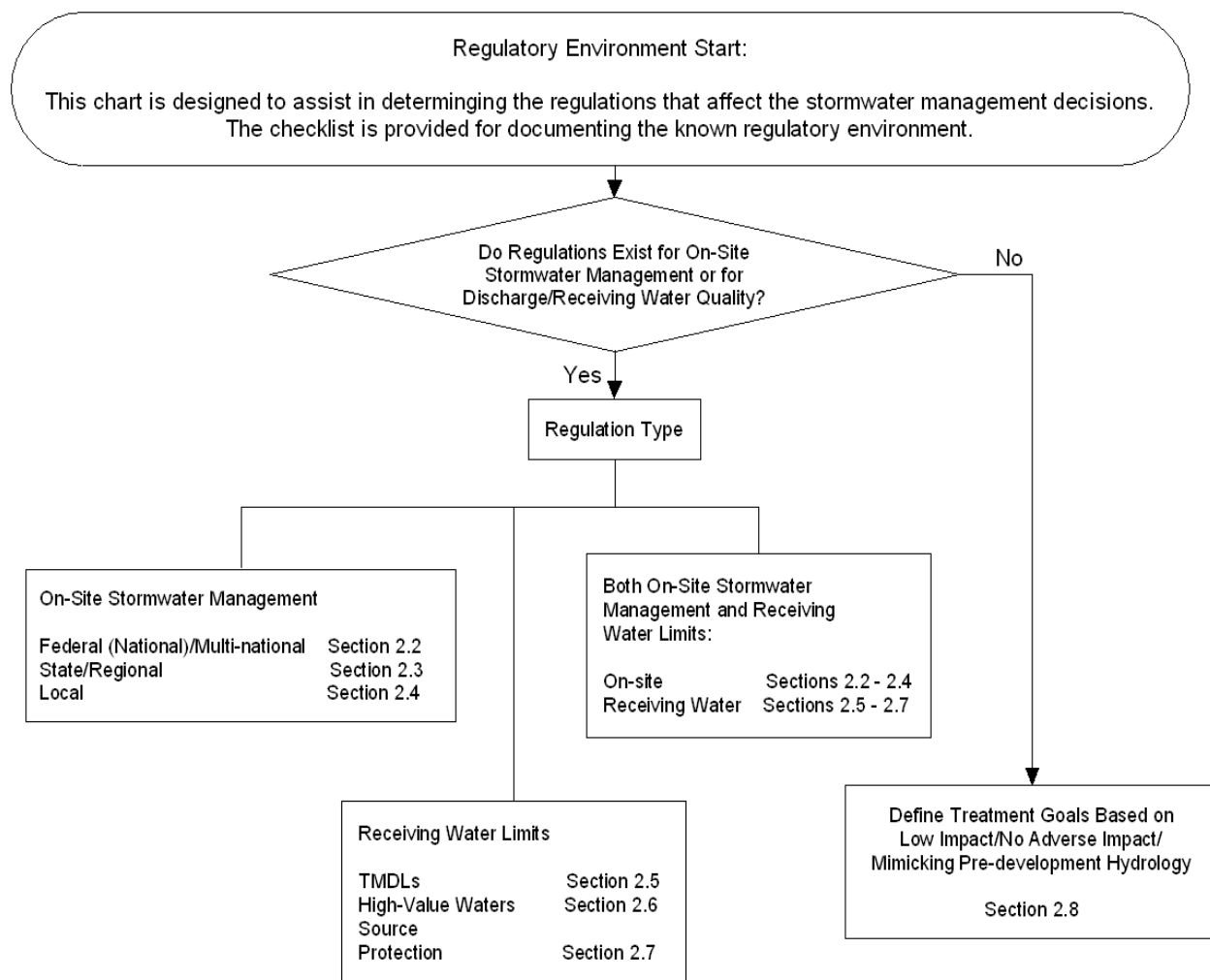


Figure 2-1. Regulatory Environment for Sustainable Stormwater Management.

2.2.1.1 The Clean Water Act

The Clean Water Act established the basic structure for regulating discharges of pollutants into the waters of the United States and gave U.S. EPA the authority to implement pollution control programs, including for nonpoint source pollution such as urban runoff. The Act required that water quality standards be set for contaminants in navigable surface waters (“[a]ll waters which are currently used, or were used in the past, or may be susceptible to use in interstate or foreign commerce, including all waters which are subject to the ebb and flow of the tide.” 33 C.F.R. § 328.3(a)(1); 40 C.F.R. §230.3(s)(1)). Under the Act, dischargers must obtain a

permit for any pollutant discharge to almost all surface waters. Many states have defined further a “water of the state” to include groundwater that is involved in commerce.

Table 2-1. Documentation of Regulatory Requirements for Sustainable Site Stormwater Management.

Regulation Type	Regulation: Yes or No	Regulating Authority or Authorities
Federal		
State		
Local/Regional		
Total Maximum Daily Load (TMDL)		
High-Value Water		
Drinking Water Source Protection		

2.2.1.2 The Coastal Zone Reauthorization Act and Coastal Nonpoint Source Pollution Control Program

The Coastal Nonpoint Source Pollution Control Program requires communities in designated coastal management areas to establish Nonpoint Pollution Control Programs (currently, 29 states and territories). The Nonpoint Pollution Control Program must describe how it will implement nonpoint source pollution controls, known as management measures, that conform with those described in Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters. This program is administered jointly with the National Oceanic and Atmospheric Administration (NOAA).

2.2.1.3 The National Pollutant Discharge Elimination System (NPDES) Program

The NPDES Program is responsible for controlling and regulating point source pollutant discharges. In 1990, Phase I of the NPDES stormwater program required permit coverage for municipalities that had municipal separate storm sewer systems (MS4s) that served populations of 100,000 or more. In 1999, NPDES Phase II extended the program to smaller communities, also known as small MS4s. Communities covered by Phase II have to apply for NPDES permits

and have to develop and implement a comprehensive stormwater management program that includes the U.S. EPA's defined six minimum measures for stormwater management. In most states, the NPDES permit program is administered by each authorized state and may require certain specific technical standards.

2.2.2 International Stormwater Management

Similar regulations and guidance to those in the U.S. exist in whole or in part throughout the world. The following is a list of countries regularly cited in the literature regarding stormwater management, plus links to the agency's website overseeing stormwater. For those countries with governmental structures with states (or other similar entities), stormwater regulations may exist at other levels of government. Flood control, instead of water quality, is still a large concern in many countries. Unlike the U.S., stormwater regulations and guidance documents in many countries are not available through the internet.

- ◆ European Union: Publications available on Sustainable Urban Drainage Systems. European Union mandated an integrated pollution prevention and control (IPPC) program.
- ◆ Australia: Australian Government National Water Commission, <http://www.nwc.gov.au/www/html/209-rainwater--stormwater.asp>
- ◆ New Zealand: Primarily established by regional councils.
- ◆ Canada: Environment Canada, http://www.ec.gc.ca/WATER/en/manage/floodgen/e_mngt.htm

Countries with active stormwater management programs establish first the goal of sustainable stormwater management with a view toward stormwater as a resource and not a waste product. The three primary schools of thought both in the U.S. and around the world for sustainable stormwater management are Low Impact Development (LID) or Conservation Design in the United States, Sustainable Urban Drainage Systems (SUDS) in the United Kingdom and parts of Europe, and Water Sensitive Urban Design (WSUD) in Australia. One of the more recent areas of research, with much of the research occurring in Europe, is the effect of climate change on the hydrologic cycle, particularly the impact on rainfall. In areas where the storms are predicted to have higher intensities, research groups and local governments are investigating whether the current drainage systems will safely convey the stormwater without substantial increases in flooding. They also are investigating whether the current design criteria for stormwater treatment devices will result in under-sized treatment devices in the future.

2.3 State Agencies with Stormwater Management Authority

The website www.stormwaterauthority.org maintains a list of current stormwater regulations for the U.S. and, in several states, for the major municipalities. The user is directed to that site as a potential reference for the current state of the regulations. Another website containing information on state stormwater manuals is hosted by the U.S. EPA Region 10 (<http://yosemite.epa.gov/R10/WATER.NSF/0/17090627a929f2a488256bdc007d8dee?OpenDocument>).

Table 2-2 lists the state agencies (as of November, 2008) that are responsible for stormwater management. The table also provides direct links to the stormwater home program (or to the permit page if a home page is not available) and describes the permit requirements.

Stormwater program information as summarized by StormwaterAuthority.org is included in Appendix C. As each state link notes, additional requirements may exist at the county and local level. In addition, only a few TMDLs are referenced in the table. It is incumbent upon the user to confirm whether TMDL limitations exist in the project watershed. TMDL requirements may impose additional discharge limits on the site runoff (see Section 2.5).

2.4 Local Agencies with Stormwater Management Authority

The website www.stormwaterauthority.org maintains a list of stormwater regulations for the United States and, in several states, for the major municipalities. The user is directed to that site as a potential reference for the recent (as of 2008) status of the regulations. Another website containing links to state stormwater manuals is hosted by the U.S. EPA Region 10 (<http://yosemite.epa.gov/R10/WATER.NSF/0/17090627a929f2a488256bdc007d8dee?OpenDocument>).

Local and regional agencies also may address stormwater management through drainage design regulations, zoning and planning requirements, and other land development ordinances. The reader is encouraged to determine where the regulatory authority for on-site stormwater management resides and the applicable regulations for the site.

2.5 The Total Maximum Daily Load (TMDL) Program

The TMDL Program was designed to restore water quality and stream health in watersheds. All watersheds with TMDLs are subject to stormwater discharge limits for the pollutant(s) of concern. The promulgation and enforcement of the resultant water quality standards is based on the surface water quality standards in the Clean Water Act. The TMDL process begins with a state assessing the water quality and stream health of a receiving water. If the waterbody's water quality indicates that it achieves its designated use (drinking water, fishable/swimmable, etc.), then no further action is taken. If waterbody is more polluted than allowed for its designated use, then the stream is assessed to determine which pollutant(s) is causing the stream to not meet its designated use. An assessment also is made of what level of that pollutant would allow the stream to meet its designated use. The states submit to the U.S. EPA a list of the streams that do not meet their designated uses (often known as a 303(d) list of impaired waters). Pollutants commonly associated with water quality degradation in urban areas include sediment, nutrients and bacteria. Industrial areas also may have problems associated with organic or metallic pollution. The state then creates a TMDL for the impaired waterbody, which designates the maximum load of that pollutant that the stream could assimilate and still maintain its designated use. That pollutant load is apportioned among the dischargers and each discharger receives a permit limit for the pollutant of concern. The primary website for the U.S. EPA TMDL program is <http://www.epa.gov/owow/tmdl/> (accessed December 11, 2008).

2.6 High-Value Waters

Many states have designated certain waterways, or portions of waterways, as special protection or high-value waters. Other terms for these waters may include *exceptional quality*, *outstanding*, or other words that indicate additional protective measures are required. This listing requires additional protection above and beyond the requirements for most fishable/swimmable or drinking source waters. These waters may be protected because of their use as drinking water sources. They also may be protected because of the biological habitat provided for fish, especially game fish, and/or the presence of endangered species. If a site's runoff will discharge

into a high-value water, the manager must determine if discharge is allowed and the level of treatment required. It should be anticipated that this level of treatment will exceed that required for most sites.

2.7 Drinking Water Source Protection

While drinking water source protection is not addressed directly in the stormwater regulations or the TMDL program, the prevention of pollution in surface and ground waters used to supply potable water to humans is one area of focus for the U.S. EPA. EPA actively encourages drinking water and state agencies to protect the watersheds draining to drinking water sources. The goal of this additional level of watershed management, which may constrain development or require additional treatment compared to a non-source site, is to reduce the burden on treatment plants to deliver potable water. The primary website for the U.S. EPA Drinking Water Source Protection Program is <http://cfpub.epa.gov/safewater/sourcewater/> (accessed December 11, 2008).

2.8 Treatment Guidance in the Absence of Regulatory Requirements

Most development or re-development sites will be subjected to one or more on-site and/or in-stream requirements. However, there will be a few sites, such as a house construction site of less than 1 acre whose runoff discharges to a receiving water not subject to TMDLs, not listed as a high-value water, and not part of an area designated as a drinking water source. It is incumbent then upon the stormwater manager to determine the required level of treatment to ensure that the site's runoff does not contribute to the degradation of its receiving water. One method of determining the required quality is to set the planned discharge quantity and quality limits based on current receiving water quality and stream health measurements, plus predictions of current storm runoff quantities for different storm sizes and durations. This assumes that the receiving water meets its designated use. If not, the guidelines/limits could be based on the literature relating stream health to chemical and biological water quality. Water quantity limits would be determined based on the literature on stream stability and its effects on stream health.

While the physical, chemical and biological parameters/values that characterize a healthy stream versus an unhealthy one may vary from stream to stream or between regions of the country, the Urban Subwatershed Restoration Manual Series published by the Center for Watershed Protection (www.cwp.org) can provide a starting location for these investigations. In addition, Burton and Pitt (2002) described chemical and biological monitoring of streams. Rosgen and Silvey (1996) and others, such as the NRCS Stream Restoration Design Handbook, have described the physical parameters required to evaluate stream stability. Methods have been developed to restore urban streams to stable conditions.

Table 2-2. Stormwater Management Agencies (adapted from www.stormwaterauthority.org).

State	Agency and Program Notes
Alabama	Agency: The Alabama Department of Environmental Management (ADEM), http://www.adem.state.al.us/waterdivision/waterdivisionpp.htm Permits required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s). Additional permitting requirements exist in the coastal regions of Baldwin and Mobile counties.
Alaska	Agency: U.S. EPA administers NPDES permits in the state, http://dec.alaska.gov/water/wnpspc/stormwater/stormwater.htm Permits Required for: construction sites, certain industrial sites, and Municipal Separate Storm Sewer Systems (MS4s) in Alaska.
Arizona	Agency: The Arizona Department of Environmental Quality (ADEQ). EPA Region 9 permits for all Indian lands in Arizona, http://www.azdeq.gov/enviro/water/permits/stormwater.html Permits Required for: industrial activity, construction activity, and municipal separate storm sewer systems (MS4s).
Arkansas	Agency: The Arkansas Department of Environmental Quality (ADEQ), http://www.adeq.state.ar.us/water/branch_permits/general_permits/stormwater/default.htm Permits required for: construction sites disturbing $\geq$ one acre must obtain permit coverage, municipal separate storm sewer systems (MS4), and NPDES Phase I communities.
California	Agency: California State Water Resources Control Board (CASWRCB), http://www.waterboards.ca.gov/water_issues/programs/stormwater/ Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s). In addition to state, regional, and local regulations, there are a number of established and proposed TMDLs impacting California's watersheds.
Colorado	Agency: Colorado Department of Public Health and Environment (CDHE), http://www.cdphe.state.co.us/wq/PermitsUnit/stormwater/index.html Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and designated Municipal Separate Storm Sewer Systems (MS4s).
Connecticut	Agency: Connecticut Department of Environmental Protection (CTDEP), http://www.ct.gov/dep/cwp/view.asp?a=2721&q=325702 Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).
Delaware	Agency: Delaware Department of Natural Resources and Environmental Control (DEDNR), http://www.swc.dnrec.delaware.gov/Pages/SedimentStormwater.aspx Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
District of Columbia	Agency: U.S. Environmental Protection Agency. Program Information: Federal NPDES program requirements. A number of D.C. rivers and watersheds, such as the Anacostia and Potomac rivers, Rock Creek, and other area rivers, are impaired and that compliance with an established Total Maximum Daily Load (TMDL) could be required. Permits Required for: construction sites, certain industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Florida	Agency: Florida Department of Environmental Protection (FDEP). FDEP subsequently delegated authority to four of the five regional Water Management Districts (WMDs), http://www.dep.state.fl.us/water/stormwater/npdes/index.htm Permits Required for: New development, while redevelopment and retrofit projects are largely permitted on a case-by-case basis.
Georgia	Agency: Georgia's Environmental Protection Division (GAEPD), http://www.gaepd.org/Documents/techguide_wpb.html#sw Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Hawaii	Agency: Hawaii Department of Health's Clean Water Branch (CWB), http://hawaii.gov/health/environmental/water/cleanwater/forms/genl-index.html Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Idaho	Agency: U.S. EPA Region 10 with the exception of Indian country. The Suck Valley Reservation is the only land that is covered under EPA. The Clean Water Act Idaho reviews and certifies all EPA permits issued in the state, http://www.deq.state.id.us/water/prog_issues/storm_water/overview.cfm Permits Required for: construction sites, certain industrial sites, and Municipal Separate Storm Sewer Systems (MS4s) in Idaho. As described in section 401 of Additional permit requirements are outlined in section 9 of the Construction General Permit.
Illinois	Agency: The Illinois Environmental Protection Agency (IEPA), http://www.epa.state.il.us/water/permits/storm-water/index.html Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).
Indiana	Agency: Indiana Department of Environmental Management (IDEM), http://www.in.gov/idem/4899.htm Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).
Iowa	Agency: The Iowa Department of Water Quality (DWQ), http://www.iowadnr.com/water/stormwater/index.html Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Kansas	Agency: Kansas Department of Health and Environment (DHE), http://www.kdheks.gov/stormwater/ Permits Required for: all construction sites disturbing $\geq$ one acre, many industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Kentucky	Agency: Kentucky Department of Environmental Protection (DEP), http://www.water.ky.gov/permitting/wastewaterpermitting/KPDES/storm/ Permits Required for: all construction sites disturbing $\geq$ one acre, many industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Louisiana	Agency: The Louisiana Department of Environmental Quality (LDEQ). The LDEQ has established the Louisiana Pollutant Discharge Elimination System (LPDES), http://nonpoint.deq.louisiana.gov/wqa/default.htm Permits Required for: construction sites $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Maine	Agency: Maine Department of Environmental Protection (MEDEP), http://maine.gov/dep/blwq/docstand/stormwater/index.htm Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Maryland	Agency: Maryland Department of the Environment (DOE), http://www.mde.state.md.us/Programs/WaterPrograms/SedimentandStormwater/home/index.asp Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Massachusetts	Agency: U.S. EPA Region 1. MADEP reviews the conditions of each permit, and certifies the program unconditionally or with specific conditions. MADEP signs each NPDES permit, creating a separate state and federal permit, http://www.mass.gov/dep/water/wastewater/stormwat.htm Permits Required for: construction sites disturbing $\geq$ one acre, and for many industrial sites under the Multisector General Permit. The Stormwater General permit for Small Municipal Separate Storm Sewer Systems (MS4s) was issued jointly by EPA and the MA DEP in Massachusetts in 2003.
Michigan	Agency: Michigan Department of Environmental Quality (MDEQ), http://www.michigan.gov/deq/0,1607,7-135-3313_3682_3716---,00.html Permits Required for: all construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Small Sewer Systems (MS4).
Minnesota	Agency: Minnesota Pollution Control Agency (MPCA), http://proteus.pca.state.mn.us/water/stormwater/index.html Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Mississippi	Agency: Mississippi Department of Environmental Quality (DEQ), http://www.deq.state.ms.us/MDEQ.nsf/page/NPS_Urban_Stormwater_Construction?OpenDocument Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Missouri	Agency: Missouri Department of Natural Resources (DNR), http://www.dnr.mo.gov/env/wpp/stormwater/index.html Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Montana	Agency: Montana Department of Environmental Quality (MDEQ), http://www.deq.state.mt.us/wqinfo/MPDES/StormWater/ms4.asp Permits Required for: all construction sites disturbing $\geq$ one acre, many industrial sites, and all designated MS4's.
Nebraska	Agency: Nebraska Department of Environmental Quality (DEQ), http://www.deq.state.ne.us/WaterPer.nsf/Pages/NPDES Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Nevada	Agency: Nevada Department of Environmental Protection (DEQ), http://ndep.nv.gov/BWPC/storm01.htm Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
New Hampshire	Agency: New Hampshire Department of Environmental Services, http://des.nh.gov/organization/divisions/water/stormwater/index.htm Permits Required for: construction sites disturbing $\geq$ 50,000 sq ft, certain industrial sites, and designated Municipal Separate Storm Sewer Systems (MS4s).
New Jersey	Agency: New Jersey Department of Environmental Protection (DEP), http://www.state.nj.us/dep/stormwater/ Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all Municipal Separate Storm Sewer Systems (MS4's).

State	Agency and Program Notes
New Mexico	Agency: U.S. EPA Region 6, http://www.nmenv.state.nm.us/swqb/StormWater/index.html Permits required for: construction sites disturbing $\geq$ one acre, certain industrial sites, and designated Municipal Separate Storm Sewer Systems (MS4s).
New York	Agency: New York Department of Environmental Conservation (NYDEC), http://www.dec.ny.gov/chemical/8468.html Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
North Carolina	Agency: North Carolina Department of Environment and Natural Resources (NCDENR), http://www.ncstormwater.org/ Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).
North Dakota	Agency: North Dakota Department of Health & Environmental Division of Water Quality (DHEWQ), http://www.ndhealth.gov/WQ/Storm/StormWaterHome.htm Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).
Ohio	Agency: Ohio Environmental Protection Agency (OEPA), http://www.epa.state.oh.us/dsw/storm/ Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Oklahoma	Agency: Oklahoma Department of Environmental Quality (DEQ), with the exception of Indian land, which is regulated by EPA region 6, http://www.deq.state.ok.us/WQDnew/stormwater/index.html Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Oregon	Agency: Oregon Department of Environmental Quality (ODEQ), http://www.deq.state.or.us/wq/stormwater/stormwater.htm Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Pennsylvania	Agency: Pennsylvania Department of Environmental Protection (DEP), http://www.depweb.state.pa.us/watershedmgmt/cwp/view.asp?a=1437&Q=518682&PM=1 Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Rhode Island	Agency: Rhode Island Department of Environmental Management (RIDEM), http://www.dem.ri.gov/programs/benviron/water/permits/ripdes/stwater/index.htm Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
South Carolina	Agency: South Carolina Department of Health and Environmental Control (SCDHEC). The SCDHEC has delegated authority to South Carolina Office of Ocean and Coastal Resource Management to regulate stormwater discharges in the states eight coastal counties, http://www.scdhec.net/environment/water/swnpdes.htm Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
South Dakota	Agency: South Dakota Department of Environment & Natural Resources (DENR). http://www.state.sd.us/denr/DES/Surfacewater/stormwater.htm Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Tennessee	Agency: Tennessee Department of Environment and Conservation (DEC), http://www.state.tn.us/environment/wpc/stormh2o/ Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Texas	Agency: Texas Commission on Environmental Quality (TXCEQ), http://www.tceq.state.tx.us/nav/permits/sw_permits.html Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Utah	Agency: Utah Department of Environmental Quality (UTDEQ), http://www.waterquality.utah.gov/UPDES/stormwater.htm Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s). Additional permitting requirements may exist where TMDLs are in place.
Vermont	Agency: Vermont Department of Environmental Conservation (VTDEC), http://www.anr.state.vt.us/dec/waterq/stormwater.htm Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Virginia	Agency: Virginia Department of Conservation & Recreation. http://www.dcr.virginia.gov/soil_&_water/stormwat.shtml Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Washington	Agency: Washington State Department Ecology (WADOE), http://www.ecy.wa.gov/programs/wq/stormwater/index.html Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
West Virginia	Agency: West Virginia Department of Environmental Protection (WVDEP), http://www.wvdep.org/item.cfm?ssid=11&ss1id=588 Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Wisconsin	Agency: Stormwater runoff is currently regulated at the state level by three agencies: Department of Natural Resources (DNR); Department of Transportation (DOT); and the Department of Commerce (COMM), http://dnr.wi.gov/runoff/stormwater/publications.htm Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Wyoming	Agency: Wyoming Department of Environmental Quality (DEQ), http://deq.state.wy.us/wqd/WYPDES_Permitting/WYPDES_Storm_Water/stormwater.asp Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

CHAPTER 3.0

CHARACTERIZING STORMWATER RUNOFF FLOW AND ITS IMPACTS

3.1 Introduction

When evaluating whether stormwater quantity controls are required, the first step is to determine the volume and flow rates requiring treatment. This typically is calculated as the difference between pre-development and post-development flow rates and volumes. The method for calculating the values associated with characterizing pre-development and post-development hydrology are not consistent between regulatory agencies. Therefore, the user is cautioned to confirm the appropriate methodology before proceeding with any calculations. Once calculated, these predicted volumes and/or flow rates then are used to size the stormwater control practices. This section summarizes the steps, which are outlined in the flow chart (Figure 3-1), required to determine the volume and maximum/peak flow rates of runoff reduction prior to discharge to receiving waters. The first part of this chapter focuses on the calculation of treatment flow rates and volume for the entire site using several common methods. The checklist, Table 3-1, is provided to document the decision process and the data used to support the decisions.

A review of multiple stormwater management guidance documents indicates that either the method of calculating the runoff from the site that requires control or the depth of runoff requiring control is specified. The reader is referred to the appropriate guidance. When calculation methods are specified, they often are those based on traditional drainage design/flood control methodologies (Section 3.2). They may be applied to the entire site's runoff volume and peak flow rate, with an understanding of their limitations and assuming that no runoff data exists. Once the total volume and peak flow requiring treatment are determined, these volumes and rates need to be allocated to the treatment device(s) based on the post-development drainage patterns. Rarely will a single treatment device be used to treat an entire site's runoff. Instead, low impact developments/conservation designs disperse treatment devices throughout the site and use much of the available pervious area to infiltrate and/or evapotranspire the runoff in excess of pre-development volumes and rates. Design of the treatment devices often requires calculation of a value termed the "water quality volume." Common methods of calculating the water quality volume are given in Section 3.2.3.

3.2 Calculation of Site-Level Pre- and Post-Development Volumes and Flow Rates

The first part of evaluating the need for water quantity treatment is to understand the peak flow and/or runoff volume from the site and compare it to a reference condition where the receiving water was in good health. The general assumption is that pre-development conditions reflect the state of the watershed prior to any development that degraded the receiving water. This may be estimated by assuming prairie, desert or forests conditions, depending on the type of growth that would be expected to reestablish over many years if development was removed

(reversion of the land to historical natural conditions). Other suggestions for selecting reference conditions include selecting a reference watershed (also called a “control” watershed) that is undeveloped and whose geographic, hydrologic and physiographic features resemble the watershed of interest. Chemical, physical and biological measurements in the reference watershed then are used to set pre-development conditions. The selection of a reference condition is still debated in the profession. For example, some states have formally or informally removed agricultural land uses as an allowed pre-development/reference condition because agriculture has been linked to stream degradation due both to runoff quantity and quality.

Many methods are available for predicting the flow rate and volume of runoff from a development area, but the two most commonly-used methods are the Rational Method and the methods based on Technical Releases 20 or 55 (USDA 1982 and 1985). These calculation methods are summarized in Appendix D, including their current extensions and the models that incorporate them. In addition, guidance for selecting the appropriate method based on development size and modeling purpose is given at the end of that appendix. For sizing specific control devices, often a water quality/treatment volume is calculated according to equations provided in the local guidance documents since the methods described in Appendix D are inappropriate for predicting volume at very small scales.

3.2.1 Factors Affecting Runoff Generation

Three primary factors affect the peak rate and volume of runoff: rainfall patterns, surface cover, and soil conditions.

3.2.1.1 Rainfall Frequency and Intensity (and Duration)

Peak rainfall-runoff rates and volumes, as well as water quality volumes, often are calculated based on design storm concepts. Design storms are referred to by their return period, where the return period is equal to the inverse of the probability of exceedence of a storm of a specified depth and duration. For example, if the 24-hour, 50-year design storm for a locality has a depth and duration of 25 mm and 24 hours, respectively, then the probability that a storm that produces more rain over the same time period equals 0.02 or 2%. Calculation of return periods can be found in Appendix D. Most drainage design regulations and discussions refer to return periods.

Drainage design calculations have focused on storms with large return periods, since the goal of drainage design is to prevent regular flooding. However, many water quality problems are associated with the smaller frequent storms. Therefore, water quality volumes, which are typically applied to sizing individual treatment devices used for chemical, biological or microbiological treatment, are associated with storms with a shorter return period (Section 3.3).

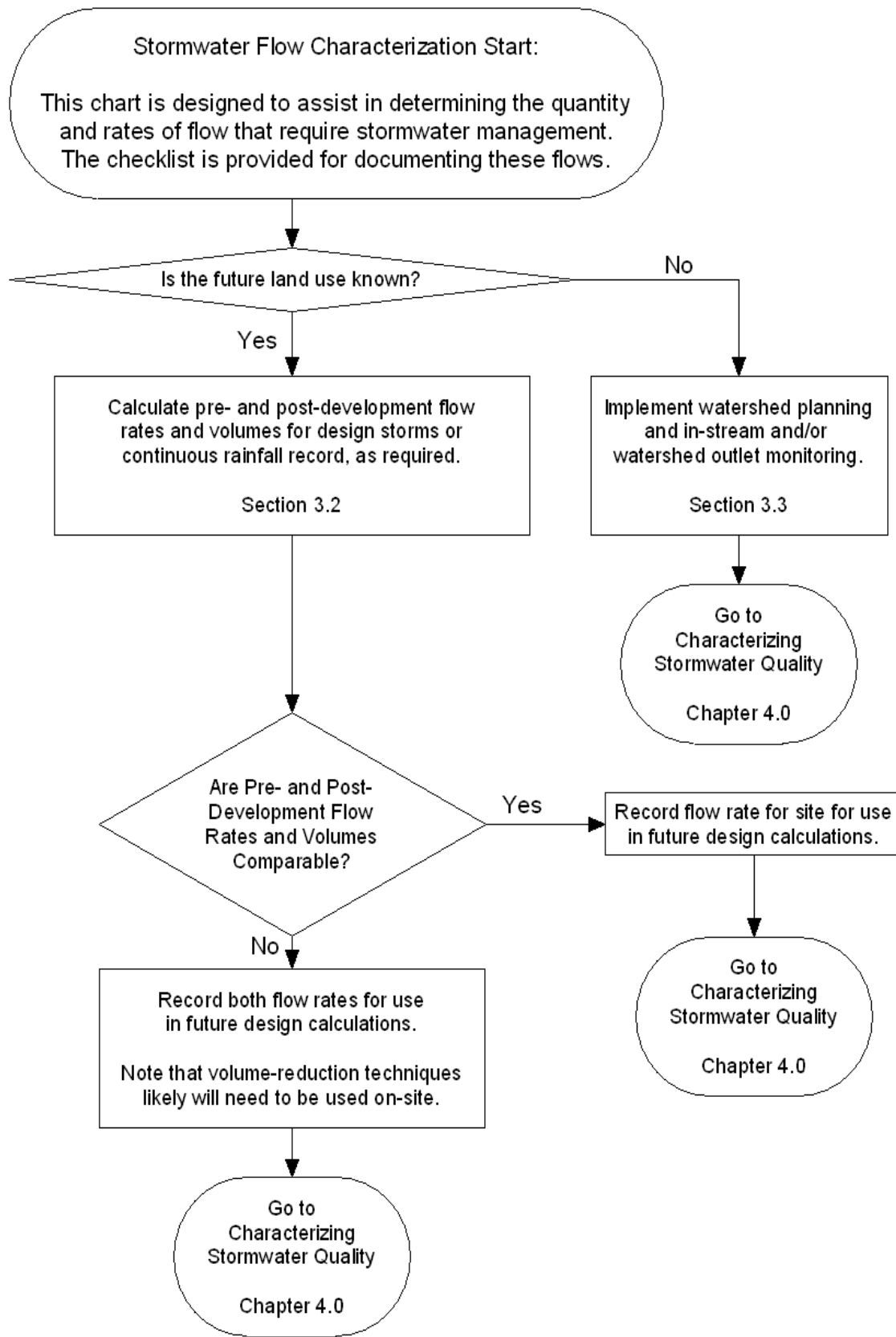


Figure 3-1. Predicting Stormwater Quantity Flow Chart.

Table 3-1. Checklist for Calculating Stormwater Volume, Peak Flow Rate, or Exceedence Storm.

Design Storm	Yes (size, yrs) No	Continuous Simulation	Years of Record:
Method of Calculation for Site Stormwater:			
	Units	Pre-development	Post-development
Peak Flow Rate	cfs cms		
Peak Volume	cf cm		
Method of Calc			
Water Quality Volume	cf cm		

Several of the models that commonly are used to calculate peak flow rate and volume of rainfall and runoff include the rainfall intensity, as described by the storm's return period. One historical source of this information is Technical Paper No. 40 (TP-40), the Rainfall Frequency Atlas of the United States. The maps generated from this statistical analysis of rainfall records include storm durations of five minutes through 10 days and for probabilities of exceedence from 1% to 50%. On-line versions of these maps can be found at http://www.srh.noaa.gov/lub/wx/precip_freq/precip_index.htm. Scanned images of National Oceanic and Atmospheric Administration's (NOAA) Atlas 2 for the Western U.S. are available from the Western Region Climate Center or from NOAA directly. The link to the NOAA Climate Center for the rainfall atlas is the following: <http://lwf.ncdc.noaa.gov/oa/documentlibrary/rainfall.html>.

For a specific locale, this data has been compiled into a series of curves, called Intensity-Duration-Frequency (IDF) curves, that relate the storm duration of interest to the rainfall intensity, using the storm's return period as the designator for each line. In many states, IDF information is available through one of the state agencies, typically the state departments of transportation because of its extensive use in highway drainage design. Updates to the older IDF curves are occurring in many states to incorporate longer rainfall records. In addition, improvements to statistical methods for analyzing the tails of a distribution have led to revised predictions of the intensity of rare events (example calculations for the state of Alabama are provided in Durrans and Brown (2001)).

3.2.1.2 Surface Cover (Land Use Category)

Land cover also impacts the amount and timing of runoff. Land uses may range from natural rangeland or forested through highly-urbanized land, where substantial pavement and roofing blocking the rainfall's access to the underlying soil structure for infiltration. Parameters used to characterize the surface cover include percent perviousness/imperviousness, percent directly connected impervious area, and time of concentration (T_c or t_c). Percent impervious historically has been measured from maps and aerial photographs, with field work required to confirm the fraction of the impervious cover that is directly connected to the drainage system. Current research is focusing on improving the predictions from satellite imagery with thermal mapping. Imperviousness increases the volume and peak flow rate of runoff and typically reduces the time of concentration. Percent imperviousness also has been linked to stream degradation (Chapter 4.0).

By definition, the time of concentration is the time required for runoff to travel from the most hydraulically distant point in the watershed to a point of interest, typically the

drainage/outlet point, within the watershed. The travel time is influenced by the type of surface over which the water travels. The methods for calculating time of concentration are specific to the rainfall-runoff model used. Introductory hydrology textbooks, such as McCuen (2004), Viessman and Lewis (2003), and Bedient et al. (2008), describe many of the methods for calculating time of concentration and provide examples of the calculation.

3.2.1.3 Soil Conditions

The characteristics of the soil affect whether the rainfall becomes runoff. Geologists and soil scientists typically classify soils according to three characteristics: texture, structure and moisture retained. Other characteristics are also important for pollutant movement and will be discussed in the appropriate section on performance of infiltration structures.

Soil Texture Soil texture refers to the proportion of the sand, silt, and clay particles in the soil (Table 3-2) and is a measure of the relative size of the grain particles in the soil. The USDA created a soil textural triangle (Figure 3-3) containing the twelve soil categories based on the percentage of sand, silt and clay in the soil. For stormwater treatment devices that incorporate soil or filter media, texture is crucial because it affects the way air and water move through the soil. Soils with uniform large particles have larger pore spaces, and therefore they typically allow water to move through them more easily. However, the larger pore space reduces the likelihood of a pollutant in the water having a successful removal interaction with the soil. Guidance documents may specify the type of soil, referencing texture, to be used in infiltration devices.

Soil Structure Structure describes how the soil particles are grouped or bound together. A well-structured soil has adequate pore space for water movement and gas exchange. When a soil is disturbed (such as through clearing or compaction), aggregates are often crushed, resulting in decreased pore space and decreased infiltration. One measure of structure is bulk density (Table 3-3), where the higher the bulk density, the higher the compaction.

Table 3-2. Soil Texture Classifications.

Soil Texture Class	Diameter, d (mm)	Characteristics	Infiltration Rate Range (in/hr)
Gravel	$d > 2$		
Sand	$0.02 \leq d \leq 2$	Typical coarse texture. Good permeability. Good drainage.	Coarse Sand: 0.75 – 2 Fine Sand: 0.5 – 1 Very Fine Sand: 0.25 – 0.75
Silt	$0.002 \leq d \leq 0.02$	Intermediate texture between sand and clay.	Silty Loam: 0.25 – 0.4
Clay	$d < 0.002$	Fine texture. Poor permeability. Poor drainage.	Clay: 0.10 – 0.25

Soil Moisture Soil moisture occurs due to water retention in the pore spaces, typically by surface tension or capillary action of water on the individual soil grains. The higher the bulk density, the less pore space is available for water flow. Other characteristics of soil that affect soil moisture and the infiltration ability include permeability, infiltration rate, and retention rate (water-holding capacity). The impacts of these characteristics are discussed in Section 6.3 because of their relationship to requirements of infiltration-facility design.

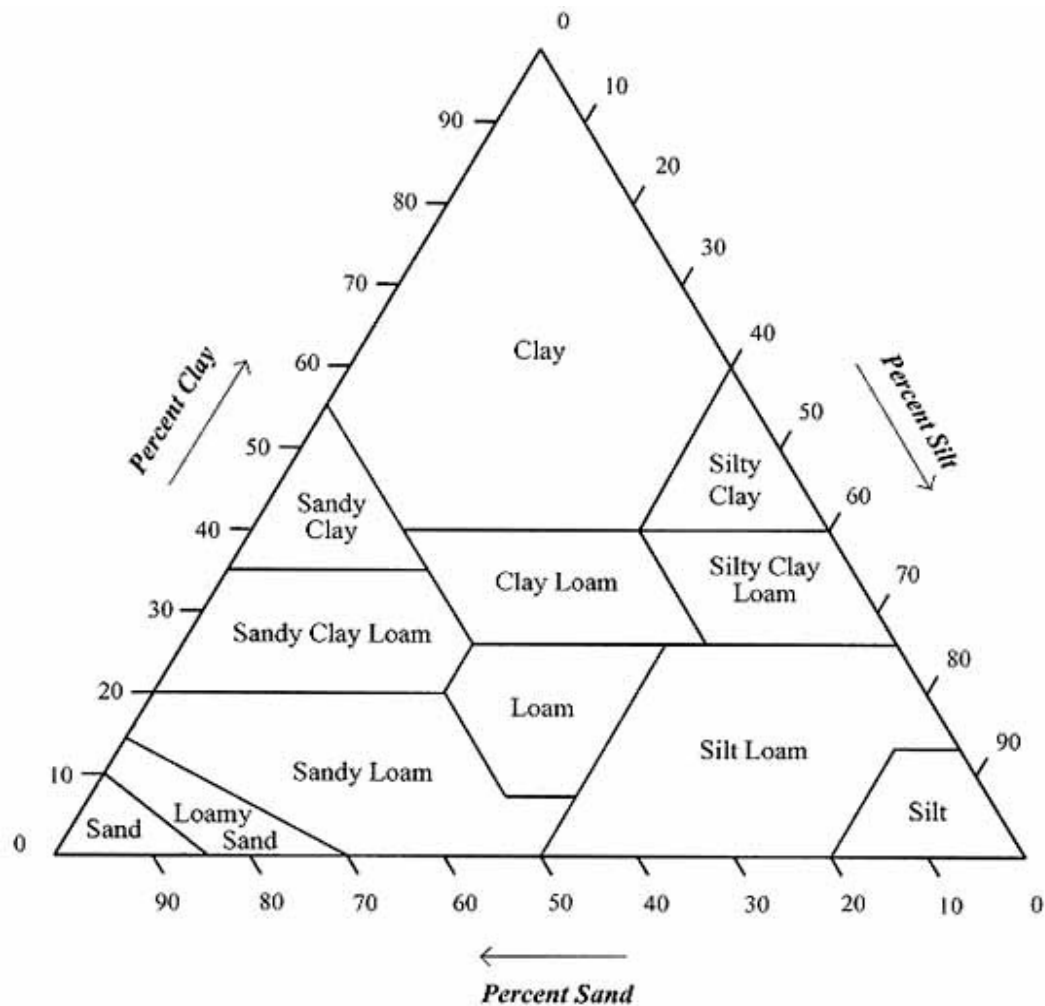


Figure 3-2. Soil Textural Triangle (USDA).

Table 3-3. Comparison of Common Bulk Densities.

Material Type	Bulk Density Measurement (g/cm ³)
Normal soils	1.0 – 1.6
Soils with restricted root growth	1.4 – 1.6
Compacted soils commonly found on construction sites	1.7 – 2.2

Hydrologic Soil Group As part of a series of USDA projects, the former Soil Conservation Service (now the National Resource Conservation Service or NRCS) surveyed, inventoried, and mapped out the predominant soil types and the extent of those types in each state. The purposes of these soil surveys were to provide a description of the soil, and their suitability, limitations and management for specified uses. For stormwater managers, typically the most important information in the soil survey is the hydrologic soil group. According to NRCS, “**hydrologic soil groups** are based on estimates of runoff potential.” This parameter is used in many older design methods to describe the infiltration ability of the soils and ranges from A soils (sandy soils that are well-draining) to D soils (poorly draining).

3.2.2 Calculating Runoff Volume

When field data is not available, runoff can be modeled as a fraction of the rainfall and can range from 0% of the rainfall to 100%. Runoff can be related to rainfall through the following relationship (Equation 3-1):

$$\text{Runoff} = (\text{Proportionality Constant}) (\text{Rainfall}) \quad \text{Equation 3-1}$$

The proportionality constant is based on two primary factors: the surface slope and the soil's infiltration rate. Increased slopes typically result in higher proportionality constants because of the increased rate of runoff travel and less time for infiltration. The infiltration rate is controlled by the soil characteristics. When site-specific information is not available on the infiltration capacity of a soil, tables are provided by the methods to estimate the proportionality coefficient based on land use and/or soil type/characteristics. Two other factors affect the amount of runoff that is generated from a site – depression storage and vegetative interception. In many of the models, these factors are lumped into the infiltration parameter, since it is difficult to estimate their individual values and it is assumed that their contributions are minimal.

More complete descriptions of the runoff calculation methodologies are provided in Appendix E.

3.2.2.1 Volumetric Runoff Coefficient, R_v : Constant Intensity Design Storm

This is the simplest method for calculating runoff. Land use category is used to predict the fraction of the rainfall that will become runoff. This calculation gives the depth of runoff that will be generated for a pre-specified storm size. The volume is then calculated by multiplying the depth of runoff by the area of the watershed. The Nationwide Urban Runoff Program (NURP) study (U.S. EPA, 1983), which measured the rainfall-runoff-pollutant characteristics of a variety of land uses in many metropolitan areas of the U.S. from 1979 through the mid 1980s, found that the use of average volumetric runoff coefficients was an effective method for calculating runoff, but the method was effective only when calculating runoff for larger-storm drainage designs. When the procedure is used to estimate the runoff associated with common small storms (the water-quality storms), the runoff predictions may be highly inaccurate. Bannerman et al. (1983) noted through plotting the observed runoff depths versus their associated rainfall depths that the volumetric runoff coefficient was not consistent across all storm depths, with the exception of the commercial site (heavily-paved site).

3.2.2.2 Rational Method: Constant Intensity Design Storm

Similar to the Volumetric Runoff Coefficient Method, the Rational Method uses a proportionality constant, the Rational C , to relate runoff to rainfall. Unlike the R_v method, the Rational Method uses the rainfall intensity, as the measure of rainfall. The rainfall intensity for the design storm is set by the storm's return period and the watershed's time of concentration. The peak intensity of the storm is used as the representative rainfall parameter, based on the assumption that the calculation will predict a peak flow rate that will ensure that the resultant drainage structure will not flood when the rainfall is equal to or less than the design predictions. Hydrology textbooks such as McCuen (2004), Viessman and Lewis (2003), etc., have tables of rational coefficients.

3.2.2.3 NRCS TR-55 and TR-20 Methods: Unit Hyetograph Storms (SCS 1975, 1982; NRCS 1986)

Urban Hydrology for Small Watersheds, also known as *Technical Release 55 (TR-55)*, was developed by the NRCS for estimating runoff estimation in small urban and urbanizing watersheds. TR-55 procedures have been adopted by many regulatory authorities for drainage design calculations because TR-55 does not use a constant intensity design storm. Instead, it uses a unit hyetograph that assumes that the rainfall is not constant over the entire storm, but instead has at least one period of greater intensity, surrounded by periods of lesser intensity. While these design storms are based on rainfall patterns in the U.S., they have been extended for use in other countries. The TR-55 methods are relatively simple to use and worksheets are provided to guide users through the calculations. TR-55 contains two methods for calculating peak flow – the Graphical Peak Discharge Method and the Tabular Hydrograph Method. Win TR-55 is the computerized version of the method and it is available for download at http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR55.html. The computer version replicates the Tabular Hydrograph Method in terms of data needs and outputs. TR-20 is the full hydrograph method without the limitations of the TR-55 calculations. Discussions of these methods and their limitations are in Appendix D.

3.2.2.4 Continuous Simulation Methods

Continuous simulation methods applied to rainfall and runoff estimation typically involve evaluating long-term rainfall and runoff records to determine the size of storms for which flooding and/or stream degradation is likely to occur. For example, Guo and Urbonas (2002) analyzed 30-40 years of continuous rainfall data from seven U.S. metropolitan areas. From that analysis, frequency distributions of rainfall event-depths were created and shown to follow an exponential decay function. When this function was applied to a rainfall data series, the normalized runoff capture curve was generated and then used to describe the non-exceedence probability of runoff depths. The runoff delivery curve that describes non-exceedence probabilities of certain flow rates also was generated.

Newer models are being developed. Many researchers are investigating linking real-time NEXRAD data to existing stormwater models in order to improve the accuracy of the rainfall forecasting. Others are experimenting with the use of artificial neural networks (ANN) to replace these models. ANN models would then be “programmed” to predict behavior for an individual watershed, based on historical data.

Continuous simulation models primarily have been used to evaluate stormwater control practices post-design and pre-installation. Their results are used to then modify the design as needed. A selection of the most commonly used models and their purpose, as it relates to stormwater management, is discussed in Chapter 9.0.

3.2.3 Water Quality Volumes and Local/Regional Design Equations

The methods listed above are the most common ones used in determining runoff volume from a development site. Other methods exist and may be acceptable in certain states. For example, several states accept the runoff values and hydrographs calculated using the USGS-developed flood regression equations for a state or region of a state. Other states or localities may accept modeling performed using the watershed models developed by the U.S. Army Corps of Engineers (the Hydraulic Engineering Center series of models).

In many localities/states, guidance exists as to how to calculate the water quality volume. Equation 3-2 is the common form of the water quality volume design equation (Knox County, Tennessee Stormwater Management Manual; Vermont Stormwater Management Manual, www.stormwatercenter.net). This equation assumes that controlling the 85th to 90th percentile rainfall event will provide adequate treatment of the pollutants of interest, primarily total suspended solids (TSS). In some localities the volumetric runoff coefficients are tabulated and in others, they are estimated using Equation 3-3. The water quality flow rate can be calculated using the charts and tables in the SCS TR-55 method and Equations 3-4 and 3-5. Equation 3-5 can be used to calculate the equivalent curve number for use with the charts that predict q_u based on the rainfall depth of interest.

$$Q_{wv} = \frac{PR_v A}{12} \quad \text{Equation 3-2}$$

Where: Q_{wv} = water quality volume (ac-ft)

P = 85th or 90th percentile runoff (in)

R_v = volumetric runoff coefficient (calculated using Equation 3-3)

A = area (ac)

$$R_v = 0.015 + 0.0092(I) \quad \text{Equation 3-3}$$

Where: I = percent imperviousness (%)

$$Q_{wq} = q_u A Q_{wv} \quad \text{Equation 3-4}$$

Where: Q_{wq} = water quality peak flow rate (cfs)

A = area (ac)

Q_{wv} = water quality volume (in)

q_u = unit peak discharge (cfs/mi²/in or csm/in)

$$CN = \frac{1000}{\left[10 + 5P + 10Q_{wv} - 10(Q_{wv}^2 + 1.25Q_{wv})\right]^{0.5}} \quad \text{Equation 3-5}$$

Where: CN = curve number

3.2.4 Limitations and Local Requirements for Calculating Runoff

Many guidance documents provide tables to aid stormwater designers in selecting the appropriate techniques for predicting runoff. Table 3-4 is adapted from the Chester County, Pennsylvania Water Resources Authority Post-Construction Stormwater Management Model Ordinance. Tables 3-5 and 3-6 are from the Knox County (Tennessee) Stormwater Management Manual. The entire suite of methods described in these tables is summarized in Appendix D.

Table 3-4. Acceptable Computation Methodologies for Stormwater Management Plans.
(Adapted from the Chester County, PA Model Ordinance, www.chesco.org/water/).

Method	Source	Applicability
TR-20	USDA – NRCS	When use of full model is desirable or necessary
TR-55	USDA – NRCS	Applicable for plans within the model's limitations
HEC – HMS	U.S. Army Corps of Engineers	When full model is desirable or necessary
PSRM	Penn State University	When full model is desirable or necessary
VT/PSUHM	Virginia Polytechnic Institute & Penn State University	When full model is desirable or necessary
Modified Rational Method	Emil Kuiching (1889)	For sites less than 20 acres
SWMM	U.S. EPA	Most applicable in urban areas
Small Storm Hydrology Method (WinSLAMM)	PV & Associates, or the website www.winslamm.com	Calculation of runoff volume from urban and suburban areas
Other Methods	Various	As approved by the municipal engineer

Note: The Small Storm Hydrology Method presented in the SLAMM model can be very useful in calculating runoff volumes from smaller storms (e.g. one inch). Runoff is calculated using volumetric runoff coefficients developed for that model.

Table 3-5. Constraints on Using Recommended Hydrologic Models.

Method	Size Limitations ¹	Comments
Rational	0 – 5 ac	Method can be used for estimating peak flows and the design of small site or subdivision sewer systems. Not to be used for storage design.
USGS Rural	0.36 mi ² to 21,400 mi ²	Method can be used for estimating peak flows for all design applications in rural areas.
USGS Urban	0.21 mi ² to 24.3 mi ²	Method can be used for estimating hydrographs for all design applications in urban areas.
TVA	> 0.36 mi ²	Method can be used for estimating peak flows for all design applications such as culverts, channels, etc.
SCS ^{2,3}	0 – 2000 ac	Method can be used for estimating peak flows and hydrographs for all design applications.
Clark ²	See Comments	Method may not be applicable to very large drainage basins. Large drainage basins may need to be subdivided to overcome limitations of this method.
Water Quality Volume (WQv)	Limits set for each Structural Control	Method used for calculating the WQv.

¹ Size limitation refers to the drainage basin/watershed area for the stormwater management facility (e.g., culvert, inlet).

² There are many readily available programs such as (HEC-1, HEC-HMS) that use this methodology.

³ 2,000-ac upper limit applies to single basin simplified peak flow only.

3.3 Long-Term Monitoring and Evaluation of Impacts

While most sites will need to reduce runoff volume and/or reduce peak flow rates, the potential exists for small-footprint development to not increase the peak volume and flow rate. However, this lack of increase in flow and runoff rate during the design storm or rainfall series does not necessarily indicate that the development will not impact the receiving water. Changes in drainage patterns and in the location of the water entering the stream may affect the waterbody at the point of discharge. Concentrations of flow may cause localized bank instability and other effects, as described in Appendix F. Therefore a long-term monitoring program, measuring the physical stability of the stream should be implemented. Guidance documents exist for determining if streams are stable, for example the Rosgen method which was developed for the western United States and has since been modified for the eastern U.S. Other researchers have used competing methods to assess stream stability and to address the limitations of the Rosgen

method. One federal resource for information on stream stability is the Agricultural Research Service of the U.S. Department of Agriculture (Water Availability and Watershed Management Program: http://www.ars.usda.gov/research/programs/programs.htm?NP_CODE=211). A specific reference for this would be the *NRCS Stream Restoration Design Handbook*, Chapter 11 (NRCS 2005), which describes the Natural Channel Design Method.

Table 3-6. Design Applications for Recommended Hydrologic Methods.

Analysis or Design Application	Rational	USGS Equations	SCS Methods	Clark Unit Hydrograph	Water Quality Volume	TVA Equations
Water Quality Volume (WQv)					X	
Channel Protection Volume (CPv)			X			
Overbank Flood Protection (Qp ₂ , Qp ₁₀ , Qp ₂₅)			X			
Extreme Flood Protection (Qp ₁₀₀)			X			
Storage Facilities			X			
Outlet Structures			X			
Gutter Flow and Inlets	X					
Storm Drain Pipes	X	X	X			X
Culverts	X	X	X			X
Small Ditches	X	X	X			X
Open Channels		X	X			X
Energy Dissipation		X	X			X
Flood Studies			X	X		X

In many stormwater programs, the volume and flow rate required to prevent downstream damage to the physical channel is termed the channel protection volume. The common approaches to calculating the channel protection volume are summarized from documentation provided by www.stormwatercenter.net and are the following:

- ◆ “X”-year control: Post-development peak discharge rates cannot exceed “X”-year pre-development levels. This method, as originally stated, used the 2-year (bankfull) storm as a reference. However, research showed that streambank erosion increased because of the extended release of stormwater from detention ponds at rates that equaled bankfull conditions. Many localities still use this method, but the criteria is to retain on-site smaller storms (such as the 0.5- to 1.5-year storms) for extended release into the receiving water.
- ◆ Two-year overcontrol: The post-development peak rate is controlled to a fraction of the pre-development level, such as 50% of the pre-development level.
- ◆ Extended detention of the 1-year, 24-hour event: The volume from the 1-year, 24-hour storm event is stored and slowly released between 12 and 24 hours. This release time has been extended in some areas because of concerns of thermal pollution in cold water streams.
- ◆ Distributed runoff control (DRC): This method was developed by MacRae (1993). Field assessments and modeling are required to determine hydraulic stresses and erosion potential of bank materials. The goal is to minimize channel erosion of the range of flows. The channel flows should just move the dominant particle size of the bedload. The hydrograph that achieves this result is the one that best mimics the pre-development hydrograph.

3.4 Urbanization Effects on Soils and Resultant Water Transport

Development changes the soil physical, chemical and biological characteristics. Potential impacts of construction and post-development activities include, but are not limited to, the following:

- ◆ Impervious surfaces interrupt the natural exchange of gases, increase soil temperature, and alter drainage patterns.
- ◆ Heavy construction equipment compact the soil.
- ◆ Grading, clearing, excavating, and/or replacing natural soils with fill dirt influence drainage and aeration and cause erosion. If topsoil is removed, the soil's ability to support plant life is reduced, which increases the time needed to re-establish vegetation and infiltration areas.

The two most prevalent impacts of development on soils are the removal of natural topsoil and compaction due to construction. These activities, especially when combined on a site, often reduce substantially the amount of infiltration and increase the amount of runoff. Table 3-7, adapted from the USDA's Urban Forestry Manual (2005), summarizes methods of quickly determining (without infiltration or percolation testing) if the soil is compacted.

Table 3-7. Signs of Compaction.

Sign	Description
Hard soil	Soil is hard to penetrate with a shovel. In previously-agricultural lands, earlier cultivation may have produced a layer of hard soil 10 – 12 inches below the surface.
Standing water	Water standing on top of the soil for a long time may indicate compaction.
Excessive water runoff	This is a sign of low permeability (little movement of water through the soil).
Vegetation loss or poor plant growth	Compacted soil reduces the air circulation and water infiltration into the root zone. A lack of water, nutrients and oxygen causes declining tree health or death. Compaction at depth may be noticed through good grass growth but poor tree establishment.
Bulk density	High soil bulk density indicates compaction. The reduced pore space limits water infiltration, aeration, root growth.
Surface crust	Development of a surface crust sometimes occurs with the compaction of fine-textured soils. This crust limits the infiltration of air and water into the soil, increases runoff and increases erosion. Surface crusts are usually found on soils subject to heavy foot traffic.

Reduction of infiltration capacity has been modeled primarily to be a result of soil saturation during a storm or as a result of small inter-event periods. However, Pitt et al. (1999) documented the impacts of compaction and the interactions of compaction and saturation on infiltration rates in soils. Compaction had significantly affected infiltration rates in sandy soils, while compaction and moisture affected the infiltration rates in clayey soils. Moisture was not a factor controlling infiltration rates in the sandy soils. Similar reductions in soil permeability due to compaction have been reported by Gregory et al. (2006) and Hamilton and Waddington (1999). Additional information on the impacts of compaction can be found in Appendix E. Brown and Hunt (2009) describe the use of the tines of the bucket of a backhoe to scarify the soil surface in infiltration areas during construction as a method of minimizing soil compaction and loss of infiltration capacity. They compared “raking” the soil surface of a planned bioinfiltration facility with the “scoop” method, where the bucket is moved smoothly along the surface, and

found that the infiltration rate after raking the soil surface was significantly greater than the rate after scooping out the dirt during construction.

Recovering infiltration capacity has been proposed by several researchers. This recovery typically only is effective at the near-surface areas. Table 3-8 lists the methods recommended by the USDA. Other methods include amending soils with more permeable materials such as compost and sand.

One of the most often proposed techniques for regaining soil infiltration capacity is the addition of an organic material. Pitt et al. (1999) examined the benefits of adding large amount of compost to a glacial till soil (poor infiltration) at the time of development. Compost-amended soils were found to have significantly increased infiltration rates, but increased concentrations of nutrients in the surface runoff. The compost-amended test plots produced superior turf, with little or no need for establishment or maintenance fertilization. Therefore, the use of soil amendments to improve infiltration capacity, whether in the natural soils of an area or in an infiltration/bioinfiltration area, can increase infiltration, but may reduce water quality.

Table 3-8. Techniques for Solving Soil Compaction Problems for New and Existing Planting Sites.

New Sites	
Techniques for Restoring Soil Infiltration (Reducing Compaction)	Description of Technique
Soil Mixing	Compacted soil can be mixed with a fully composted organic mulch to improve the soil quality, but up to 50% of the soil volume is needed.
Rototilling or grading	The compacted soils may be rototilled, disked or graded to improve near-surface infiltration.
Subsoiling or drilling hardpan	If there is a compacted layer of soil 1 to 2 feet below the surface, subsoiling or deep plowing with a plow or backhoe when soil is dry may break up this layer. Also, holes can be drilled into the hardpan to provide drainage and root penetration.
Top Mulching	Organic content of soils can be increased by adding mulch on top of existing soil. However, the organic material takes many years to breakdown and combine effectively with the native soil.
Existing Sites	
Core aeration	Pore space in compacted soil may be increased by removing small soil cores to a depth of about 3 inches.
Vertical mulching	Holes 1 – 2 inches in diameter may be drilled in the compacted soil and filled with perlite, vermiculite or other amendment material.
Radial trenching	Trenches 6 – 8 inches wide and no deeper than the root system or depth of compaction could be dug with trenching equipment. The trenches are then backfilled with a mixture of soil and amendments.

CHAPTER 4.0

CHARACTERIZING STORMWATER RUNOFF POLLUTION AND ITS IMPACTS

4.1 Introduction

Almost half of the 23% of U.S. rivers and streams that have been evaluated as part of the TMDL program are threatened (1%) or impaired (47%). Twenty-eight thousand miles, of the 822,000 miles assessed, are impacted by urban runoff (U.S. EPA summary of impaired waters, accessed July 2008). Past studies have identified urban runoff as a major contributor to the degradation of many urban streams and rivers (examples of literature include Field and Turkeltaub, 1981; Pitt and Bozeman 1982; the annual Urban Wet-Weather Flows Literature Review published by *Water Environment Research*; Clark et al. 2008, which contains a literature review for the period of 1996 - 2007). A wide variety of pollutants have been found in urban runoff, including organic and metallic toxicants that can contribute to receiving water degradation (U.S. EPA, 1983; Hoffman et al., 1984; Fram et al., 1987; Pitt et al., 1995; and others – see annual literature reviews). Solids, while not a toxicant *per se*, potentially affect the receiving water by blocking light penetration, abrading fish gills, and smothering fish eggs and benthos. Pathogenic microorganisms can affect the health of the aquatic ecosystem, as well as the health of swimmers and other recreational users (New South Wales Department of Primary Industries; U.S. EPA Water Quality Criteria).

The first step is to determine the pollutants requiring treatment and their sources, plus, as needed/required, to evaluate the quality of the receiving water. Source control is the cost-effective solution to treating runoff. The pollutant concentrations may be directly measured in the field or may be estimated from the literature. These concentrations, or loads if multiplied by the anticipated runoff volume (as calculated in Chapter 3.0), may be compared to the stormwater quality standards or TMDLs or other regulatory criteria to determine whether control of a specific pollutant is required. Figure 4-1 is the flow chart describing this evaluation process. Table 4-1 contains the checklist for evaluating the stormwater quality, the in-stream receiving water quality and comparing the results to the standards and guidance for allowed discharges and receiving water health. The checklist is divided into six categories of pollutants and in-stream effects measurements (general water quality, nutrients, metals, organics and pesticides, microbiological quality, and receiving water biotic health).

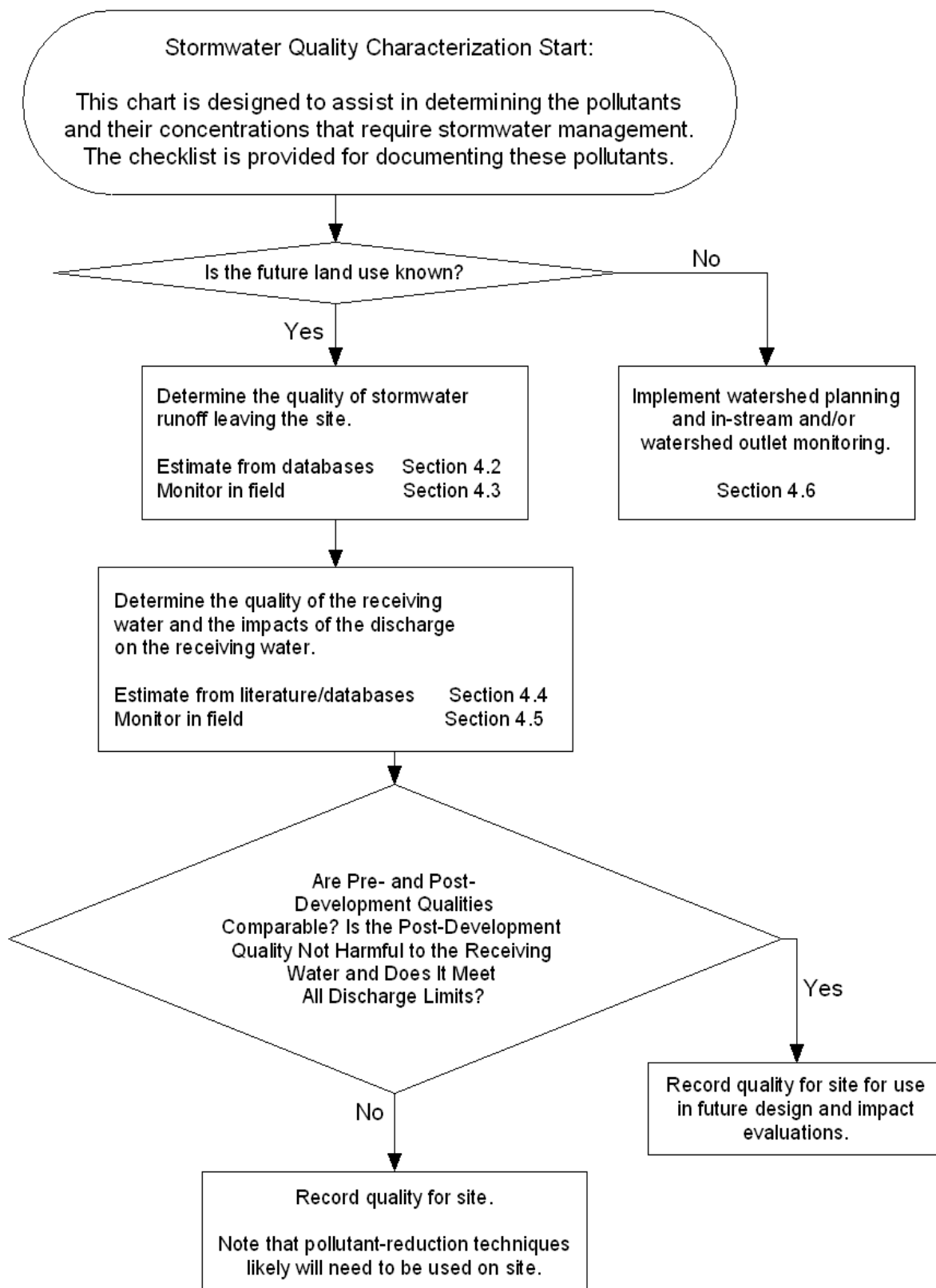


Figure 4-1. Stormwater and Receiving Water Quality Evaluation Flowchart.

Table 4-1. Checklist for Evaluating Stormwater and Receiving Water Quality Compared to Standards.

WATER QUALITY CONSIDERATIONS

Regulatory based discharge limits: Yes No

TMDL imposed on outfall: Yes No

Sources of Data:

Stormwater _____

Stormwater Quality Limits _____

Receiving Water _____

Receiving Water Limits _____

Groundwater Quality _____

Groundwater Limits _____

General Quality Parameters

Parameter	Units* (Circle One)	Receiving Water (Actual)	Receiving Water Limits	Stormwater Quality (Actual)	Stormwater Quality Limits	Groundwater Quality (Actual)	Groundwater Quality Limits**
pH							
Temperature	°C °F						
Specific Conductance	µS/cm						
Suspended Solids (TSS)	mg/L						
Suspended Solids (SSC)	mg/L						
Dissolved Solids	mg/L						
Turbidity	NTU						
Hardness	mg/L as CaCO ₃						
Alkalinity	mg/L as CaCO ₃						
Dissolved Oxygen	mg/L						
Toxicity, Total	LD ₅₀ LC ₅₀						
Toxicity, Dissolved	LD ₅₀ LC ₅₀						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable.

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Nutrients

Parameter	Units* (Circle One)	Receiving Water Quality (Actual)	Receiving Water Quality Limits	Stormwater Quality (Actual)	Stormwater Quality Limits	Groundwater Quality (Actual)	Groundwater Quality Limits**
Ammonia/ Ammonium	mg/L as NH ₄ NH ₃ N						
Nitrate	mg/L as NO ₃ N						
Nitrite + Nitrate	mg/L as NO ₃ N						
Total Kjeldahl Nitrogen	mg/L as N						
Dissolved Nitrogen	mg/L as N						
Total Nitrogen	mg/L as N						
Orthophosphate	mg/L as PO ₄ P						
Dissolved Phosphorus	mg/L as PO ₄ P						
Total Phosphorus	mg/L as PO ₄ P						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Metals

Parameter	Units* (Circle One)	Receiving Water Water (Actual)	Receiving Water Limits	Stormwater Quality Quality (Actual)	Stormwater Quality Limits	Groundwater Quality Quality (Actual)	Groundwater Quality Limits**
Arsenic, Total	µg/L mg/L						
Arsenic, Dissolved	µg/L mg/L						
Cadmium, Total	µg/L mg/L						
Cadmium, Dissolved	µg/L mg/L						
Chromium, Total	µg/L mg/L						
Chromium, Dissolved	µg/L mg/L						
Copper, Total	µg/L mg/L						
Copper, Dissolved	µg/L mg/L						
Iron, Total	µg/L mg/L						
Iron, Dissolved	µg/L mg/L						
Lead, Total	µg/L mg/L						
Lead, Dissolved	µg/L mg/L						
Mercury, Total	µg/L mg/L						
Mercury, Dissolved	µg/L mg/L						
Nickel, Total	µg/L mg/L						
Nickel, Dissolved	µg/L mg/L						
Zinc, Total	µg/L mg/L						
Zinc, Dissolved	µg/L mg/L						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Organics

Parameter	Units* (Circle One)	Receiving Water Quality (Actual)	Receiving Water Quality Limits	Stormwater Quality (Actual)	Stormwater Quality Limits	Groundwater Quality (Actual)	Groundwater Quality Limits**
Total Organic Carbon (TOC)	mg/L						
Oil & Grease	mg/L						
Total Petroleum Hydrocarbons	mg/L						
5-day Biochemical Oxygen Demand (BOD ₅)	mg/L						
7-day Biochemical Oxygen Demand (BOD ₇)	mg/L						
Chemical Oxygen Demand (COD)	mg/L						
1,3-Dichlorobenzene	µg/L						
Benzo(a)anthracene	µg/L						
Bis(2-ethylhexyl) phthalate	µg/L						
Butyl benzyl phthalate	µg/L						
Chlorobenzene	µg/L						
Ethylbenzene	µg/L						
Fluoranthene	µg/L						
Pentachlorophenol	µg/L						
Pyrene	µg/L						
Toluene	µg/L						
Atrazine	µg/L						
Lindane	µg/L						
Chlordane	µg/L						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Microbiological Water Quality

Parameter	Units* (Circle One)	Receiving Water (Actual)	Receiving Water Limits	Stormwater Quality (Actual)	Stormwater Quality Limits	Groundwater Quality (Actual)	Groundwater Quality Limits**
Total Coliforms	CFU/100 mL						
<i>E. coli</i>	CFU/100 mL						
Enterococci	CFU/100 mL						
<i>Clostridium perfringens</i>	CFU/100 mL						
Somatic coliphage	PFU/100 mL						
<i>Giardia lamblia</i>	cysts/100 mL						
<i>Cryptosporidium parvum</i>	cysts/100 mL						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Receiving Water Biology and Habitat

Habitat Evaluation	Percent		
Pool			
Riffle			
Parameter	Units* (Circle One)	Receiving Water (Actual)	Receiving Water Limits
Chlorophyll a	mg/L		
Biotic Integrity Indices			
Index of Biotic Integrity (IBI)	n/a		
EPT Index	n/a		
Primary Production	n/a		
Gross Primary Productivity (GPP) and CR			
Fish Community: Taxa Richness & Diversity			

4.2 Estimation of Stormwater Runoff Quality from Databases or Large Studies

Where available or readily collectible, site data is preferred. If site data is not available, then local or regional data should be obtained. In the United States, this information may be available from the regional authority that controls the area's stormwater discharge permits. Where local or regional data is not available, national databases may be good sources of data for estimating pollutant concentrations from a source area.

For stormwater runoff quality, two potential sources of U.S. stormwater data are the Nationwide Urban Runoff Program (NURP) and the National Stormwater Quality Database (NSQD). The NURP study, funded by the U.S. EPA, was performed in the late 1970s and early 1980s with the results published in 1983. The NSQD, also funded by the U.S. EPA, was performed as an update of the NURP data and contains the NURP data as well as data from other

small- and large-scale studies. These studies analyzed stormwater runoff data from many municipalities for relationships between water quality and readily available parameters such as land use, pollutant source, season, rainfall region, percent impervious area, etc. The sections below summarize these two programs, while Appendix G provides more information about these studies and others on the impacts and concerns associated with urban runoff pollution.

4.2.1 Nationwide Urban Runoff Program (U.S. EPA 1983)

The NURP was designed to supplement stormwater quality data collection activities in several locations around the U.S. in the late 1970s and early 1980s. The data from these locations was analyzed primarily for relationships to season and land use. The linkage between land use and quality was found for several parameters and led to many other researchers attempting to establish similar relationships in other geographic regions of the world and in cities not involved in the NURP study. Two parameters, TSS and total phosphorus, where land-use linkages were seen are shown in Figure 4-2. The NURP results also highlighted the tremendous variability in the data set, indicating that specific pollutant concentrations cannot be estimated simply by knowing the land use.

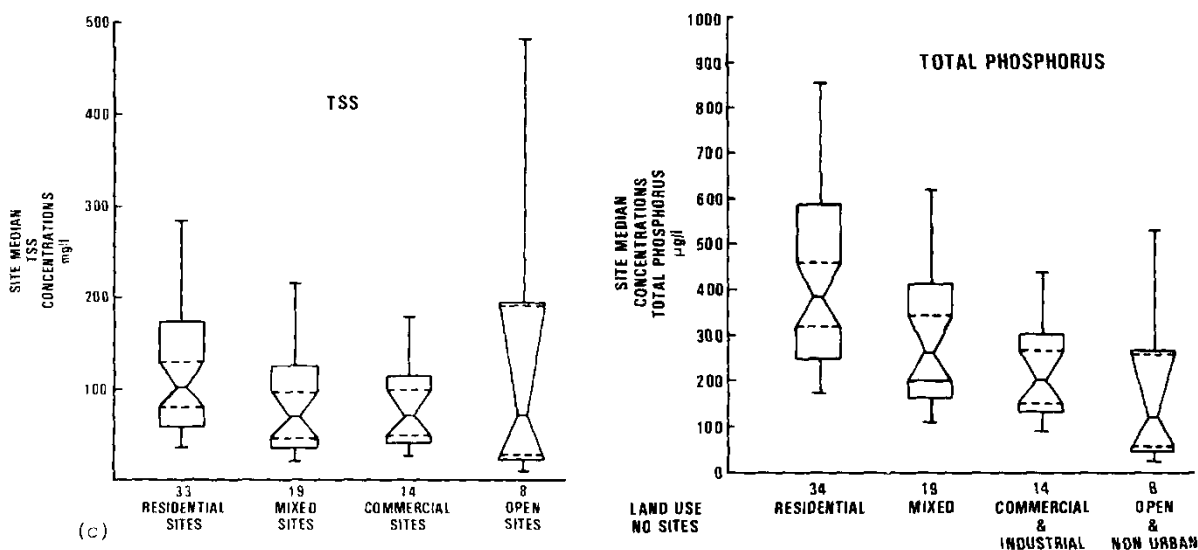


Figure 4-2. Comparison of Pollutant Concentrations by Land Use (U.S. EPA, 1983).

4.2.2 National Stormwater Quality Database (Pitt et al., 2008)

The latest version, Version 3.0, of the National Stormwater Quality Database (NSQD), (<http://rpitt.eng.ua.edu/Research/ms4/mainms4.shtml>), compiles data collected from various stormwater sampling efforts including the NURP program (U.S. EPA, 1983), the International BMP Database (ASCE, 2002), the U.S. Geological Survey Urban-Stormwater Database (Smullen and Cave, 2002; Driver, et al. 1985), and from Phase 1 NPDES (National Pollutant Elimination System) MS4 (municipal separate storm sewer system) stormwater permit holders. Most of the data are from MS4 communities and monitored during the current permit cycle. The earlier NURP data was used to supplement the MS4 data from the upper Midwest and northeastern areas of the country. The other databases provided data for under-represented situations in the MS4 analysis. The NSQD contains data from more than 8,500 events. The data

has been sorted and analyzed for relationships between the pollutant concentrations and the factors that are presumed to affect the concentration, including land use, season, geographical location, drainage system type, and antecedent dry days. Temporal trends also were analyzed, with the primary trend being the reduction in lead concentration between the NURP and MS4 data sets, due to the phase-out of leaded gasoline. The general conclusions from this data evaluation included the following:

- ◆ Substantial fractions of the pollutants at the outfall were particulate-associated.
- ◆ Comparing NURP and NSQD, most pollutant concentrations were similar, with the exception primarily of lead.
- ◆ The NSQD confirmed the effects of land use and source areas (parking areas, vehicle service stations, rooftops, streets, landscaped areas, etc.) on stormwater runoff quality.
- ◆ Critical source areas of urban runoff pollution, and where treatment should be installed prior to the runoff mixing with water from cleaner areas, include large paved areas, heavy vehicular traffic or areas with many vehicular starts, and the outdoor use and/or storage of problem pollutants. These critical source areas likely needing special stormwater treatment are industrial manufacturing facilities, vehicle service stations, vehicle maintenance facilities, scrap yards, highways and some other commercial developments.

4.3 Monitoring Stormwater Runoff Quality

If a municipality falls within the guidance of an MS4 program, they are required to monitor outfall water quality both during storm events and during dry-weather events. Dry-weather quality monitoring is performed to search for illicit connections to the storm drainage system.

Guidance on establishing a stormwater runoff quality monitoring program has been developed by many agencies and researchers. This section is not designed to repeat that guidance but instead to provide references to it. For specific MS4 monitoring to meet the needs of the NPDES permit, the user is advised to consult the individual permit for information on numbers of storms and on the parameters requiring measurement. For general stormwater monitoring, Burton and Pitt (2002) and FHWA (2001 and 2003) provide guidance on establishing stormwater monitoring at specific sites to measure for specific pollutants. A variety of USGS-funded research projects have developed guidance on stormwater sampling and have raised and tried to answer issues related to sample preparation and analysis for solids. In addition, researchers such as Roseen (University of New Hampshire), Clark (Penn State University – Harrisburg), Pitt (University of Alabama), Stenstrom (University of California Los Angeles), and Sansalone (University of Florida), have been investigating the issues and errors associated with the current methods of sample collection, processing and analysis.

Prior to any monitoring activity, the program must address the following questions:

- ◆ What chemical and microbiological parameters are of interest? Are there previously-established relationships in the literature between certain parameters that will allow for monitoring of only a few selected parameters and predicting the concentrations of others?
- ◆ What is the inherent variability in the measurement of these parameters at a single site (including storm-to-storm, season-to-season, first-flush, etc., variability)?

- ◆ How many samples are needed to establish the pollutant concentration with an acceptable variability?
- ◆ What methods are appropriate to sample for these parameters? Can these parameters be measured through composite sampling or is grab sampling required?
- ◆ If this is source area monitoring, where and how should the monitoring equipment be set up to ensure that the water collected for analysis represents the source area of interest?
- ◆ What are the limitations of the analytical methods for each parameter?

Appendix H provides additional details on stormwater and receiving water monitoring programs, including references on how to calculate numbers of samples and limitations of the methodologies for analysis. Comparisons of historical data or historical to current data cannot be performed adequately without a basic understanding of the limitations of the data.

4.4 Predicting Receiving Water Health from the Literature, Databases and Models

Many researchers (Appendix F) have investigated the impacts of urbanization on stream health and biodiversity. Their results show that urbanization, especially as practiced before stormwater control practices became common, has resulted in substantial stream degradation and loss of habitat. As noted earlier in this chapter, urban runoff has been linked to a substantial fraction of stream miles not being supportive of their beneficial uses. Modeling to predict stream health has fallen into two broad categories: use of land characteristics to predict stream effects (e.g., the Impervious Cover Model) and the prediction of flow and water chemistry in a receiving water with comparison to known standards for biotic integrity and biodiversity.

4.4.1 Impervious Cover Model (ICM)

The impervious cover model states that stream health generally can be predicted as a function of the amount of impervious cover in its watershed (Figure 4-3). Sensitive subwatersheds typically have less than 10% impervious surface cover (ISC). Streams in these watersheds have experienced few impacts and are close or at predevelopment levels. The goal would be to have the streams remain in this condition where pollution-sensitive species should thrive. Degrading/impacted streams have between 11 and 25% ISC. Once the stream is in the degrading condition, typically some sensitive species have disappeared, riparian zones have decreased, and stream channels and composition have been slightly altered. Nonsupporting subwatersheds have more than 26% ISC. Streams in these watersheds are severely impaired and may never recover. Reducing peak flows, plus removal and prevention of urban pollutants, are the suggested objectives to abate these degraded conditions (U.S. EPA, 2002). Greater than 60% ISC in the watershed results in streams that are simply urban drainage channels with limited life. These thresholds between stream-health types are not concrete, but may vary based on the drainage system and patterns, plus the use of stormwater control practices may shift the ranges of stream health types.

Other researchers have proposed models to replace the ICM. One simple replacement has been to relate stream health to the amount of directly connected impervious area (DCIA). The rationale is that the runoff of most concern from both a flow and pollution standpoint comes from surfaces that are directly connected to the outfall through impervious flow paths such as gutters and drainage pipes. Runoff that flows over pervious surfaces before reaching the outfall,

especially vegetated surfaces (versus bare soil which might erode), is more likely to be cleaner and have slower flows.

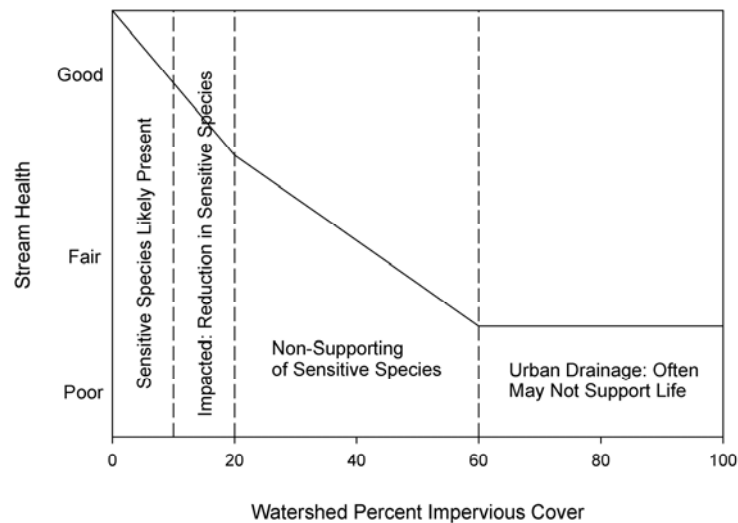


Figure 4-3. Impervious Cover Model (U.S. EPA, 2002).

4.4.2 Receiving Water Models

As noted in WEF Manual of Practice 23/ASCE MOP 87 (Urban Runoff Quality Management, 1998 and currently being updated for publication in 2009), modeling is “such a dynamic process that reviews and surveys are rapidly outdated.” Therefore, this section, in order to remain useful, will provide linkages to the three primary sources of receiving water models in the U.S.

- ◆ The U.S. EPA Center for Exposure Assessment and Modeling.
<http://www.epa.gov/ceampubl/>
- ◆ The U.S. Army Corps of Engineers Hydrologic Engineering Center.
<http://www.hec.usace.army.mil/>
- ◆ The U.S. Geological Survey. http://water.usgs.gov/software/lists/surface_water/

The U.S. EPA model that is being advertised for its use in watershed management and whose use has been documented in the literature, including for modeling the impacts of watershed development and stormwater runoff pollution on receiving waters, is the model BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) (<http://www.epa.gov/waterscience/basins/basinsv3.htm>). The goal of BASINS is to take point and nonpoint source data in a GIS format (so that spatial effects can be analyzed) and predict the pollutant fate and effects in receiving waters through its incorporation of receiving water fate and transport (HSPF) and aquatic organism uptake models (AQUATOX).

4.5 Monitoring Watershed and Receiving Water Health

Watershed assessments should focus on two specific endpoints: the current state and what the watershed’s present “natural” state (reference state) would be in the absence of substantial urbanization (i.e., before polluted discharges and/or other anthropogenic stressors). In many

cases, this assessment requires that a number of chemical, biological and physical habitat parameters be monitored. Many of the chemical monitoring parameters would be selected based on the likely pollutants in the watershed, while the biological parameters would be selected based on the anticipated keystone or indicator species for the watershed in its “natural” state. As noted in Chapter.0 3 for water volume and flow rate calculations, these could be estimated based on assumptions of pre-development conditions (focusing on natural land cover) or a reference reach or watershed in a similar meteorologic, geographic and physiographic area could be selected for monitoring.

The following discussion is based on Burton and Pitt (2002) and the Center for Watershed Protection’s Unified Stream Assessment (Kitchell and Schueler, 2005). Phased receiving-water investigations are highly recommended, if possible. It is much more cost-effective to begin with a relatively simple and inexpensive monitoring program to document problems than it is to conduct a large and comprehensive monitoring program with little prior knowledge. Without having information on the potential existing problems, the initial list of parameters to be monitored has to be based on the investigator’s best judgment. The parameters to be monitored can be grouped into general categories depending on expected beneficial use impairments, as follows:

- ◆ Flooding and drainage:
 - ◆ Debris
 - ◆ Other Obstructions affecting flow conveyance
- ◆ Biological integrity
 - ◆ Habitat destruction
 - ◆ Presence/absence of large woody debris for habitat
 - ◆ High/low flows
 - ◆ Inappropriate discharges
 - ◆ Polluted sediment (sediment oxygen demand [SOD] and toxicants)
 - ◆ Aquatic plant, benthic macroinvertebrate and fish species impairment (toxicity and bioaccumulation of contaminants)
 - ◆ Wet-weather quality (toxicants, nutrients, DO).
- ◆ Non-contact recreation
 - ◆ Odors
 - ◆ Trash
 - ◆ High/low flows
 - ◆ Aesthetics
 - ◆ Public access.
- ◆ Swimming and other contact recreation
 - ◆ Pathogens

- ◆ Above listed non-contact parameters
- ◆ Water supply
 - ◆ Water quality standards (especially pathogens and toxicants)
- ◆ Shellfish harvesting and other consumptive fishing
 - ◆ Pathogens
 - ◆ Toxicants
 - ◆ Those listed under biological integrity

For a full characterization of the potential sources of pollution, point source discharges, stormwater runoff, snowmelt, base flows in receiving waters, sediments, and biological specimens may all need to be sampled and analyzed. The following paragraphs briefly describe a long list of analytes that could be monitored in urban receiving waters. It is expected that the list could be significantly reduced in most cases through screening analyses and better selections based on site-specific conditions.

4.5.1 Selection of Biological Endpoints for Monitoring.

The optimal assessment parameters depend on the project objectives, and can be defined as measured characteristics, responses, or endpoints. Characteristics typically are those items that define the current conditions and may define the desired conditions. Examples of characteristics are stream depth, stream morphology, water temperature, dissolved oxygen concentration, and length of pools and riffles. Responses are those system behaviors that occur when one of the characteristics are changed. In many cases, particular responses can be predicted rather easily. Endpoints are typically the outcomes, either preferred or not, that result from changes in the characteristics and the resulting responses. Endpoints vary dramatically in their sensitivity to pollutants and ecological relevance. The endpoints which are more sensitive are often more variable or respond to natural “nonpollutant” factors, so that adverse effects (stressors) are more difficult to classify with certainty.

Aquatic ecosystems are very complex and consist of a wide variety of organisms, each of which has their own unique function in the ecosystem. Each group contains a number of species with varying tolerance to stressors, and each have specific functionality in the ecosystem (e.g., organic matter processing, nitrogen cycling). The most commonly used biological groups in aquatic assessments are fish, benthic macroinvertebrates, zooplankton and algae. In lotic (flowing water) systems, fish and benthic macroinvertebrates (organisms retained in sieves larger than 0.3 to 0.5 mm) are often chosen as monitoring tools. The macroinvertebrates include a wide range of invertebrates: worms, insect larvae, snails, and bivalves. They are excellent indicators of water quality because they are relatively stationary, i.e., they do not move between different parts of a stream or lake, compared to fish. In addition, they have been well-studied in the past and so much is known about their life histories and pollution sensitivity. Algae, zooplankton, and fish are used more in lentic (lake) environments. Of these, fish are most often used (and have been used in lotic systems also). The drawback to using fish is that they are transient, moving between sites; therefore determining the location of their exposure is more difficult. However, they are excellent indicators of overall water quality and provide a direct link to human health and

wildlife consumption advisories since they bioaccumulate, and potentially biomagnify, many chemicals. Rooted macrophytes and terrestrial plant species are good wetland health indicators because many of them also may uptake pollutants in the sediments, but they are used less frequently for assessing receiving water health.

In order to effectively and accurately evaluate ecosystem integrity, biosurveys should use two to three types of organisms which have different roles (functions) in the ecosystem, such as decomposers, producers, and primary to tertiary consumers. This increases the power of the assessment (greater certainty that if there is a type of organism(s) [species, population, or community] being adversely affected, either directly or indirectly, it will be detected). It also allows for better predictions of effects, such as food web bioaccumulation. Substantial databases exist for these indicator species concerning their life history, distribution, abundance in specific habitats/ecoregions, ecological function and pollutant (stressor) sensitivity.

For monitoring fish and benthic macroinvertebrates communities, many approaches have been used, with the most common and most recommended being a “multi-metric” approach. The multi-metric approach collects basic data on which organisms are present at the site (and their relative numbers) and analyzes the data using a number of different metrics, such as richness (number of species present), abundance (number of individuals present), and pollution sensitivity/tolerance. Structural metrics describe the community’s composition and associate the composition with tolerance rankings (e.g., is the community overall more pollution tolerant or pollution sensitive?). Functional metrics may measure photosynthesis, respiration, enzymatic activity, nutrient cycling or proportions of feeding groups, such as omnivores, herbivores, insectivores, shredders, collectors, and grazers. The various metrics provide unique and sometimes overlapping information on the quality of the aquatic community.

Toxicity testing has been used successfully to determine if the water quality is acceptable to representative aquatic organisms. The Microtox™ toxicity screening test has been used in numerous studies to indicate the sources and variability of toxicant discharges. However, these tests have not been standardized by the U.S. EPA or state environmental agencies. More typically, whole effluent toxicity (WET) test methods are employed (see review by Burton et al., 2000). The drawback to WET testing is that WET tests may miss toxicant pulses and their in-lab simulated conditions do not reflect real-world exposure dynamics. *In-situ* toxicity tests, in conjunction with biological surveys (at least habitat and benthic macroinvertebrates evaluations) and sediment chemical analyses, can provide more useful information to document actual receiving water toxicity problems than relying on chemical analyses alone. If a waterbody tests “toxic,” a toxicity identification evaluation (TIE) study then can be conducted to attempt to isolate the specific problematic compounds (or groups of compounds) before long lists of toxicants is analyzed.

4.5.2 Selection of Chemical Endpoints for Monitoring

The beneficial use of a waterbody will dictate the chemical analyses required. In many cases, the initial monitoring program will be fairly extensive and will include sediment generation and deposition, nutrients, oxygen demand, pathogens or indicators, and toxic chemicals (with the list dependent on the anticipated sources and chemicals in the watershed – such as from the Toxic Release Inventory [TRI] or from NPDES discharge monitoring reports from the permitted outfalls in the watershed). Walking the stream and analyzing the outfalls may lead to the conclusion that many outfalls are not causing the problem(s), thus reducing the

number of parameters and number of locations requiring testing. It has been recommended that periodically conducting more detailed analysis (increased number of outfalls and parameters) should be used as a screening tool to observe less obvious, but persistent problems. Sediment chemical analyses also should be included. In many cases, they are more likely to indicate problems (because they supply food for the benthos – the organisms low in the food chain), since their characteristics often do not change over the time frame used in many water quality studies. Changes over many years are often found through core sampling of stream beds. In addition, the geochemical composition of the upper layer of sediment can be used to determine the source of the sediment, such as whether the sediment resulted from land or stream bank erosion and whether the sediment was localized or had been transported large distances.

Table 4-2 provides a list of potential analytes that should be considered based on the type of evaluation being performed (based on Burton and Pitt, 2002 and references in Appendix F).

Table 4-2. Parameters of Concern when Evaluating Different Receiving Water Uses.

	Drainage	Biological life and integrity	Non-contact recreation	Swimming and other contact recreation	Water supply	Shellfish harvesting and other consumptive fishing uses
Debris and obstructions (channel conveyance capacity)	X					
Habitat destruction (channel stability, sediment scour and deposition)		X				X
High/low flows (rates and durations)		X	X	X		X
Aesthetics, odors and trash			X	X	X	
Safety (bank condition, garbage)			X	X		
Public access			X	X		
Inappropriate discharges		X	X	X	X	X
Large woody debris to provide habitat and nutrients		X				X
Benthic macroinvertebrates species present		X	X			X
Fish species present		X				X
Polluted sediment (SOD, toxicants ¹)		X				X
Toxicity and bioaccumulation of toxicants ¹		X				X
Health-related water quality standards (especially microorganisms ² and toxicants ¹)				X	X	X
Wet-weather quality (toxicants ¹ , nutrients ³ , DO, temperature, alkalinity, and hardness)		X			X	X

Primary constituents are underlined and should be analyzed for most, if not all, samples. Others can be analyzed less often as screening tests. In all cases, the common constituents should also be analyzed for all samples.

¹Toxicants (organic toxicants [pesticides, herbicides, and PAHs]; metallic toxicants [zinc, copper, lead, cadmium, arsenic, and mercury]); toxicity tests [Microtox screening test, plus other *in-situ* and laboratory toxicity tests].

²Microorganisms (indicator bacteria and selected pathogens such as: fecal coliforms, E. coli, enterococci, Clostridium perfringens, Pseudomonas aeruginosa, bacteriophages)

³Nutrients (ammonia, TKN, nitrates, TP, phosphates)

Common constituents added to all water quality investigations (pH, conductivity, turbidity, suspended solids, COD)

CHAPTER 5.0

SELECTING APPROPRIATE STORMWATER CONTROL PRACTICES

5.1 Introduction

The data collected in the checklists in Chapters 2.0 through 4.0 should allow the user to perform a simple comparison between the quantity and quality of stormwater runoff and the receiving water post-development compared to pre-development. If the post-development quality and/or quantity are higher, then typically stormwater runoff treatment is necessary.

This chapter is designed to aid in the selection of stormwater control practices based on the goals of reducing the impact of stormwater runoff through quantity reduction and quality improvement. In addition to the reduction in receiving water impacts described in Chapter 4.0, controlling stormwater on-site can have other benefits, including groundwater recharge, opportunities for rainwater harvesting for on-site use, etc. This chapter, and the following ones, assume that the development or re-development will occur and focuses on the selection phase of the process. Weinstein et al. (2007) outline a higher-level, five-step framework for selecting decentralized stormwater controls for urban retrofit. Their five steps (understanding the drivers for stormwater control, characterizing the site, evaluating suitability, analyzing cost-effectiveness, and selecting controls) can be used to determine whether a decentralized control system should be built. This document assumes that the no-build option will not be selected, and, therefore, it focuses on selecting appropriate control practices for the site for water quality and quantity treatment for small storms, but also understands that a drainage system (swales, pipes, ponds) for larger storms likely will be required.

The selection of the appropriate control practice(s) depends on four separate, but integral and synergistic, points:

- ◆ Regulatory requirements – Chapter 2.0
- ◆ Local site hydrology (amount of runoff to be treated, frequency of runoff of a specific size and duration) – Chapter 3.0
- ◆ Expected pollutant loading from the drainage area – Chapter 4.0
- ◆ Local conditions (surface treatment vs. infiltration vs. a treatment train of surface treatment followed by infiltration, availability of appropriate locations for each selected practice, development practices that include or exclude a specific BMP, drainage requirements for large storms) – Chapters 5.0 through 8.0

For example, the State of Maryland states in the opening paragraph of their stormwater management manual (http://www.mde.state.md.us/Programs/WaterPrograms/SedimentandStormwater/stormwater_design/index.asp),

...Maryland states that “...the management of stormwater runoff is necessary to reduce stream channel erosion, pollution, siltation and sedimentation, and local flooding, all of

which have adverse impacts on the water and land resources of Maryland.” ...The counties and municipalities ... are responsible for administering effective stormwater management programs that “...maintain after development, as nearly as possible the predevelopment characteristics...”

Maryland outlines fourteen design standards (eight are summarized below) for developments disturbing more than 5,000 square feet of earth. These are listed as a reference because they are common goals of a modern stormwater management program and serve as guidance of the tenets that should be followed when developing such a program.

Standard No. 1. Site designs shall minimize the generation of stormwater and maximize pervious areas for stormwater treatment.

Standard No. 2. Stormwater runoff generated from development and discharged directly into a jurisdictional wetland or waters of the State shall be adequately treated.

Standard No. 3. Annual groundwater recharge rates shall be maintained by promoting infiltration through the use of structural and non-structural methods. At a minimum, the annual recharge from post development site conditions shall mimic the annual recharge from pre development site conditions.

Standard No. 5. Structural BMPs used for new development shall be designed to remove ... (the appropriate pollutants). It is presumed that a BMP complies with this performance standard if it is:

- ◆ *sized to capture the prescribed water quality volume (WQ_v),*
- ◆ *designed according to the specific performance criteria outlined in this manual,*
- ◆ *constructed properly, and*
- ◆ *maintained regularly.*

Standard No. 8. Stormwater discharges to critical areas with sensitive resources may be subject to additional performance criteria or may need to utilize or restrict certain BMPs.

Standard No. 9. All BMPs shall have an enforceable operation and maintenance agreement to ensure the system functions as designed.

Standard No. 11. Redevelopment is governed by special stormwater sizing criteria depending on the amount of increase or decrease in impervious area created by the redevelopment.

Standard No. 13. Stormwater discharges from land uses or activities with higher potential for pollutant loadings may require the use of specific structural BMPs and pollution prevention practices. In addition, stormwater from a hotspot land use may not be infiltrated without proper pretreatment.

5.2 Selecting Treatment Devices Based on Program Goals

As another form of guidance, the Commonwealth of Pennsylvania describes their accepted practices/BMPs, depending on the purpose of the installation (groundwater recharge, water quality, and/or rate and volume control). Table 5-1 is based on those descriptions. Developers then may select from the suite of appropriate BMPs based on site conditions. As can be seen in the tables, infiltration is the only option if the goal is groundwater recharge. Surface treatments with no recharge are applicable only if recharge is not a goal. While this list was created for Pennsylvania, the thought processes of treatment selection as they relate to the goals of the stormwater program are applicable to other locations.

Table 5-1. Appropriate Control Practices/BMPs Based on Management.

Control Practice/Treatment Device	Groundwater Recharge	Water Quality	Rate and Volume Control
Wet Pond (Extended Detention Pond)		X	X
Dry Pond			X
Stormwater Wetlands		X	X
Bioretention	X	X	X
Permeable Paving	X	X	X
Stormwater Infiltration	X	X	X
Grass Swale	X	X	X
Filter Strip	X	X	
Water Quality Structures		X	
Sand Filter		X	
Riparian Corridor Management		X	X
Rooftop Runoff Management		X	X

The treatment devices also may be separated into two categories, surface treatment and infiltration, based on whether infiltration is part of the treatment process. This document uses this separation to describe the theory and issues affecting the design of these two device categories.

5.3 Selecting Appropriate Stormwater Management Practices – Process Steps

A review of NURP-collected rainfall-runoff data for several cities around the country indicate that cumulative distributions take the shape seen in Figure 5-1. As the figure highlights, the runoff quantity distribution can be broken into four distinct categories: small storms (in this case, < 10-12 mm), medium-sized storms (10-30 mm), drainage design (large) storms (30-75 mm), and flooding events (> 75 mm). The research in NURP, and by other researchers since then, has shown that the small storms, which may be up to 40-60% of the annual number of storms, are the ones that typically result in water quality violations, especially for bacteria. If these storms are removed from the drainage system through infiltration, then runoff from the small storms is never transported directly to the receiving water and water quality violations may be minimized. The upper end of this small-size storm range is the storm depth that many regulatory agencies are now designating as the water quality event and which is used in their manuals to calculate treatment volume for the control practices.

Pitt and Clark (2008) describe the use of figures such as Figure 5-1, in conjunction with the type of development, to illustrate how storm size can guide stormwater management. For example, in most locations, storms smaller than 10 mm constitute almost half of the rain events, but contribute less than 20% of the runoff mass. These frequent storms, at most sites, could be treated by infiltration or evaporative techniques and removed from the traditional drainage

systems. This also will reduce the effective impervious cover in the watershed for small storms, since these areas only contribute direct runoff to the receiving water to the drainage system during larger storms. The next larger sized storms contain most of the pollutant mass. A portion of those storms, typically the first flush, will be treated by infiltration or evaporation/transpiration, with the remaining water potentially needing further treatment through a surface device. Drainage design storms and flooding events require control in the larger drainage systems (pipes, swales, ponds, etc.) because of the threat to human safety. Implementation of distributed water quality/runoff control practices in a watershed does not negate the need to understand the flow path of runoff during large storms and may not remove conventional drainage systems from a development area. These drainage systems, however, may be smaller (at less cost), may allow for increased spacing between inlets, and/or may be surface systems such as swales that perform water quality treatment at low flows and function for drainage only during larger storms.

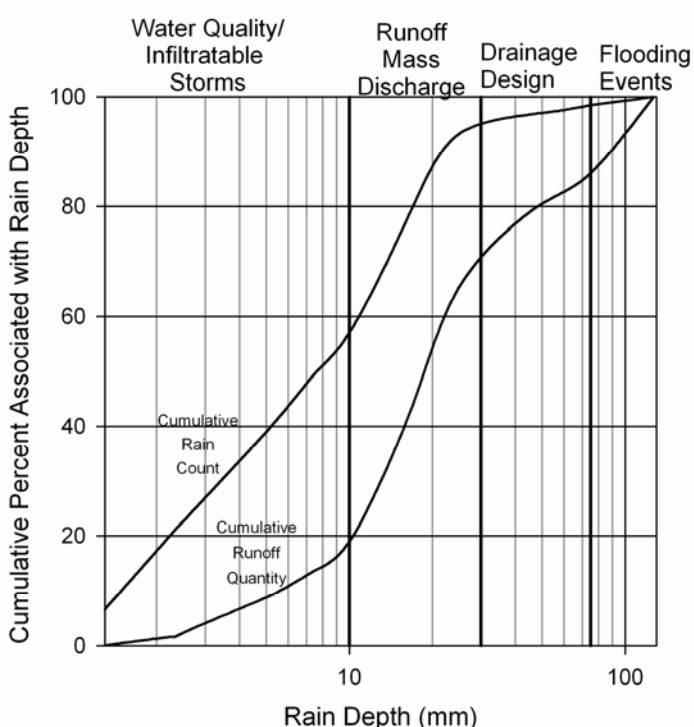


Figure 5-1. Separation of Cumulative Rainfall and Runoff Distributions into Treatment Objectives. The darker vertical lines highlight the separation of the cumulative rainfall and runoff functions into design objectives/requirements.

The Federal Highway Administration (FHWA), in Chapter 6 of *Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring*, also propose a process for selecting stormwater control practices (Figure 5-2). The FHWA process divides the selection into three phases: scoping, evaluation, and final selection. They list the analyses required to perform each phase and then the equations that should be answered in each phase.

The two flowcharts in Figures 5-3 and 5-4 and the checklist (Table 5-2) developed as part of this project follow similar logic as the FHWA chart, but with a stronger focus on selecting infiltration devices first. They are designed to assist in determining whether infiltrative treatment devices are capable of providing sufficient stormwater treatment. The focus on infiltration first

has two origins. First, a review of the newer stormwater guidance documents advocate infiltration first to reduce water quantity and peak flow rates leaving the site, in addition to the treatment provided by infiltration devices. Second, the pollutant loading concerns, the impaired streams 303(d) listings due to urban runoff, and the need to minimize erosive forces in the streams have focused interest in viewing stormwater management as an integrated process.

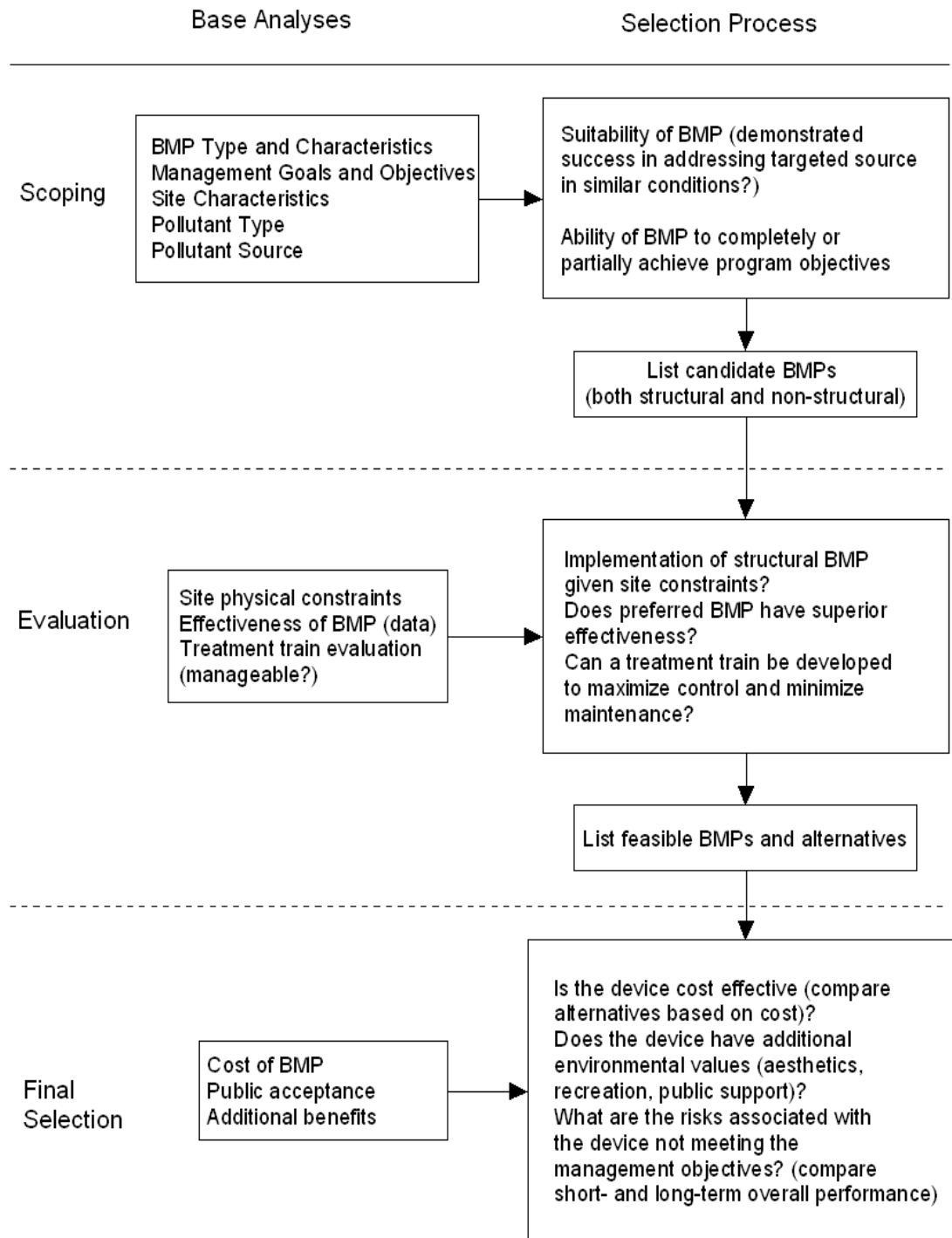


Figure 5-2. FHWA Flow Chart for Selecting Appropriate Stormwater Control Practices.

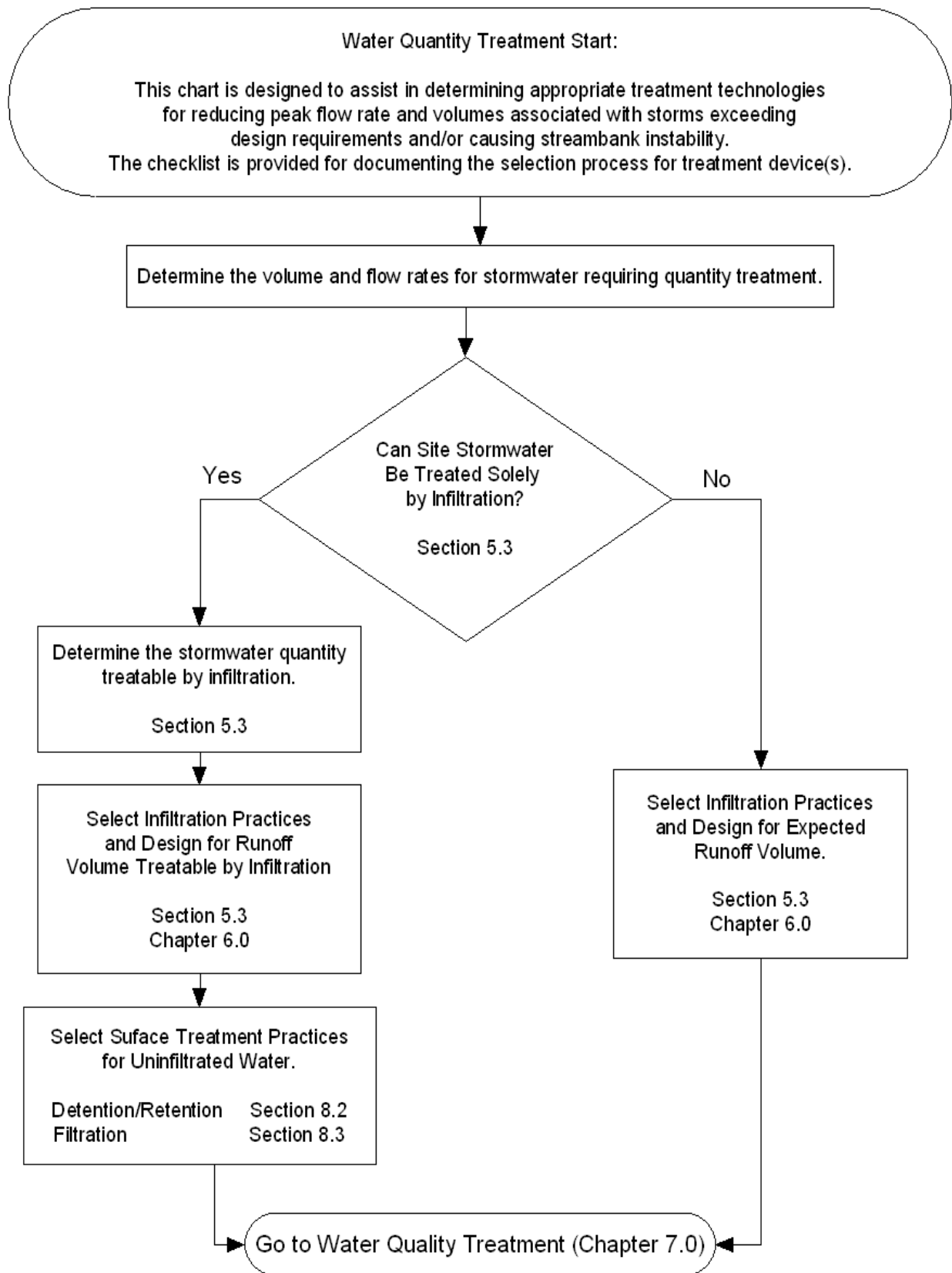


Figure 5-3. Flow Chart for Stormwater Runoff Quantity Treatment.

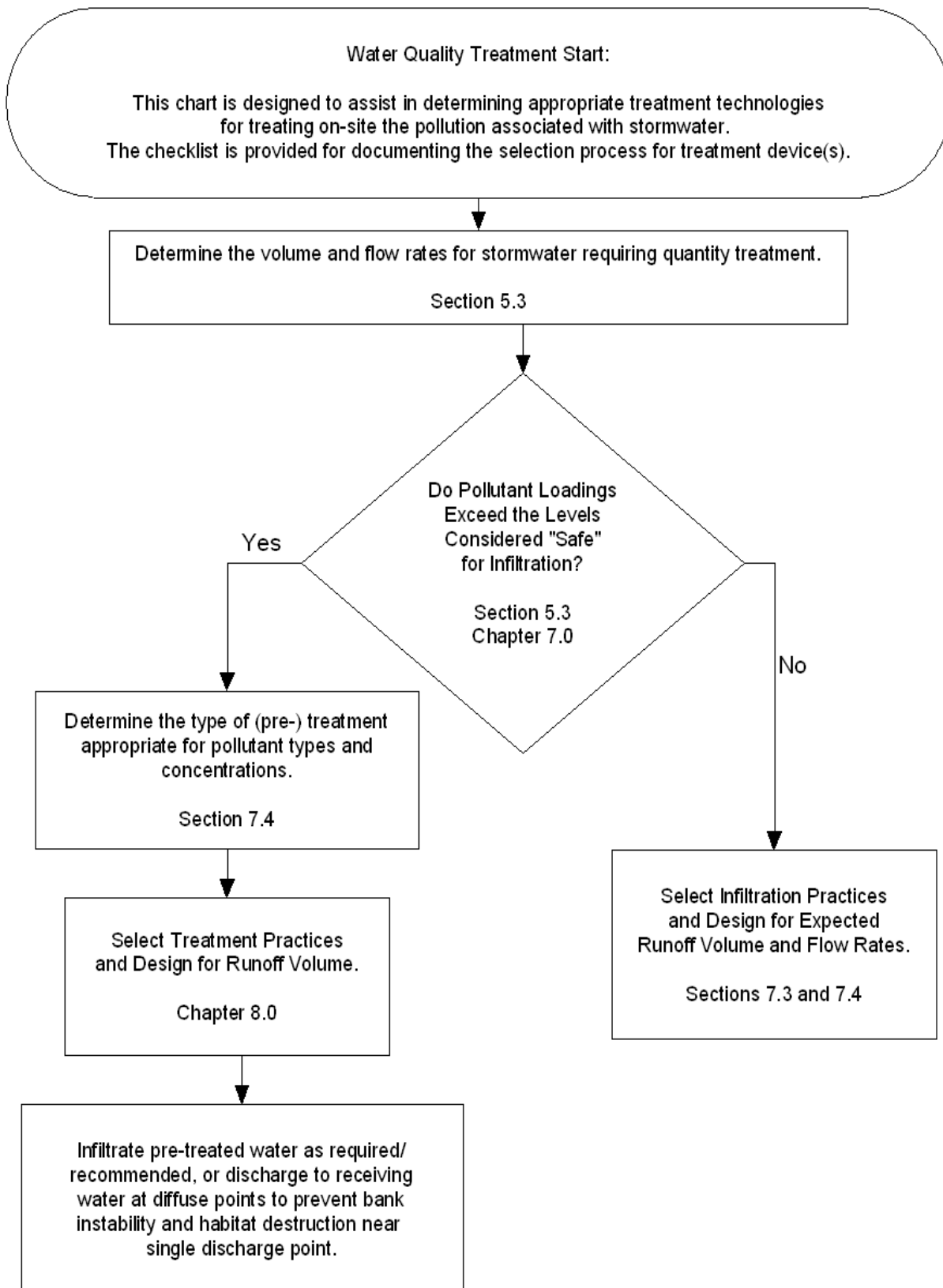


Figure 5-4. Flow Chart for Stormwater Runoff Quality Treatment.

Table 5-2. Checklist for Determining Whether to Use Infiltration, Surface Treatment, or a Combination.

Selecting a Control Practice: Water Quantity

Is post-development flow rate control required for the entire site?	Yes	No
If Yes, how much flow requires control? cfs cms	_____	
Is post-development volume control required for the entire site?	Yes	No
If Yes, how much volume requires control? cf cm	_____	

If both flow rate and volume control are required, select treatment device from Group A.

If only flow rate control is required, select treatment device from either Group A or B.

If quantity control is not required, select treatment device from Groups A, B or C.

GROUP A: Stormwater Control Practices Appropriate for Control of Both Flow Rate and Volume

Infiltration Basins, Infiltration Trenches, Pervious Pavement, Bioinfiltration Devices (Rain Gardens), Infiltrating Grass Swales, Underground Injection Control (UIC) (clean water only)

NOTE: The sizing of these devices is dependent on the desired flow rate of infiltration.

GROUP B: Stormwater Control Practices Appropriate for Rate Control Only

Detention Basins, Retention Basins, Grass Swales (limited infiltration), Underground Injection (clean water only)

NOTE: The sizing of these devices depends on the rate attenuation desired.

GROUP C: Stormwater Control Practices Designed Primarily for Water Quality Control

Manufactured Hydrodynamic Devices, Manufactured Filtration Devices

Selecting a Stormwater Control Practice: Water Quality

List the water quality parameters that require control starting with the primary criterion (rank in order of importance).

Water quality parameter	Potential Treatment Device (Table 5-6, after consulting with Tables 5-3 through 5-7)

The process now becomes iterative as described below. If the local guidance does not provide checklists, generic checklists for the steps are found in the appropriate chapters.

1. Tentatively site the planned infiltration devices.
2. Calculate the surface area available for infiltration at each device and in total for the site.
3. Estimate the approximate flow rate and volume that can be controlled through infiltration (Chapter 6.0).
4. Estimate the approximate pollutant treatment provided by the infiltration devices (Chapter 7.0).
5. Calculate the flow rate, volume, and pollutant levels requiring treatment in non-infiltrative (surface) devices.
6. Estimate the approximate water quantity and quality improvements with the surface treatment devices (Chapter 8.0).
7. Predict the water quantity, flow rate, and pollutant treatment provided by the selected design practices (Chapter 9.0).
8. Compare to the required treatment level.
9. Repeat Steps 1 – 8 until the required treatment meets or exceeds the volume, flow rate, or pollutant reductions required for low/no impact development.
10. Where groundwater depletion is an issue or where additional infiltration is needed to reduce post-development flow rates, investigate potential infiltration locations for surface-treated runoff.

While the flowcharts assume that the runoff is treatable and then dischargeable to the receiving water after either infiltration, surface treatment, or a combination of surface treatment followed by infiltration of the clean water, rarely the runoff from a site may be sufficiently polluted that it cannot be treated on site. If this condition exists, either a local/package treatment plant containing one or more conventional treatment practices may have to be built to address the

pollutants of concern in the runoff. The other option would be to direct the runoff to the municipal wastewater treatment plant. Designing a system to treat this runoff and addressing the concerns of sending runoff to a treatment plant are outside of the scope of this document. In this case, the user is directed to the appropriate agencies to determine the best method for handling the site's runoff.

The remainder of this chapter has been heavily adapted from the design guidance in the New York State Stormwater Management Manual (accessed 2008). The New York State guidance was selected because it incorporates many of the ideas contained in recent manuals and reflects recent thinking in the literature. The series of matrices in this section aid in the selection of the “best” stormwater management practice(s) for a site, given the constraints of land use, physical feasibility, watershed/regional factors, stormwater treatment capability, and community and environmental factors. However, these charts have been generalized and practices added that are not accepted in New York State.

5.3.1 Land Use

Land uses are divided into six categories: rural/low density residential, medium/high density residential, highways, commercial, critical source areas/hotspots, and ultra-urban/redevelopment sites (limited space, disturbed soils, and potential high levels of pollution). The matrix (Table 5-3) then is used to select potential treatment practices based on whether the practice is acceptable for the land use. The limiting factors are described in each box. For example, infiltration may provide excellent removal of water in residential areas, but only if the soils are appropriate for infiltration and the water is relatively clean. Systems where the treatment media can be changed easily may be more appropriate in commercial and, especially, industrial sites, but at higher pollutant loadings, clogging with solids or pollutants such as oils and greases may limit the utility of the device. Detention ponds are well-known to treat many pollutants, especially those associated with particulate matter. However, they often are not appropriate in ultra-urban areas because there is insufficient land available for the pond surface.

5.3.2 Physical Feasibility Factors

Once treatment devices applicable to the land use have been selected for further evaluation, issues of physical constraints on the project site must be evaluated. Table 5-4 can be used to do a preliminary evaluation based on literature information. On many sites, site-specific data will be needed. The constraints include soils and special geologic features (karst/carbonate/gypsum geology, faults, heterogeneity in the subsurface), depth to the water table, depth to bedrock, depth to clay lens (perched water table), size of the drainage area, land slope, and elevation/head available for gravity operation of the treatment device. For the soils constraint, the initial evaluation is based on the NRCS hydrologic soils groups at the site (found in the county soil survey). In almost all circumstances, detailed geotechnical tests will be required for infiltration feasibility and during design to confirm permeability and other factors. The water table depth must be evaluated based on the seasonal high water depth and the soil depth between the bottom of the treatment device and the top of the seasonal high water table. The drainage area constraint assumes that no pretreatment is installed prior to the device.

5.3.3 Watershed Factors Affecting Treatment Device Selection

The treatment device selection will be influenced to some extent by the water resource(s) being protected, such as sensitive streams (high-quality waters), aquifers (with special care taken

with sole source aquifers), drinking water reservoirs, lakes, and estuary/coastal waters. Another consideration is whether the device is appropriate for cold climates without flow diversion during cold weather. The following matrices (Tables 5-5a and 5-5b) show the relationship between appropriateness of a treatment device and the presence of a protected water resource.

Table 5-3. Land Use Selection Matrix.

Practice Type	Device	Rural and Low Density Residential	Medium/ High Density Residential	Highway	Commercial/ High Density Residential	Critical Source Areas	Ultra-Urban Areas
Pond	Wet Pond Extended Detention (ED)	Good	Good	Good	Site specific; Typically insufficient land available	Good ¹	Typically insufficient land available
	Wet pond	Good	Good	Good	Site specific; Typically insufficient land available	Good ¹	Typically insufficient land available
Wetland	Shallow Wetland	Good	Good	Site specific; Concerns about metals and sediment loading	Site specific; Typically insufficient land available for treatment	Good ¹	Typically insufficient land available
	Extended Detention Wetland	Good	Good	Site specific; Concerns about metals and sediment loading	Site specific; Typically insufficient land available for treatment	Good ¹	Typically insufficient land available
Infiltration	Infiltration Trench	Appropriate soils needed	Appropriate soils needed; Clogging or overloading concern	Good	Good	Pollutant concerns; Clogging	Pollutant concerns
	Shallow Infiltration Basin	Appropriate soils for infiltration	Appropriate soils for infiltration; Clogging or overloading concern	Site specific; Concerns about metals and sediment loading	Site specific	Pollutant concerns; Clogging	Pollutant concerns
	Dry Well ³	Appropriate soils for infiltration	Good	Clean water only; Limited treatment available in subsurface	Clean water only; Limited treatment available in subsurface	Pollutant concerns; Clogging	Clean water only; Limited treatment available in subsurface

Practice Type	Device	Rural and Low Density Residential	Medium/ High Density Residential	Highway	Commercial/ High Density Residential	Critical Source Areas	Ultra-Urban Areas
Filters	Surface Sand Filter	Limited additional treatment if runoff is clean; Limited removal of fertilizer nitrogen	Clogging or overloading concern	Good	Good	Good ²	Good
	Organic Sand Filter	Limited additional treatment if runoff is clean; Limited removal of fertilizer nitrogen	Clogging or overloading concern	Good	Good	Good ²	Good
	Bioretention	Appropriate soils for infiltration; plants will provide uptake of nutrients	Clogging or overloading concern	Good	Good	Good ²	Good
Open Channels	Dry Swale	Good	Clogging or overloading concern	Good	Clogging or overloading concern	Good ²	Clogging or overloading concern
	Wet Swale	Good	Clogging or overloading concern	Good	Clogging or overloading concern	Clogging or overloading concern	Clogging or overloading concern

NOTE: ¹ May require pond liner or other protection to prevent groundwater contamination.

² Acceptable if not designed for exfiltration.

³ Some jurisdictions do not allow direct injection of stormwater runoff into the ground. Therefore, this practice may be limited by the regulatory agency and not by the suitability of the practice to the land use.

5.3.4 Stormwater Management Capability

The goal of this step, shown in Table 5-6, is to determine whether one treatment practice or whether a treatment train where two or more practices are connected in series to improve treatment will be required. Issues include water quality, channel protection, and flood control. Devices should not be eliminated because they cannot meet one of the criteria, but instead may be used in a treatment train.

5.3.5 Community and Environmental Factors

Finally, the potential treatment devices must be evaluated through the eyes of the community. In this step, the management practices are compared with regard to cold climate restrictions, maintenance, habitat, community acceptance, cost, and other environmental factors. The treatment devices listed in Table 5-7 are assumed to meet the water quality criteria for TSS removal. This matrix uses a comparative index approach for the following factors. Additional information on operations and maintenance costs can be found in Chapter 10.0.

Table 5-4. Physical Feasibility Matrix.

Practice Type	Device	Soils*	Water Table, Bedrock, Clay Lens Layer**	Drainage Area (ac)	Site Slope	Head (ft)
Pond	Wet Extended Detention (ED) and Wet Pond	HSG A soils may require pond liner	2 ft separation if hotspot or aquifer	25 min ¹	No more than 15%	6 to 8
Wetland	Shallow Wetland	HSG A Soils may require liner	2 ft separation if hotspot or aquifer	25 min	< 8%	3 to 5
	ED Wetland					
Infiltration	Infiltration Trench	$f_c > 0.5$ in/hr; additional pretreatment required over 2.0 in/hr	3 ft, 4 ft if sole source aquifer	5 max	< 15%	1 ⁶
	Shallow Infiltration Basin			10 max ³		3
	Dry Well			1 max ⁴		1
Filters	Surface Sand Filter	OK	2 ft ⁵	10 max ²	< 6%	5
	Organic Sand Filter			5 max ²		2 to 4
	Bioretention			5 max ²		5
Open Channels	Dry Swale	Engineered Soil	2 ft	5 max	< 4%	3 to 5
	Wet Swale	OK	Below Water Table	5 max		1

NOTES: *Karst topography, rock formations near the surface, and geologic faults requires special attention and this table is not appropriate for evaluating stormwater treatment in these areas. The users are directed to local guidance, since different agencies have their own rules for stormwater management in special geologic areas.

**To prevent saturated soils below a device, these are the minimum values seen in the guidance documents.

¹Unless adequate water balance and anti-clogging device installed.

²Drainage area can be larger in some circumstances.

³May be larger in areas where the soil percolation rate is greater than 5.0 in/hr.

⁴Designed to treat rooftop runoff only.

⁵If designed with a permeable bottom, must meet depth requirements for infiltration practices.

⁶Required ponding depth above geotextile layer.

5.4 Design and Performance Guidance References

5.4.1 Design References

The design(s) required to control the quantity and rate of runoff leaving the site is covered in many fundamental textbooks in hydrology. These primarily-flood-control books demonstrate the methods required to calculate the required size and volume of detention basins and the design of outlet structures to control the discharge flow rate. Three commonly-used undergraduate/graduate textbooks in hydrology are Bedient et al. (2008), McCuen (2004), and Viessman and Lewis (2003).

Other books have been written directly to address stormwater management, sustainable development, water-sensitive designs, and the treatment of stormwater-borne pollutants. These include, but are not limited to, the following books: ASCE/WEF Manual of Practice (MOP) on Urban Runoff Quality Management (1998), Ferguson (1998), France (2002), Minton (2005), and the update of the Manual of Practice (scheduled for publication in 2009) called “Design of Urban

Stormwater Controls.” In addition, many conference papers, journal papers and research reports have been written on the design of these controls. For example, the series of monographs published by Computational Hydraulics Inc. of Canada publishes peer-reviewed manuscripts from the annual Urban Water Systems conference. The user is directed first to their state stormwater manual for design guidance. However, these references, especially the two MOPs because of the rigorous peer-review process before publication, may be useful in supplementing the state guidance.

Table 5-5a. Relationship between Watershed or Regional Selection Issues and Treatment Device Selection.

Management Practice	Sensitive Stream	Aquifer	Lakes
Ponds	1. Emphasize channel protection. 2. Restrict in-stream practices. 3. In trout areas, minimize permanent pool area, and encourage shading.	May require liner if HSG A soils are present. Pretreat 100% of water-quality volume from critical source areas.	Encourage the use of a large permanent pool to improve phosphorus removal (where P is a concern).
Wetlands	1. Require channel protection. 2. Restrict in-stream practices. 3. Restrict use in trout waters.	Provide a 2 ft separation distance to water table.	
Infiltration	1. Strongly encourage use for groundwater recharge. 2. Combine with a detention facility to provide channel protection.	Provide 100 ft horizontal separation distance from wells and 4 ft vertical distance from the water table.	OK. Provides high phosphorus removal.
Filtering Systems	Combine with a detention facility to provide channel protection.	Excellent pretreatment for infiltration or open channel practices.	OK, but designed with a submerged filter may result in phosphorus release.
Open channels		Ok, but pretreatment required for critical source areas.	OK, moderate phosphorus removal.

Table 5-5b. Relationship between Watershed or Regional Selection Issues and Treatment Device Selection.

Management Practice	Reservoir	Estuary/Coastal	Cold Climates
Ponds	1. Encourage use of a large permanent pool to improve sediment and phosphorus removal. 2. Promote long detention times to encourage bacteria removal.	1. Encourage long detention times to promote bacteria removal. 2. Provides high nitrogen removal. 3. In flat coastal areas, a pond drain may not be feasible.	Incorporate design features to improve winter performance.
Wetlands			Encourage the use of salt-tolerant vegetation.
Infiltration	1. Provide a separation distance from bedrock and water table. 2. Pretreat runoff prior to infiltration practices.	2. OK, but provide a separation distance to seasonally high groundwater (water table). 2. In the sandy soils typical of coastal areas, additional pretreatment may be required.	1. Incorporate features to minimize the risk of frost heave. 2. Discourage infiltration of chlorides.
Filtering Systems	1. Excellent pretreatment for infiltration or channel practices. 2. Moderate to high coliform removal.	1. Moderate to high coliform removal. 2. Designs with a submerged filter bed appear to have very high nitrogen removal.	Incorporate design features to improve winter performance.
Open channels	Poor coliform removal for wet swales	Poor coliform removal for grass wet swales.	Encourage the use of salt-tolerant vegetation.

Table 5-6. Stormwater Device Performance Matrix.

Management Practice	Device	Water Quality			Channel Protection	Flood Control
		Nitrogen	Metals	Bacteria		
Pond	Wet Pond	Good	Good	Good	Good	Good
	Wet Extended Detention (ED) Pond				Good	Good
Wetland	Shallow Wetland	Good	Fair	Good	Good	Good
	ED Wetland				Good	Good
Infiltration	Infiltration Trench	Good	Good	Good	Poor	Poor
	Shallow Infiltration Basin				Poor ²	Poor ²
	Dry Well				Poor	Poor
Filtration	Surface Sand Filter	Good	Good	Fair	Poor ¹	Poor
	Organic Sand Filter				Poor	Poor
	Bioretention				Poor ¹	Poor
Open Channel	Dry Swale	Fair	Good	Poor	Poor	Poor
	Wet Swale				Poor	Poor

Good: Should meet management goal. Estimated pollutant removal: >30% TN, > 60% Metals, > 70% Bacteria.

Fair: Estimated pollutant removal: 15 – 30% TN, 30 – 60% Metals, 35 – 70% Bacteria.

Poor: Estimated pollutant removal: < 15% TN, < 30% Metals, < 35% Bacteria.

¹ In most cases, device cannot meet this goal but design may be adapted to add storage.

² Generally cannot meet this goal except in areas with soil percolation rates greater than 5.0 in/hr.

Table 5-7. Community and Environmental Factors Matrix.

Management Practice	Device	Maintenance Ease	Community Acceptance	Affordability	Safety	Habitat
Ponds	Wet pond	Good	Good	Good	Poor	Good
	Wet Extended Detention (ED) Pond	Good	Good	Good	Poor	Good
Wetlands	Shallow Wetland	Moderate	Good	Moderate	Good	Good
	ED Wetland	Moderate	Moderate	Moderate	Moderate	Good
Infiltration	Infiltration Trench	Poor	Good	Moderate	Good	Poor
	Shallow Infiltration Trench	Poor	Poor	Moderate	Good	Poor
	Dry Well	Poor	Moderate	Moderate	Good	Poor
Filters	Surface Sand Filter	Moderate	Moderate	Poor	Good	Poor
	Organic Sand Filter	Moderate	Good	Poor	Good	Poor
	Bioretention	Moderate	Moderate	Moderate	Good	Moderate
Open Channels	Dry Swale	Good	Good	Moderate	Good	Poor
	Wet Swale	Good	Moderate	Good	Good	Moderate

5.4.2 Performance References

The performance of various stormwater control practices has been studied and the results published in many formats. The peer-reviewed literature, both journal papers and governmental reports, has a wealth of information about these practices and their ability to treat stormwater pollutants. In addition, several research groups have published their results both as databases of performance and in reports. The following is a list of stormwater research groups/investigators

whose websites provide research information/summaries that may be useful. This list is not exhaustive.

- ◆ Water Environment Research Foundation (www.werf.org)
 - Browsing Stormwater Best Management Practices...
(<http://www.werf.org/AM/Template.cfm?Section=Search&Template=/CustomSource/KnowledgeAreas/GetTaggedContent.cfm&TagId=91>)
 - Using Rainwater to Grow Livable Cities (Shoemaker et al. 2008)
(<http://www.werf.org/livablecommunities/index.htm>)
- ◆ U.S. Environmental Protection Agency
(<http://www.epa.gov/ebtpages/watestormwater.html>)
 - Urban Watershed Management Branch
(<http://www.epa.gov/ednnrmrl/index.htm>)
 - Nonpoint Source Program (<http://www.epa.gov/nps/>)
- ◆ U.S. Geological Survey (<http://water.usgs.gov/pubs/>)
- ◆ U.S. Department of Transportation
(<http://www.fhwa.dot.gov/environment/h2o.htm>)
- ◆ Urban Water Technology Centre (hosted by the University of Abertay Dundee)
(<http://www.uwtc.tay.ac.uk/Site/aboutUWTC.htm>)
- ◆ Cooperative Research Centre for Catchment Hydrology (Australia)
 - eWater CRC (<http://www.ewatercrc.com.au/index.html>)
- ◆ Landcare Research (New Zealand) (<http://www.landcareresearch.co.nz/>)
- ◆ Sustainable Urban Water Management (Sweden)
(<http://www.urbanwater.org/dyndefault.asp?p=2413>)
- ◆ Denmark (Chalmers University, Technical University of Denmark, Lulea University)
- ◆ France (OTHU : Field Observatory in Urban Hydrology)
- ◆ California Department of Transportation (CALTRANS)
(<http://www.dot.ca.gov/hq/env/stormwater/>)
- ◆ Center for Watershed Protection (www.cwp.org)
- ◆ Chesapeake Stormwater Network (www.chesapeakestormwater.net)
- ◆ Florida Department of Environmental Protection
(<http://www.dep.state.fl.us/water/nonpoint/pubs.htm>)
- ◆ Washington State Department of Transportation
(<http://www.wsdot.wa.gov/Environment/WaterQuality/Research/>)
- ◆ Academic Institutions: University of Central Florida, Monash University, North Carolina State University, Rutgers University, Penn State University –

Harrisburg, University of Alabama, University of Auckland, University of California Los Angeles, University of Florida, University of Maryland, University of New Hampshire Stormwater Center, University of Texas Water Resources Research Institute, University of Utah, Villanova University Urban Stormwater Partnership, Washington State University

Conferences and their proceedings also provide case studies of performance, plus information on cost, financing and maintenance of stormwater practices. The user is directed to the reference section of this document to see the variety of conferences and sponsoring organizations that address stormwater.

As the user will note in Chapters 7.0 and 8.0, the data in the International BMP Database (sponsored by WERF, ASCE, U.S. EPA, Federal Highway Administration, American Public Works Association, plus others) is referenced heavily. The BMP Database contains information about more than 300 monitoring projects which met the quality control requirements. The database now includes the information from the Florida Department of Environmental Protection's activities. Unlike many of the other summaries of control practice treatment effectiveness, it does not rely on percent removals to assess performance. The 2006 National Cooperative Highway Research Program (NCHRP) report also noted a lack of effluent quality data in the literature they reviewed, with percent removals being the preferred reporting measure. As described further in Chapter 9.0 and summarized in Jones et al. (2008), percent removals are not comparable between studies since the testing conditions are not identical. Another advantage of the International BMP Database is that these are not single event evaluations; a minimum of three storm events must be entered before the data set is accepted for evaluation. The breakdown on projects as of 2007 (when there were results from 279 monitoring studies in the database) is given in Table 5-8.

Table 5-8. Number of BMP Studies in the International Stormwater BMP Database.

Treatment Device Type	Number of Studies
Biofilters (grass swales/buffers/bioinfiltration)	64
Media Filters	46
Retention pond	42
Detention Basin	31
Non-structural BMPs (maintenance practices)	28
Hydrodynamic devices	27
Wetland basin	16
Wetland channel	14
Pervious pavement	8
Infiltration basin	2
Percolation trench/well	1

For certain devices (pervious pavement, infiltration basin, percolation trench), the number of studies is small, and many parameters were not monitored by every study. Therefore, the number of studies for each device for each parameter is smaller. However, in spite of these limitations, the International BMP database can provide information about the effluent quality and about the volume reductions that are potentially achievable. The annual summary of the entire dataset could be useful and can be found on the website www.bmpdatabase.org. The summary report does not separate out different land uses, but it does report the 95% confidence intervals of the dataset for a given device, plus the median for pollutants monitored and reported.

A smaller study, but focusing on the performance of devices retrofit into the urban and highway landscape, was performed by the California Department of Transportation (CALTRANS 2004). The devices evaluated included an Austin and a Delaware sand filter, lined and unlined extended detention basins, a retention pond (wet basin), an infiltration basin, an infiltration trench, a biofiltration swale, a biofiltration strip, a Storm-Filter™, a CDS® unit, and a multi-chambered treatment train (MCTT). They used probability plots of the results to calculate expected effluent concentrations by type of treatment device, given a known influent concentration.

The U.S. EPA also has created a searchable Urban BMP Performance Tool (www.cfpub.epa.gov/npdes/stormwater/urbanbmp/bmpeffectiveness.cfm). Their database combines studies in the International BMP Database with studies performed by the State of California. As of March 2009, most of the studies were from the International BMP Database. For example, a search of biofilters for solids removal returned only studies in the BMP Database. It is not clear whether studies entered into the BMP Database studies after early 2008 are contained in the EPA database. Therefore, this database could be considered a separate tool for obtaining information on treatment device performance.

CHAPTER 6.0

WATER QUANTITY ISSUES RELATING TO INFILTRATION DESIGN

6.1 Introduction

Infiltration devices, such as bioretention/biofiltration areas, infiltration trenches, French drains, permeable pavement, etc., contribute to stormwater management by removing water from the surface into the soil profile. If these devices are connected to the native soil profile (not lined) and do not have an underdrain, they also promote groundwater recharge. This reduction of water from the surface flow system helps meet the goal of mimicking pre-development hydrology where surface runoff typically is a small percentage of the rainfall.

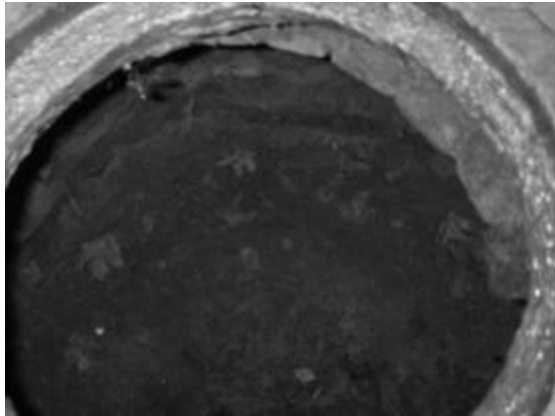
Many guidance documents provide very specific criteria for the design of infiltration devices. The user is directed to those documents provided the relevant regulatory agencies. This chapter has been developed to assist the user in addressing the questions raised during those designs plus other issues that are being raised by current research.

In Chapter 5.0, the user has calculated the quantity and flow rate of water to be controlled through infiltration. Now these flows and volumes need to be divided among the selected infiltration devices and the flows and quantity of water to each calculated. Infiltration devices are often divided into four categories in the design manuals: basins (Figure 6-1a), trenches and underground dry wells (Figure 6-1b), pervious pavement (Figures 6-1c), and grassed swales and filter strips (Figure 6-1d). Additional information on these specific devices is in Appendix I.

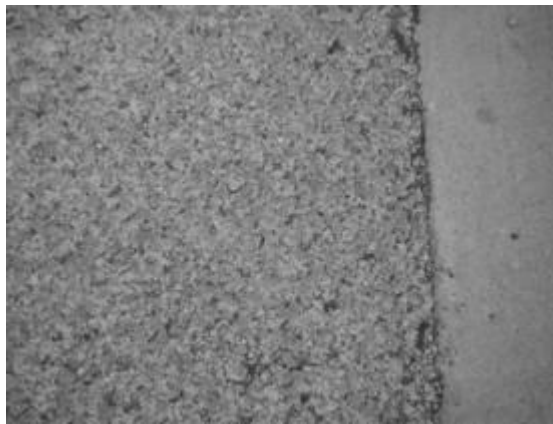


a. Newly Planted (left) and Well-Established (right) Bioinfiltration Basins.

Figure 6-1. Examples of Installed Infiltration Practices.



b. Infiltration Dry Well for Roof Runoff (left) and Below-Ground Trench (right).



c. Pervious Pavement for Sidewalks (left) and Parking lot (right).



d. Infiltration Grass Swales and Filter Strips.

Figure 6-1. Examples of Installed Infiltration Practices.

6.2 General Siting Considerations

Infiltration practice designers must consider both the site restrictions and the soils issues in order to ensure that the design remains operational throughout its design life. The guidance in this section is drawn from a variety of sources, including the U.S. EPA and its fact sheets on infiltration practices. If differences with EPA guidance were located, they are referenced herein. A summary of design criteria for bioretention and infiltration systems from a representative guidance document in each of the nine EPA rainfall regions is given in Section 6.3.6.

6.2.1 Adequate Infiltration Surface Area and Media Depth

The process referred to as infiltration in stormwater management books is actually a combination of two processes, infiltration (the movement of the water through the soil surface layer) and percolation (the movement of the water through the soil profile). Water movement through the unsaturated (vadose) zone is controlled by the smaller of those two values. These values also change over the life of an infiltration basin as the stormwater solids are captured in the soil media (see Clogging, Section 6.5). An example of how to size an infiltration basin using the clogging values is given in that section.

Instead of using clogging calculations to size infiltration basins, many guidance documents have chosen to simplify the calculations and address the infiltration basin size question through ratios of the drainage area to the surface area of the basin (referred to as water loading rates). Typical ratios include the following:

- ◆ Maximum Impervious Loading Ratio of 5:1 (total paved or compacted soil drainage area to infiltration device surface area).
- ◆ Maximum Total Loading Ratio of 8:1 (total drainage area [pervious + impervious] to infiltration area).
- ◆ Maximum Impervious Loading Ratio for karst areas of 3:1 (total paved or compacted soil drainage area to infiltration area).

In addition, infiltration devices are not recommended for the treatment of large drainage areas. In the guidance, maximum drainage areas appear to range between 5 and 25 acres, depending on the infiltration device type. Offsets also are required between the edge of the device and the lot lines and building foundations. Several guidelines recommend offsets between infiltration devices and sensitive water resources or septic systems.

Media depth also may be specified, typically to provide sufficient contact time for water pollution reduction. In relation to water quantity treatment, Brown and Hunt (2009) showed in North Carolina that deeper media devices (0.9 m vs. 0.6 m) were better able to meet the volume reduction requirements of low impact development (35% compliance with the goal for 0.9 m media depth vs. 9% for the 0.6 m media depth).

6.2.2 Site Slope

Infiltration devices should not be located at the toe of or along severe slopes. In general, infiltration devices should have flat bottoms (slopes less than 1%) in order to spread the water evenly throughout the basin and use the entire infiltration surface. A study in France on a two-decade old infiltration basin showed that pollutant accumulations were highest in the soils near

the inlet and at the low point of the basin. Grassed swales, because they are also a part of the drainage system, will have a slight slope, typically less than 4%, and, preferably, a 1 to 2% slope.

6.2.3 Depth to Groundwater

Groundwater depth below the bottom of the infiltration devices is important in design for two reasons. First, the depth to groundwater should be sufficient to ensure that the soil has adequate time to provide pollutant treatment as required. Second, saturated soils have slower flow rates than unsaturated soils. Having saturated soils directly below the infiltration basin reduces the amount of water that pass through soils downward to the groundwater. This results in the creation of groundwater mounds beneath the basin. Mounding is a problem because of soil stability. Also, if the horizontal spread of the mound is large, the soils near building foundations and/or sensitive water resources or septic systems (if applicable) may become saturated with resultant leaking of untreated stormwater into basements. Equations to estimate mounding beneath infiltration basins were presented by Zomorodi (2005 and 2009).

Regulatory guidance typically focuses on the first concern – adequate depth for treatment prior to encountering the groundwater. This can be modeled using either simple spreadsheets or vadose zone models (Section 7.5) that estimate the subsurface transport of the pollutants of interest. While modeling will improve the predictions of groundwater contamination potential, the state of the science still has many data gaps. Therefore, guidance documents typically state the minimum depth to the seasonal high water table. Depending on the jurisdiction, that minimum depth may range from 2 to 5 feet. Because of mounding and spread concerns, distances to drinking water wells also may be specified, typically 100 feet in the horizontal direction. However, a full site investigation is recommended, including evaluating the pumping rate of the nearby wells, plus the subsurface geology and whether the well is pumping from a confined or the unconfined aquifer. This will aid in determining whether drinking water contamination is a concern and if pre-treatment may be required. Certainly, areas with nearby drinking water wells are almost always unsuitable for direct injection (also called underground injection) systems. These minimum depths may not apply in all jurisdictions if the infiltration basin is designed to have standing or slowly-flowing water as part of the treatment process.

6.3 General Soils Considerations

Soils and topography are strongly limiting factors when locating infiltration practices. Soils must be permeable enough to ensure that the water infiltrates within a certain time period and minimizes surface ponding. Minimization of surface ponding is especially important for practices such as pervious pavements, any practices that drain transportation infrastructure, and where the ponded water would interfere with the primary use of the infrastructure. However, the need for rapid infiltration must be balanced with the need for long contact times for runoff treatment and prevention of groundwater contamination. In areas with sandy soils and high infiltration rates, treatment is minimal because of the lack of contact time and of treatment ability of the sandy soil. Some state, federal, and international guidance documents limit the makeup, typically listed as a texture range or by a maximum and/or minimum infiltration rate, of the underlying soil that can be used for infiltration devices. Soils that do not fit into those classifications must be amended to be acceptable for use, according to the guidance.

6.3.1 Soil Characteristics that Affect Infiltration Rates

6.3.1.1 Soil Classification

Soils have been classified based on their physical characteristics and their formative processes. The Unified Soil Classification System (USCS) and the U.S. Comprehensive Classification System, developed by the USDA, are the two most common classification systems used in the U.S. (Selker et al., 1999). Soil is classified by each of the following factors which may affect infiltration rate (which can be interpreted differently depending on the soil classification system):

- ◆ Particle (grain) size distribution (used by the major classification systems)
- ◆ Particle shape
- ◆ Structure
- ◆ Color
- ◆ Texture (e.g., the USDA Soil Triangle or other classification triangles).

Table 6-1 shows particle size distributions in the different soils as determined by the major classification systems. Shape affects how the soil particles interact to create a specific structure for water flow. Soil structure describes the geometric orientation of the soil grains with respect to each other. Finally, soils have specific textures based on the grain size, shape, and consistency (Winegardner, 1996).

The physical weathering processes in the vadose zone have combined these particles in different proportions to create several soil textures, e.g., sandy clays, silty clays, loams, clay loams, sandy loams, etc. The USDA soil textural triangle can be found in Chapter 3.0.

6.3.1.2 Porosity

Soil contains voids (pore spaces) between the mineral grains. These pore spaces transport water or air, or both. The *porosity* (n) of soil is defined as the ratio of the volume of the voids to the bulk volume (total volume of the soil). Porosity is expressed as a percentage (Selker et al., 1999). Table 6-2 shows the porosities of the common soil types. High porosity, however, does not guarantee high permeability.

6.3.1.3 Bulk Density

Bulk density refers arrangement of the particles in the soil. Soil particles of uniform size and shape will pack together loosely resulting in higher porosities. On the other hand, particles of varying sizes have the tendency to pack together more tightly and reduce porosity. Compaction also will rearrange soil particles, often resulting in increased bulk density and reduced infiltration rates. Soil density often is expressed as dry bulk density and is measured by weighing and drying a portion of soil, then weighing it again after drying (after water removal) (Sumner, 2000).

6.3.1.4 Intrinsic Permeability

Intrinsic permeability refers to the ease at which water will flow through the pore spaces in the soil. Each primary type of soil has a range of intrinsic permeabilities. For example, sand is much more permeable than clay because its void spaces tend to arrange into connecting pores, whereas clay pores often dead end. Thus, clay has a high porosity and a low permeability (Freeze and Cherry, 1979; Fetter, 1994). Table 6-3 shows the permeability of different soil types.

Table 6-1. Grain Size Limits by Various Classification Systems.

Sediment Type	Size	Unified Soil Classification System	American Association of State Highway and Transportation Officials	U.S. Department of Agriculture	Massachusetts Institute of Technology
Cobble	Grain Size (mm)	> 80	> 80	> 80	> 80
	Sieve Size	> 3 inches	> 3 inches	> 3 inches	> 3 inches
Coarse Gravel	Grain Size (mm)	20 – 5.0			
	Sieve Size	3 inches – ¾ inch			
Fine Gravel	Grain Size (mm)	5.0 – 2.0			
	Sieve Size	¾ inches – 4			
Gravel	Grain Size (mm)		80 – 2.0	80 – 2.0	80 – 2.0
	Sieve Size		3" – 10	3" – 10	3" – 10
Medium Sand	Grain Size (mm)	2.0 – 0.3			
	Sieve Size	10 - 40			
Sand	Grain Size (mm)		2.0 – 0.08	2.0 – 0.05	2.0 – 0.06
	Sieve Size		10 – 200	10 – 270	10 – 240
Fine Sand	Grain Size (mm)	0.3 – 0.07			
	Sieve Size	40 – 200			
Silt	Grain Size (mm)		0.08 – 0.002	0.05 – 0.002	0.06 – 0.002
	Sieve Size		< 200	< 270	< 240
Clay	Grain Size (mm)		< 0.002	< 0.002	< 0.002
	Sieve Size	< 200	< 270	< 270	< 270
Fines (Silt or Clay)	Grain Size (mm)	0.07 – 0.001			
	Sieve Size	< 200			

Table 6-2. Soil Porosities.

Soil Type	n (%)
Sand	25-50
Silt	35-50
Clay	40-70

Table 6-3. Ranges of Intrinsic Permeabilities for Soils and Sediments. (Summarized from Fetter, 1994).

Material	Intrinsic Permeability (cm²)
Clay	10 ⁻¹⁵ – 10 ⁻¹²
Silt, sandy silts, clayey sands, till	10 ⁻¹² – 10 ⁻¹⁰
Silty sands, fine sands	10 ⁻¹¹ – 10 ⁻⁹
Well-sorted sands, glacial outwash	10 ⁻⁹ – 10 ⁻⁷
Well-sorted gravel	10 ⁻⁸ – 10 ⁻⁶

Intrinsic permeability and infiltration rate are directly related. Soils with greater permeability allow surface water to infiltrate through the vadose zone at higher rates, resulting in a more rapid groundwater recharge. However, when soil is disturbed its intrinsic permeability changes. Typically if a soil is compacted, its bulk density increases and its permeability

decreases. Once the soil is disturbed, it cannot be returned exactly to its original permeability because the connections between the pores have been changed (Selker et al., 1999).

6.3.2 Soil Infiltration Rates

The flow of water in vadose zone soils can be characterized assuming either that the soil is unsaturated at the beginning, as is typically done in hydrologic modeling of rainfall-runoff, or that the soil is saturated, as would be expected during the course of infiltration.

Many guidance documents establish minimum (and potentially maximum) infiltration rates for treatment devices. A review of guidance documents indicated accepted ranges of 0.1 to 10 in/h. These typically are based on the infiltration/percolation tests that measure flow rates in previously unsaturated soils. Testing methods and further descriptions of the models used to describe unsaturated flow rates are in Appendix I. Some jurisdictions require higher initial site infiltration rates, such as 5 to 10 in/hr, because of the reduction in infiltration rate over time due to clogging. These rates typically require a sand to be included in the infiltration soil; however, other researchers have suggested that if the goal is to mimic pre-development hydrology, some infiltration should be allowed on clayey soils, even though it will not be as much as on sandy soils. The logic is that the clayey soil device should try to replicate the poor, but functional, infiltration on a site with originally clayey soils.

Unsaturated flow can be expressed in terms of gravity potential Z and moisture potential ψ . *Gravity potential* is the vertical distance that water must travel to reach saturated soil. The *moisture potential* is the tension on water in the pore spaces due to its attraction to soil particles. The potential for water to flow in the vadose zone can be calculated as total potential ϕ by the equation:

$$\phi = \psi(\theta_v) + Z \quad \text{Equation 6.1}$$

where θ_v is the volumetric water content of the soil (Fetter, 1994).

The three most commonly used infiltration flow rate models are the phi-index, Horton's equation, and the Green-Ampt equation. Newer models use the Richard's equation and its approximate solutions. These equations are described further in Appendix I and in basic hydrology and hydrogeology textbooks.

Saturated flow usually is described using Darcy's law and research has shown that Darcy's Law also can describe the flow in the unsaturated zone during infiltration events. For saturated flow, the hydraulic conductivity of the soil is a constant and can be measured or predicted based on the grain size distribution of the soil. During unsaturated flow, because the amount of water in the soil fluctuates, the unsaturated hydraulic conductivity $K\theta_v$ is not a constant. The volumetric water content of the soil θ_v allows the fluctuation in soil water to be accounted for in the Darcy's law equation:

$$Q = -(K\theta_v)A \left(\frac{dh}{dL} \right) \quad \text{Equation 6-2}$$

Where Q = the discharge rate of groundwater flow (m^3/sec); $K\theta_v$ = the unsaturated hydraulic conductivity (m/sec or cm/sec); A = the cross sectional area of flow (m^2); and dh/dL = the hydraulic gradient ($(h_2-h_1)/L$) where L is the distance between h_1 and h_2 .

Despite the validity of Darcy's law in the vadose zone, it may not apply to all unsaturated flow conditions. Because water flow in soil is very complex, it still is not fully understood as to when non-Darcy flow exists. Therefore predictions of water flow in the vadose zone using Darcy's law may be quite poor in areas where the hydraulic conductivity varies with the volumetric water content. Caution should be exercised when applying Darcy's law to soils with low permeability, such as clays (Tindall and Kunkel, 1999).

6.3.3 Hydrologic Soil Group as an Indirect Measure of Infiltration Rate

In the U.S., the NRCS has classified 14,000 soils series and organized them into a comprehensive database, which now can be accessed online (Web Soil Survey, <http://websoilsurvey.nrcs.usda.gov/app/>). These soil surveys provide important information such as the soil description, suitability for construction, hydrologic cover, tendency to erode, hydrologic conductivity, and hydrologic soil group classification. The USDA classified soils into one of four hydrologic soil groups (A, B, C, and D) as a way of describing how well water will move through a specific type of soil (Table 6-4).

Table 6-4. Hydrologic Soil Group Descriptions. (Summarized from McCuen, 2004)

Hydrologic Soil Group (HSG)	Drainage Characteristics
A	Deep sand; deep loess, aggregated silts; rapidly draining
B	Shallow loess; sandy loam; well drained
C	Clay loams; shallow sandy loam; low organic content; high clay content; slow draining
D	Soils that swell significantly when wet; heavy plastic clays; certain saline soils; very poorly drained

Since soil surveys show general locations of soils types and the hydrologic soil groups for each soil type, they can be useful in selecting a general area to be used for infiltration on a large site. Soil surveys cannot substitute for field testing in specifically siting an infiltration device, since soils vary greatly in properties in even a small area and soil properties often change substantially after the compaction associated with construction. In general, hydrologic soil group D will not be suitable for infiltration. Some jurisdictions restrict infiltration to A and B soil groups, while others allow limited infiltration on HSG C soils. C soils infiltrate slowly, which may replicate the pre-development conditions and be appropriate for areas that have poorly-draining soils.

6.3.4 Soil Media for Engineered Infiltration Devices

While natural, undisturbed soils will provide some infiltration, many jurisdictions mandate the soil mixtures to be used in engineered infiltration devices. One common mixture is referred to as the Prince George's County (Maryland) mixture and it is based on both soil texture (water flow) and chemistry (pollutant removal) properties. According to the Maryland Department of the Environment (2000), the soils should have no greater than 20% clay content, and less than 40% silt/clay content. Several jurisdictions recommend a mixture that contains 50% coarse-grained sand, 20-30% leaf compost, and 20-30% topsoil. According to "Rain Gardens of Western Michigan," this mixture will maximize infiltration, filtration and storage (<http://www.raingardens.org/bioretention.php>, accessed 2008). Use of this mixture should be restricted primarily to devices with an underdrain. Otherwise, the final soil mixture in an infiltration device should be designed based matching the infiltration rate in the native soil below the device. If the infiltration device with a rapid-draining mixture meets a slower-infiltrating subsoil, the bottom of the device may become a perched water table. The Western Michigan mix

has been designed as a well-drained soil mixture; however, it may have limitations such as nutrient leaching from the compost. If the installation will be affecting a nutrient-limited waterbody, the user should specify the compost as a low-phosphorus compost (see Section 7.3.4). A comparison of the various soil requirements for infiltration and biofiltration systems is given in Section 6.3.6.

6.3.5 Restrictions in Specific Physical Settings

6.3.5.1 Carbonate/Karst Topography

Many jurisdictions prohibit infiltration in karst terrain because of the concern of excess, concentrated water inflows into the soil profile eroding the karst and causing sinkholes. Studies on karst terrain stormwater management are referenced in Appendices I and K. However, the recent research on the water budget and hydrologic cycle in karst has indicated that banning infiltration in karst also causes problems because the groundwater level drops, leaving air pockets underground that are not able to support the soil and structures above them.

Recommendations in current papers on karst infiltration tend to encourage limited infiltration in these areas using dispersed infiltration techniques. Use of injection wells and other rapid infiltration techniques is not recommended. The design criteria for infiltration in karst should encourage mimicking the entire pre-development hydrograph (rate and volume) with low ratios of drainage area to basin area (3:1 or 2:1). Other recommendations made by some jurisdictions including amending the soils through soil compaction or amendments designed to reduce the flow rate.

6.3.5.2 Locations Near Wetlands and Streams

Some jurisdictions require setbacks between the edge of infiltration devices and wetlands or streams. Setback distances appear to range between 25 and 100 ft. Other guidance suggests that the distance should be based on a site characterization. According to the Commonwealth of Pennsylvania, soils near streams and wetlands typically have high water tables and/or have low permeability. Past land use may indicate areas that are suitable for infiltration. For example, when converting agricultural land to urban land uses, prior cultivated areas may be suitable for infiltration, but lands left out of cultivation may be too wet or too rocky.

6.3.5.3 Compacted Fill and Soil Survey Designations as Urban Land

Compacted fill and urban lands typically are highly disturbed soils. As a rule of thumb, compacted fill is not appropriate for infiltration. Urban land designations in the NRCS Soil Survey may indicate compacted soil (possibly fill). Infiltration may be possible in these areas; however, local testing should be undertaken to determine the actual site infiltration rates. Amendments have been used with mixed results in recovering infiltration capacity on fill, low permeability lands, and urban land areas.

6.3.6 Comparison of Guidance for Bioretention/Bioinfiltration and Infiltration Systems

Tables 6-5 and 6-6 compare the guidance for constructing either a bioretention or infiltration system across rainfall regions. A representative guidance document was selected from each region. As can be seen, many of the guidance documents have similar criteria, regardless of climatic differences between the rainfall regions, and some of them reference the guidance documents from other regulatory agencies.

Table 6-5. Infiltration System Design Criteria by Representative Locality per Rainfall Region.

EPA Rain Zone	City, State	Depth to Ground-water (ft)	Depth of Basin (ft)	Ponding Depth (ft)	Cold Weather (online vs. offline)	Soil Hydraulic Conduct. ¹	Soil Type	Chemical Properties	Basin Surface Relative to Drainage Area
1	PA	> 2		< 2			loamy		< 5:1 (imperv. to infiltration area)
2	VA	2 - 4	3 - 12	< 2		I1: 0.52-8.27 in/hr	loamy mix (<30% clay)		< 50 acre drainage (38-66% imperv.)
3 ²	Orlando, FL	4	3 - 12			I1: 3-5 in/hr			
4	Columbia, MO			< 2			HSG A and B		< 2 acre drainage area
5	Austin, TX		> 1.5	< 2		3.5 ft/day			
6 ³	CA	3 - 10		< 2	double storage / pretreatment for winter	I1: 0.2-0.38 in/hr w/ ponding	A-D type soils w/ low clay		< 2 acre drainage area
7	WA ⁴	≥ 5	1.5 - 6			I1: 0.13 - 10 in/hr	loamy sands	CEC: ≥ 5 meq/100g	
8	WA ⁴	≥ 5	> 1.5			I1: 0.5-2 in/hr	loamy sands	CEC: ≥ 5 meq/100g	
9	Casper, WY	≥ 3				I1: > 0.5 in/hr			drainage area: 2-15 acres

¹ If noted, infiltration rate requirements and not hydraulic conductivity given in regulations

² Florida uses mostly retention ponds or infiltration trenches due to too much clay in soil.

³ California stormwater manual references Minnesota BMP manual

⁴ Zone 7 is Western Washington, while Zone 8 is Eastern Washington. There are two different manuals, depending on where in the state a municipality is located.

Table 6-6. Bioretention System Design Criteria by Representative Locality per Rainfall Region.

EPA Rain Zone	City, State	Ground-water Depth (ft)	Basin Depth (ft)	Ponding Depth (inches)	Cold (online vs. offline)	Soil Hydraulic Conduct. ¹	Soil Type ²	Chemical Properties	Basin Surface Relative to drainage area	Plant List
1	PA	>2	> 1.5	< 12		l1: 0.1 in/hr	75% L ² , 25% C, <10% clay	pH: 5.5-6.5 OM: 5-10%	< 5:1 (impervious drainage area to infiltration area)	Yes
2	VA	2 - 4	2.5 ft w/o sand bed	6		l1: 0.52-8.27 in/hr	50% S, 20% C, 30% top soil		0.25-1 acre drainage area (min 1090 ft ² per imperv. acre)	Yes
3	Atlanta, GA	>2	4	6		0.5 ft/day	L w/ 10-25% clay	pH: 5.5-6.5 OM: 1.5-3% Soluble salts: <500 ppm	Min. 200 ft ² or 5% tributary imperv. area max 5 acre drainage area	Yes
4	Columbia, MO	> 4	4	9		> 1 ft/day	10-25% clay; 30-55% silt; 35-60% S	pH: 5.2-7.0 OM: 1.5-4% Mg: 35 lb/acre P2O5: 75 lb/acre K2O: 85 lb/acre Soluble salts: <500 ppm	Max 1 acre drainage area	Yes
5	Austin, TX		> 1.5	6		3.5 ft/day	S: 70-90%; clay: 2-10%	n = 0.45 OM: 1-4% CEC: 10 meq/100g	drainage area < 1acre filtration area 10% drainage area	Yes
6 ³	CA	> 3	4	6-9	account for snow storage and salt runoff	infiltration: > .5 in/hr	L (10-25% clay)	pH: 5.5-6.5 OM: 1.5-3% Soluble salts: <500 ppm	Surface area 5-10% drainage area (max 2 acres)	Yes
7	WA	1 - 3	> 1.5	< 12		> 1.0 in/hr at 80% compact	65% LS; 35% C	pH: 5.5-7.0		Yes
8	WA	≥ 5	> 1.5	< 6			LS	CEC: ≥ 5 meq/100g		No
9	Colorado Springs, CO		> 1.5	6-12			SL and sand-peat mix			No

¹ If noted, infiltration rate requirements, and not hydraulic conductivity, given in regulations.

² Soil type abbreviations: L = loam; C = compost; S = sand; SL = sandy loam; LS = loamy sand

³ California stormwater manual references Minnesota BMP manual.

6.4 Modeling of Water Transport beneath Infiltration Basins

The stormwater management models that regularly are cited in the literature include an infiltration component as part of their low impact development design. The following table (Table 6-7) describes the infiltration calculations used by each model. The table can be used to determine which method a model uses and then the appropriate appendix can be referenced to determine the required input data for the model. Little (2009) describes in the report text the purposes of the models and the limitations, as described in the literature and users' manuals.

Table 6-7. Infiltration Methodologies of Stormwater Management Software.

Model	Version	Developer	Infiltration Method					Primary/Intended Use
			SCS CN	G-A	Horton	Phi	User defined	
RUNQUAL	1993	Haith, Cornell U	X					Preliminary Planning/Education
SWMM	5.0.009	EPA & Huber, Oregon State U	X	X	X			Urban Hydrology and Water Quality simulation; Detailed model for planning and preliminary design
WinSLAMM	9.2	Pitt, U of Alabama					X	Planning – Contaminant Loading; Evaluates pollutant loadings in urban areas using small storm hydrology
DURMM		Lucas, Delaware	X					Planning and Contaminant Loading
HEC-HMS	3.1.0	USACE	X				X	Large Storm Events
TR-20		USDA NRCS	X					Large Storm Events Hydrology
TR-55			X					Hydrology of Large Storm Events
HSPF	5	U.S. EPA					X	Best suited for rural hydrology and water quality simulation
Prince Georges County BMP Model		Prince Georges County, MD	X*	X*	X*		X*	Uses HSPF to derive flow and pollutant loads. Applies loads to LID BMPs.
MUSIC		Wong, Monash U						Simulates hydrology, water quality; scale: city-block to large catchment. Planning/conceptual design
LIFE™		CH2M HILL					X	Simulate LID microhydrology
P8		Walker	X					Urban stormwater pollutant loading
SET		Upper River Basin Assn., NC Div. Water Quality	X					Predictive tool for quick assessment of environmental impacts of development
SMADA		U Central Florida	X		X			Single watershed/event routing
RECARGA	2.3	U Wisconsin	X	X				Model performance of bioretention and infiltration facilities.

NOTES: Infiltration Methodologies

SCS-CN = USDA Natural Resource Conservation Service Curve Number

G-A = Green-Ampt

Horton = Horton Infiltration

Phi = Phi Index

* The Prince George's County evaluation module accepts runoff data from SWMM and/or HSPF and therefore, the infiltration tools available in those models are available in the Prince George's County BMP Evaluation Module

6.5 Clogging and the Need for Pretreatment

6.5.1 Estimating the Life Span of Infiltration Devices

Most infiltration devices fail due to clogging of the surface and upper layers. Therefore, it is important to be able to predict the service life and maintenance intervals for the device. Prior research on stormwater filters have shown that these devices may start to show significantly reduced infiltration capacities after approximately 1 to 5 lb/ft² (5 to 25 kg/m²) of particulate solids have been loaded (Clark, 1996 and 2000; Clark and Pitt, 2009; Urbonas, 1999). Deeply rooted vegetation and a healthy soil structure can extend the service life longer than those loading values because more of the soil depth is used to trap solids and the rooted vegetation opens up flow channels. However, abuse (especially compaction and excessive siltation) can significantly reduce the life of the system. The following sections present the three levels of clogging calculations, from simplest to most complex. While the first model, the Urbonas (1999) model may be a simplification of the clogging process, it may be the only model for which data is available for developing the predictive equations. For more detailed information about the other two models, the user is directed to the appropriate references.

6.5.1.1 The Urbonas (1999) Model – Application and Limitations: Case Study

Urbonas (1999) presented the following equation based on field filter performance observations in Colorado to predict the unit flow rate through a sand filter as a function of the suspended solids load. The suggested equation (Equation 6-3) for predicting the unit flow rate, u , through the filter in feet per day (ft³/day)/ft², is based on the suspended solids load, L_m , accumulated on/in the filter in pounds per square foot of filter area, with k_i and c being regression coefficients.

$$u = k_i \bullet L_m^{-c} \quad \text{Equation 6-3}$$

Although developed for Lakewood, Colorado, sand filters, Equation 6-3 has been applied by Clark (2000) to a variety of natural filter media, by Barrett (2003) to Austin sand filters, and by Gironas et al. (2008) to perlite stormwater filters.

Further laboratory work on this model (Clark 2000) using sand and a peat-sand mix media showed that influent concentration, filter diameter, filter depth, media size, stormwater solids size likely affect the lifespan of the filter. Therefore, until the model is refined to account for these factors, the use of this equation may be media specific.

6.5.1.2 Clogging Modeled Using Resistance Factors (Dechesne et al., 2005)

This model defines a parameter called the hydraulic resistance, R . It is developed from the Bouwer model (Bouwer, 1969) and is a representative of the interface layer between the water and the soil. It contains potentially the surface crust of the basin soil and the cake layer of solids removed from the stormwater. R is defined as the ratio of the thickness to the hydraulic conductivity of the interface layer. The hydraulic resistance then can be incorporated into Darcy's Law to predict flow rate through the infiltration basin. The authors found that the resistance model was not applicable on a single-storm event but it was effective at comparing basin performance on a year-to-year basis.

6.5.1.3 Clogging Modeled Assuming both Cake and Depth Filtration (Li and Davis, 2008a,b)

This model, which was developed to describe particulate capture in bioretention media, describes the column as containing three layers: pristine zone (bottom), a working zone (middle), and a cake layer (top). The mechanisms controlling solids removal include both depth filtration and the buildup of a cake on top of the media. The flow rate through the biofilter over time then is described as a function of the changing porosity and hydraulic conductivity of the media as solids build up in the working zones of the media. Clark (2000), in an investigation of several media mixes, also found cake and depth filtration were responsible for the decrease in a filter's flow rate over time.

6.5.2 Pretreatment

As noted above, clogging is related to the solids loading on the media. Therefore, the use of pretreatment such as sedimentation forebays or gravel trench at the entrance where solids settle out prior to encountering the zones of active infiltration will extend the life of the device.

A second area of focus for pretreatment is soil stabilization in the device. For all infiltration practices, and in particular for grass swales, upland soils must be stabilized to ensure that the basin does not become clogged with sediment.

6.5.3 Use of Clogging Data to Size an Infiltration Device for a Given Lifespan

Because of concerns regarding vectors (typically mosquitoes) in devices that allowed ponded water, many jurisdictions require that infiltration devices drain down within 24-72 hours after the end of runoff entering the device. Because of flooding concerns, many of these devices also have a maximum allowable ponding depth. The drawdown and maximum ponding depth information can be used to calculate the infiltration rate at failure. If the media has been pre-tested and an estimate of the suspended solids loading at failure is known, then the infiltration can be sized to meet the desired lifespan. This is a hypothetical example of these calculations.

The flow rate through the infiltration device can be predicted as a function of the suspended solids loading. The suspended solids loading to the filter is a function of the rainfall amount and the resultant runoff. As an example, volumetric runoff coefficients (R_v) (Table 6-8) can be used to approximate the fraction of the annual rainfall that would occur as runoff for various land uses and surface conditions. This runoff then contains the suspended solids that will cause clogging of the filter. Table 6-9 summarizes likely suspended solids concentrations associated with different urban areas and waters.

Table 6-8. Volumetric Runoff Coefficients by Land Use. (Data derived from Pitt et al., 1996)

Area	Volumetric Runoff Coefficient (R_v)
Low density residential land use	0.15
Medium density residential land use	0.3
High density residential land use	0.5
Commercial land use	0.8
Industrial land use	0.6
Paved areas	0.85
Sandy soils	0.1
Clayey soils	0.3

Table 6-9. Suspended Solids Concentration by Land Use. (from literature review in Clark, 2000)

Source Area	Suspended Solids Concentration (mg/L)
Roof runoff	10
Paved parking, storage, driveway, streets, and walk areas	50
Unpaved parking and storage areas	250
Landscaped areas	500
Detention pond water	20
Mixed stormwater	150

Using the information above and the local annual rain depth, it is possible to estimate the annual suspended solids loading from an area and to size the infiltration device. The cumulative suspended solids loading then can be used to estimate the flow rate at any time in the device's lifespan. The scenario for this infiltration device is given in Table 6-10.

Table 6-10. Model Application Scenario.

Site Description	1 ha parking lot
R_v	0.85 (industrial)
Suspended Solids Concentration	50 mg/L (paved parking, etc.)
Rainfall Description	35 in/yr average rainfall depth = 0.89 m
Desired lifespan before substantial maintenance	5 yr

Step 1: Size the filter based on suspended solids loading until clogging.

For the 5-year period, the total amount of suspended solids heading for the filter is calculated to be almost 2,000 kg (1,891 kg).

$$\begin{aligned}
 TSS_{total} &= (\text{TSS conc. per storm})(\text{years})(\text{Rainfall Depth per year})(R_v)(\text{Drainage Area}) \\
 &= \left(50 \frac{\text{mg}}{\text{L}}\right)(5 \text{ yr})(0.85)(0.89 \text{ m})(1 \text{ ha}) \left(10,000 \frac{\text{m}^2}{\text{ha}}\right) \left(\frac{1,000 \text{ L}}{\text{m}^3}\right) \left(\frac{\text{g}}{1,000 \text{ mg}}\right) \\
 TSS_{total} &= 1,891,000 \text{ g}
 \end{aligned}$$

Step 2: Assume that the solids loading that causes a peat-sand flow rate of less than 1 m/day is approximately 5,000 g/m² (data from Clark and Pitt 2009, which also contains information about other filter media). The required surface area of the filter is then calculated using the equation below.

$$\begin{aligned}
 A_{\text{infiltration}} &= \frac{TSS_{total}}{TSS_{load}} = \frac{1,891,000 \text{ g}}{5,000 \text{ g} / \text{m}^2} \\
 A_{\text{infiltration}} &= 378 \text{ m}^2
 \end{aligned}$$

The final surface area for the infiltration basin is just less than 40% of the total drainage area (drainage area:device area = 2.5:1). As noted in the earlier sections, the addition of vegetation is likely to increase the filter life or for the same lifespan, it will decrease the required surface area into the low end of the ranges recommended by the guidance documents. In addition, using filter media other than this mixture where the suspended solids loading to failure is greater will decrease the required surface area.

6.6 Maintenance

Regular maintenance is critical to the successful operation of infiltration devices because older basins have a poor track record and have left many regulatory agencies wary of further use (Galli 1992 on trenches and basins; Hilding 1996 on basins in permeable soils). Many of these practices did not incorporate advanced pretreatment. Lack of proper installation also may have caused these failures.

Several guidance documents recommend the installation of underdrains for drawing down the basins for maintenance if they become clogged. However, regular use of underdrains defeats the purpose of removing runoff from surface and piping systems. Other guidance documents recommend installing observation wells (perforated PVC that leads to the bottom of the device) to observe flow rates in the subsurface. In particular, periodic observations of flow rates and comparisons to the flow rates when newly installed should warn the device owner when clogging is affecting performance and maintenance is required. Pervious pavements are a unique infiltration device because they require periodic sweeping to remove fine particles from the cement or asphalt structure. Many pavements have larger subbase drainage storage areas because water cannot pond on the travel surface, but instead must be stored until the trench below the pavement has drained. Table 6-11 is a matrix of suggested maintenance by device type and the suggested schedule for these activities.

6.7 Climate Issues in Infiltration Design

6.7.1 Arid or Semi-Arid Climates

Infiltration practices are highly desirable in arid or semi-arid climates to recharge the groundwater. However, protection against clogging is critical because many storms wash off high loads of sediment. Vegetated devices should be planted with drought-tolerant species and/or covered with an alternative material such as sand or gravel. The trench sides should be planted with drought-tolerant species or covered with an alternative material. The value of vegetated practices for water quality, though, needs to be balanced against the cost of water needed to maintain them in arid and semi-arid regions.

6.7.2 Cold Climates

Infiltration devices can be used in cold climates, although they are not recommended in areas with permafrost. Although the literature has reported on basins where snowmelt is stored and that are still operational, infiltration devices are not recommended as storage areas for snow piles. First, the device volume may need to be increased in order to treat snowmelt in conjunction with a melting rain event. Road salt also is problematic, depending on the chemical composition of the salt. Increasing the sodium adsorption ratio in the soil through the infiltration of sodium salts in de-icers have the potential to destabilize the clay component of an infiltration device soil. If the soil destabilizes, the basin will behave as if clogged and will require maintenance to regain some infiltration capacity. Because these destabilization reactions are chemical reactions, they are discussed in further detail with guidance provided in Chapter 7.0. If the device is used for snow storage, or to treat roadside or parking lot runoff, the basin bottom should be planted with salt-tolerant vegetation. A minimum setback from roads is needed to ensure that the practice does not cause frost heaving. Pervious pavements will need to have the base of any stone storage reservoir below the frost line or a second drainage system should be designed to remove stormwater away from the aggregate recharge bed.

Table 6-11. Typical Maintenance Activities for Infiltration Basins (Modified from WMI, 1997; U.S. EPA, 2005).

Activity	Schedule
Infiltration Basin	
Inspect facility for signs of wetness or damage to structures. Note eroded areas. If dead or dying grass on bottom, check to ensure that draindown is 2-3 days. Note signs of petroleum hydrocarbon contamination and handle properly.	Semi-annual inspection
Mow and remove litter and debris. Stabilize of eroded banks. Repair undercut and eroded areas at inflow and outflow structures.	Standard maintenance (as needed)
Disc or otherwise aerate bottom. Dethatch basin bottom.	Annual maintenance
Scrape bottom and remove sediment. Restore original cross-section and infiltration rate. Seed or sod to restore ground cover.	5-year maintenance
Infiltration Trenches	
Check observation wells following 3 days of dry weather for complete draindown. Inspect pretreatment devices and diversion structures for sediment build-up and structural damage.	Semi-annual inspection
Remove sediment and oil/grease from pretreatment devices and overflow structures.	Standard maintenance
If bypass available, use it and allow the basin to dry for an extended period of time. It may be possible to regain the infiltration rate in the short term.	5-year maintenance
Total rehabilitation of the trench should be conducted to maintain storage capacity within 2/3 of the design treatment volume and 72-hour exfiltration rate limit. Trench walls should be excavated to expose clean soil.	Upon failure
Pervious Pavement	
Do not seal or repave with non-pervious materials.	N/A
Ensure that paving area is clean of debris. Ensure that paving dewater between storms. Ensure that the area is clean of sediments.	Monthly
Mow upland and adjacent areas, and seed bare areas. Vacuum sweep frequently to keep the surface free of sediment.	As needed (typically three to four times per year).
Inspect the surface for deterioration.	Annual
Grassed Swale	
Inspect pea gravel diaphragm for clogging and correct the problem. Inspect grass alongside slopes for erosion and formation of rills or gullies and correct. Remove trash and debris accumulated in the inflow forebay. Inspect and correct erosion problems in the sand/soil bed of dry swales. Plant alternative grass species if the original grass cover did not successfully establish. Replant wetland species (for wet swale) if not sufficiently established.	Annual (semi-annual the first year)
Rototill/cultivate surface of the sand/soil bed of dry swales if draw down > 48 hours. Remove sediment build-up within the bottom of the swale once it has accumulated to 25 percent of the original design volume.	As needed (infrequent)
Mow grass to maintain a height of 3–4 inches	As needed (frequent seasonally)

CHAPTER 7.0

WATER QUALITY AND SOILS CHEMISTRY ISSUES RELATING TO INFILTRATION DESIGN

7.1 Introduction

Infiltration devices also possess the ability to remove pollutants from stormwater runoff. The soil media behaves as a filtration media. If these devices, however, are connected to the native soil profile (not lined) and do not have an underdrain, they also have the potential, if not properly sited, to contribute to groundwater contamination. Predicting the pollutant removal potential of infiltration media requires an understanding of soil and water chemistry. This chapter summarizes important concepts in soil and water chemistry and applies them to the design of infiltration devices and media.

Many guidance documents have provided information on expected pollutant removal in infiltration devices based on the literature. However, these have generally been presented as efficiencies of removal and have been misapplied. This chapter first describes the known information on pollutant removal in infiltration/filtration media. Then it describes the important soil and water chemistry concepts that need to be evaluated when selecting a media. Third, the two levels of modeling that can be used to predict groundwater contamination potential. Finally, the chapter describes the limitations of modeling for predicting pollutant removal in infiltration/filtration devices.

In Chapter 5.0, the user was guided through the process of considering/describing the quality of stormwater runoff on the site and identifying/listing the problem pollutants requiring treatment. Now, these pollutants need to be attributed to sources and the infiltration devices which will be expected to treat them.

7.2 Treatment Ability of Stormwater Infiltration Devices

Research has been performed and is ongoing in many areas of the world on the various stormwater control practices. Summaries of the recent literature on urban wet-weather flows and management practice performance can be found in the on-line annotated literature review (Clark et al., 2008). References to case studies on stormwater treatment also are located in Appendix J.

One project that has evaluated existing control practice performance (based on reported monitoring data) is the International Stormwater BMP Database (www.bmpdatabase.org). Table 7-1 is derived from the 2007 Performance Summary. Users are directed to the case studies in Appendix J for additional case studies that exist on groundwater pollution and soils' chemical buildup below stormwater infiltration devices.

Many guidance documents and literature studies report removal efficiencies for these devices. The problem with the use of removal efficiencies is evident in the data described above. Many of the efficiency calculations reported in the literature either were performed in the laboratory using influent concentrations greater than reported at actual field installations or were based on load reductions. As the BMP Database results and other studies such as Clark (2000)

show, there appears to be a lower limit to the effluent quality that can be achieved by these types of treatment devices. Improving that effluent quality will require different treatment technologies, such as membranes, chemical pretreatment, or use of more expensive and specialized media. The limitations of removal efficiencies are discussed again in Chapter 9.0.

Table 7-1. Median Influent and Effluent Concentrations for Infiltration Treatment Devices.

Parameter	Sample Point	Biofilter (Rain Garden)	Media Filtration Device	Pervious Pavement
Suspended Solids (mg/L)	Influent	53	43	NA
	Effluent	18	11	17
Nitrate-Nitrogen (mg/L)	Influent	0.59	0.41	NA
	Effluent	0.36	0.66	NA
TKN (mg/L)	Influent	1.8	1.5	NA
	Effluent	1.3	1.2	1.2
Nitrogen, Total (mg/L)	Influent	1.3	1.3	NA
	Effluent	0.6	0.74	NA
Phosphorus, Dissolved (mg/L)	Influent	0.09	0.09	NA
	Effluent	0.33	0.08	NA
Phosphorus, Total (mg/L)	Influent	0.25	0.20	NA
	Effluent	0.27	0.11	0.09
Cadmium, Total (µg/L)	Influent	0.54	0.25	NA
	Effluent	0.30	0.19	NA
Cadmium, Dissolved (µg/L)	Influent	0.25	0.16	NA
	Effluent	0.21	0.13	NA
Copper, Total (µg/L)	Influent	32	15	NA
	Effluent	9.6	7.6	2.8
Copper, Dissolved (µg/L)	Influent	14	7.8	NA
	Effluent	7.4	7.0	NA
Chromium, Total (µg/L)	Influent	5.6	2.2	NA
	Effluent	4.6	1.5	NA
Lead, Total (µg/L)	Influent	20	11	NA
	Effluent	5.4	2.6	7.9
Lead, Dissolved (µg/L)	Influent	2.3	1.4	NA
	Effluent	1.8	0.86	NA
Zinc, Total (µg/L)	Influent	180	92	NA
	Effluent	28	32	17
Zinc, Dissolved (µg/L)	Influent	58	69	NA
	Effluent	24	32	NA

Two areas of concern regarding urbanization's impact on surface waters and groundwater are the potential increase in temperature of surface runoff entering temperature-sensitive waters and the depletion of groundwater because of the removal of groundwater recharge sites and reducing the water in the hyperheic zone of the soil (the zone next to and just below a stream where groundwater and surface water mix). Infiltration devices can address both concerns. As the water travels through the soil, if the transport length is sufficiently long, the water temperature will approach the soil temperature (Jones et al., 2007). The Jones et al. (2007) paper indicates that there are minimum media depths for infiltration devices that have underdrains connected to the sewer system and eventually the receiving water. Infiltration with groundwater recharge also increases the soil water and encourages transport of water horizontally in the soil

profile to the hyperheic zone. The result may be potentially increasing stream baseflow plus some temperature modifications during soil transport.

7.3 Soil Chemistry and Pollutant Removal and Retention

Stormwater pollutants may interact with the soil both in the vadose zone and the saturated zone (groundwater). To prevent chemical breakthrough in the soils of and beneath the infiltration, pollutants should react and be removed in the upper layers of the vadose zone. The further in the soil that the pollutants penetrate, the greater the likelihood of groundwater contamination or transport out of the device through the underdrain. The soil chemistry and pollutant removal ability reflect the parent material of the soil.

7.3.1 Soil Horizon Impacts on Geochemistry

Because soil reflects the underlying geology, the mineral components may exist in their original form or be transformed into new compounds by infiltrating water, microbial activity, plant enzymes, or pollutants. Organic matter results from decaying plant and animal material. Numerous species of microorganisms exist in the soils and feed on and create organic matter.

Many generalizations have been made in the literature about chemical behavior of soils based on textural designations. However, soil texture does not define the soil's pollutant removal ability. The physical properties of interest for chemical pollutant removal are porosity and intrinsic permeability. These properties, because they dictate the rate of water transport, also dictate the minimum contact time the pollutants have in the medium. If the pollutant can react with the soil in that time, it is reasonable to assume that pollutant removals will be good.

The general composition of the soil horizons may indicate how the soils will behave in terms of pollutant removal. These horizons are designated as O, A, E, B, C, and R (Table 7-2 illustrates the orientation of the horizons and briefly describes their composition).

Table 7-2. Orientation and Description of Soil Horizons (Surface to Depth).

O – Horizon	Surface litter consisting primarily of organic matter
A – Horizon	Topsoil consisting of humus and inorganic minerals; zone of maximum biological activity
E – Horizon	Zone of leaching where percolating water dissolves soluble material. Sometimes called the A ₂ -horizon.
B – Horizon	Subsoil below the A-or-E horizons that contains minerals and humic compounds; zone of clay accumulation
C – Horizon	Zone consisting primarily of undecomposed mineral and rock fragments
R – Horizon	Layer of very low permeability that can also be called bedrock

In general, the chemical makeup of soils is the following:

- ◆ Inorganic mineral matter (50-60% in total). This is soil material consisting mostly of oxygen, silicon, and aluminum, plus many other metals in small quantities.
- ◆ Organic mineral matter (< 10%). This is soil material derived from plant residues and consisting mostly of carbon, oxygen and hydrogen.
- ◆ Solutes. This component is the portion of the soil that includes water and mostly dissolved salts (plant nutrients).
- ◆ Air. Soil air is composed of the same gases as the atmosphere, but in different ratios.

Soil horizon chemistry affects the ability of soils to remove pollutants. As noted in Table 7-2, each layer has a different chemical composition, and it is these differences that change the

chemical reactivity of the soil as water passes from the O horizon through to the groundwater. Treese et al. (2009) highlights the impacts of soil horizons on stormwater pollutant removal in two natural soils – a silt loam and a loamy sand. This study is summarized in Appendix J.

7.3.2 Effects on Soil Chemistry of Pore Water and Infiltrating Stormwater

The properties of water affect soil reactions. For example, the expansion of water after freezing causes the soil to expand and the surface elevation to rise. Water can dissolve at least a small concentration of almost any chemical. Although water molecules have no net charge, the spatial distribution of charges on a water molecule causes it to be dipolar and therefore, it tends to react with polar molecules. Water also undergoes hydrolysis reactions. As a rule of thumb, inorganic molecules are soluble in water, but most organic molecules are only slightly soluble (Winegardner, 1996).

Because of hydrogen bonding, water molecules resist deformation (shearing forces), called viscosity. The viscosity of water affects infiltration rates with high infiltration rates occurring in warmer weather when the water is warmer and the viscosity is lower (Winegardner, 1996; Emerson and Traver 2008).

7.3.3 Soil Chemical Properties Affecting Pollutant Transport

The six primary chemical properties of soil that impact pollutant transport include the following (Evangelou 1998):

1. Permanent charge (permanent Cation Exchange Capacity [CEC])
2. Variable charge (pH-dependent CEC)
3. Point of zero charge, ZPC (pH at which the net surface charge is zero or the pH where the CEC minus the Anion Exchange Capacity [AEC] is zero)
4. Inner-sphere/outer-sphere complexes (defined as strong surface complexes or inner-sphere complexes, as opposed to weak surface complexes or outer-sphere complexes)
5. Hydrophobic-hydrophilic potential (defined as the potential of soil to adsorb water)
6. pH buffering (ability of the soil to resist pH change).

7.3.3.1 Cation Exchange Capacity

Much of the groundwater protection offered by soils is associated with its ability to remove cationic (positively-charged) pollutants, measured as cation-exchange capacity (CEC) (Pitt, et al. 1996; Johnson et al. 2003). The CEC of a material is defined as the sum of the exchangeable cations that can be adsorbed at a given pH and is used to evaluate the ability of a soil to sorb phosphorus, heavy metals, and other target cations of concern. The CEC is pH-specific. Sands have low CEC values, typically ranging from about 1 to 3 cmolc/kg (centimol positive charge per kg of soil; also equal to meq/100 g) of material. As the organic content of the soil increases, so does its CEC content. Natural soils therefore vary widely in their CEC content. Organic soil amendments, such as compost, increase the CEC of a soil that is naturally low in organic material or clays. CEC generally diminishes over time in a soil used to treat stormwater runoff because the number of exchangeable cations decreases as cations, such as metals, are removed from the infiltrating water.

7.3.3.2 Anion Exchange Capacity

Similar to the cation exchange capacity, the anion exchange capacity (AEC) is the sum of the exchangeable anions that can be adsorbed at a given pH. It is a measure of the positive charges on the surface of the soil particles that can participate in pollutant removal. The AEC also is pH-specific. AEC values rarely are measured for stormwater filter/biofilter media.

In general, soils where the predominant colloids are oxides of Fe and Al may have a net positive charge and may contribute to ion exchange. For example, a clay-size particle of hydrous aluminum oxide has a positive charge under acid conditions. However, this charge may be pH-dependent. At sufficiently high pH, this soil may contribute to cation exchange capacity. These soils, though, are naturally acidic and are more likely to contribute to AEC (UBC Soil Web, accessed 2008). According to Troeh and Thompson (2005), anion-exchange sites in soils result from 1) amine groups in humus, 2) structures terminating in a cation at the edge of a silicate-clay material, 3) OH^- ionizing from materials such as $\text{Al}(\text{OH})_3$ or $\text{Fe}(\text{OH})_3$, and 4) isomorphic exchange of Ti^{4+} for Fe^{3+} in iron oxides. Anion exchange capacity can increase in a soil as the soil ages and weathering occurs. Younger soils, such as illite, vermiculite and smectite, have higher cation exchange ability compared to anion exchange. As the soil weathers, the fraction of kaolinite and oxide clays increases and the anion exchange ability increases as the cation exchange capacity decreases. AECs are typically low in natural soils.

7.3.3.3 Mineral Matter

Aluminosilicates make up a large fraction of soil particles < 0.2 mm. They are commonly referred to as clay minerals. The silica or aluminum ion is surrounded by four or six oxygen atoms. Substituting aluminum for silica and substituting divalent cations for the aluminum is common. If the substitution replaces the given coordinating cation with a cation of lower valence, a permanent negative charge or CEC increase occurs (Evangelou, 1998). These substitutions do not occur in the molecular structure itself so further substitutions with preferred cations may occur. In addition, although this is likely impractical in stormwater infiltration devices, this material may be regenerable through washing of the media with high concentrations of the readily exchangeable cation. The concern with road salt entering infiltration devices is that sodium may act as an exchangeable cation and wash out previously-captured heavy metals. Table 7-3 describes the soil chemical properties of several mineral materials.

Table 7-3. Clay Minerals and Surface Properties.

Mineral	CEC (cmolc/kg)	Specific Surface (m ² /g)
Kaolinite	3 – 15	10 – 20
Montmorillonite	60 – 100	600 – 800
Vermiculite	110 – 160	600 – 800
Illite	20 – 40	40 – 180
Chlorite	10 – 30	70 – 150
Mica	20 – 40	70 – 120

Metal oxides, such as those of iron and manganese, have oxygen atoms at the edges of the mineral. These oxygen atoms release and capture cations in reactions that are pH dependent. This cation exchange capacity, which captures heavy metals and releases protons, can range from 1-30 meq/100 g. The release of the proton (or hydronium ion) may result in a more acidic water (Evangelou, 1998). Green roof researchers, such as Long et al. (2008), have demonstrated

the pollutant removal ability of certain expanded shales, slates and clays, indicating that these materials may be candidates for underdrains in constructed infiltration devices.

7.3.3.4 Organic Matter Content

Soil organic matter results from two major groups of compounds – the non-nitrogenous compounds (primarily carbohydrates) and the nitrogenous compounds (compounds derived from proteins). The organic matter results from the degradation of cellulosic compounds, eventually resulting in humus. Seventy to eighty percent of the organic matter by weight in soils are humic substances (condensed polymers of organic compounds). They are amorphous, dark-colored, and hydrophilic. They have a wide range of molecular weights and a large number of functional groups which participate in reactions in the soil that remove large quantities of pollutants.

Heavy metal and soil colloid (including soil clays, humic substances or a combination) interactions result from ion exchange, surface adsorption, or chelation reactions. Humic substances may form complexes with heavy metals because of their oxygen-containing functional groups on their surface. The retention of heavy metals in native soils by the clays and humics varies with ionic strength, pH, clay mineral type, functional group type, and types of competing cations (Evangelou 1998). Commonly, the amount of metal ions adsorbed increases with increasing pH for humics and clays. The reactions that may occur in humic substances include the following:

- ◆ Protons (H^+) compete with cations for organic binding sites
- ◆ Hydroxyl ions (OH^-) competes with humic substances for the cationic-metal ion
- ◆ Soft metals (Ca^{2+} , Mg^{2+} , etc.) compete with the hard/heavy metals for organic functional groups.

Complexation of metals also is a viable reaction in humic substances. These complexation reactions may be weak (outer-sphere of the particle) and reversible, or relatively strong (inner-sphere). Inner-sphere cations can be displaced only by other cations that can form inner sphere complexes (Evangelou 1998).

7.3.3.5 Soil pH

As noted above, soil pH plays a strong role in the resultant reactions. As Evangelou (1998) describes, low soil pH and acidity often results from hydrolysis reactions occurring in the soil. Aluminum ions on a mineral surface hydrolyze to produce H^+ , which attacks the clay surface to produce more acidity. Soil pH is a controlling factor for CEC and AEC, which in terms describes the ability of a soil to remove charged pollutants.

Soil and water pH also affect precipitation reactions. Many metals form sparingly soluble hydroxide precipitates at certain pHs. These precipitates would be expected to remain in the soil profiles once created, unless the soil and water pH change sufficiently to cause the precipitate to dissolve and the metal to be transported further.

7.3.3.6 Oxidation-Reduction Potential

Many metals in soil-water systems, such as iron and manganese, have the potential to change oxidation states. In oxidized soil-water systems, the system is electron deficient, and the higher oxidation states are more stable. The reverse is true for reduced environments. The implication for pollutant removal and retention is that the lower valence states of these metals

generally are more soluble. This solubility may be mitigated by the presence of ions that will react with these lower valence ions to form insoluble compounds. Soil-water mineral-ion properties affected by oxidation-reduction chemistry are the following:

- ◆ Mineral solubility
- ◆ Soil-water pH
- ◆ Mineral surface chemistry
- ◆ Availability/presence of certain species
- ◆ Persistence or toxicity of chemical species
- ◆ Salt content or electrical conductivity of the water solution
- ◆ Volatility of chemical species

(Evangelou, 1998).

The impact of redox chemistry on pollutant retention is especially important when infiltration devices go quiescent between storms. Water remains in the pores and microbial activity may consume the oxygen, converting the water from aerobic to anaerobic. This may result in the release of previously-captured pollutants. Adsorption under anaerobic conditions has been shown to lead to weaker bonding between phenolic compounds and activated carbon (Abuzald and Nakhla, 1994). As shown in Johnson et al. (2003) and Clark (2000), heavy metal retention, except for iron, was good under anaerobic conditions, but previously-trapped nutrients were released from the organic media.

7.3.3.7 Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio is defined as the ratio of the sodium concentration to the square root of the average of the calcium and magnesium concentrations. The ratio of these ions in the soil can affect radically the performance of a infiltration device that contains even relatively small amounts of clay in the soil-media mixture. Clays in soils with an excess of sodium ions, compared to calcium and magnesium ions, remain in a dispersed condition, and are almost impermeable to rain or applied water. A “dispersed” clayey soil is extremely sticky when wet, tends to crust, and becomes very hard and cloddy when dry. Water infiltration is therefore severely restricted.

An SAR value of 15, or greater, indicates that an excess of sodium will be adsorbed by the soil clay particles. SAR values near 5 also can cause problems, depending on the type of clay present. Montmorillonite, vermiculite, illite and mica-derived clays are more sensitive to sodium than other clays. The larger the amount of clay in the mixture, the more dramatic the problems, but even moderate amounts of clay in soil mixtures can cause degraded infiltration. Suarez, et al. (2006) reported that SAR values above 4 caused decreased infiltration rates in a clay soil; SAR levels starting above 2 degraded infiltration in a loam soil. Additions of gypsum (calcium sulfate) to the soil can be used to prevent the exchange of sodium onto the soil and allow it to pass freely through the soil column.

Even when soils have SAR values well below the critical values, if the runoff water contains comparatively high levels of sodium (such as snowmelt in areas using salt for de-icing control), an SAR problem may occur in the future. Again, these calculations indicate the

direction and relative severity of the potential problem. They cannot predict exactly the amount of degradation. If the runoff has a higher SAR than the soil, SAR problems may eventually develop. Seasonal changes in runoff sodium and leaching of sodium from the soil, results in variable conditions throughout the year. In some coastal areas, upwelling brackish groundwater may also affect an infiltration device's SAR status.

7.3.4 Leaching/Release of Pollutants from Soil during Infiltration

Soils are not chemically inert. They can react in various ways, even with clean water and have the potential to release pollutants into the infiltrating water. In studies of North Carolina bioretention devices, Hunt et al. (2006, 2007) investigated the potential of a low-phosphorus compost, measured as a P-index, to provide phosphorus removal from infiltrating stormwater. They found that low P-index compost/soil, provided consistent removal of phosphorus from the influent. Therefore, North Carolina recommends a low-phosphorus compost for their bioretention systems and ranges of acceptable P content have been established. The user is cautioned, however, about using the North Carolina numbers directly. A review of the literature found that, while P-index is calculated based the same six agricultural erosion/nutrient loss factors, the weighting of these factors varies around the country, depending on which factor is deemed most important to that geographic region. Future research will be required to determine P concentrations in the soil that encourage phosphorus retention by the media and reduce the amount of P leaching. Other potential pollutants that may be released from the media include those in the peat and compost rows of Table 8-4 for filtration media. Treese et al. (2009) demonstrated that disturbing soils to create an engineered media likely will release nutrients and sulfate for several storm events, with very elevated concentrations slowly decreasing to the concentrations found in undisturbed areas. In addition, disturbing the soil increased the likelihood of microbial transport in the soil (Katherine Baker, unpublished data).

7.4 Water Chemistry

The primary stormwater chemistry factors that affect pollutant removal in infiltration devices are pH, salinity, and the form and concentration of the pollutant in runoff. For organic pollutants, the K_{oc} and K_{ow} are important measures of organic pollutant partitioning between the soil and water.

7.4.1 Water pH and Salinity

As noted in the soil section, pH affects the ability of the soil to remove ions from water because of its effects on the CEC. The pH also affects the speciation of these pollutants in water. For example, the solubility of heavy metals typically has a parabolic shape with a minimum solubility typically in the range of natural waters. For phosphates and carbonates, the form of the phosphate or carbonate is highly dependent on the pH.

The ions that affect salinity (chloride, bromide, etc.) interfere with chemical reactions by depressing the activity of other ions. They also compete with the ionic form of pollutants such as nitrate and may occupy the limited removal sites in a soil instead of the pollutant. Salts also are regeneration fluids in ion-exchange resins. While most monovalent cations and anions (Na, Cl, Br, K) are only weakly bound to a resin/soil and may be easily displaced by a polyvalent ion (Ca, Mg, CO_3 , Cu, Pb, etc.), saturating the column with large concentrations of monovalent salts causes the displacement of captured polyvalent ions simply due to the concentration gradient

difference between the water and the soil. This releases the previously-trapped pollutants, potentially allowing them to pass through the column.

7.4.2 Predictors of Organic Pollutant Removal

Most organic compounds are hydrophobic and preferentially bind to the soil organic matter. The two primary predictors of the tendency of a compound to bind to soil organic matter are the octanol-water partitioning coefficient (K_{ow}) and the organic carbon-water partitioning coefficient (K_{oc}). Because of the magnitude of these coefficients, they often are reported as their log (base 10) values. The larger the K_{oc} and K_{ow} value, the greater the preference of the compound for the organic/soil phase and not for the water. As a general rule, compounds with a large K_{oc}/K_{ow} tend to be removed quickly in the organic layers of the soil and tend to remain there and not transport through the column.

7.4.3 Form of the Pollutants in Water

Much of the prior research in stormwater runoff divided pollutants into two categories, particulate-associated and dissolved, based on whether the pollutant passed through a filter of a particular size. As part of the efforts to better predict treatability of stormwater pollutants, current research (ASCE Task Committee on Gross Solids, 2009; Roesner et al., 2007; Morquecho et al., 2005; Pitt et al., 2004; Kim and Sansalone, 2008; Clark, 2000) has attempted to improve the prediction of pollutant associations with particle size. Clark (2000) investigated the association of heavy metals with stormwater solids in scrapyard runoff and found that most of the concentration was associated with particles smaller than 5 to 10 μm . Morquecho et al. (2005) agreed with this general conclusion when looking at stormwater outfalls. Large particles with higher relative pollutant concentrations were more prevalent in source-area runoff. Kim and Sansalone (2008) investigated highway runoff as a source area and found that much of the metal mass was associated with settleable particles (particles greater than 75 μm). This research shows that particulate associations control pollutant treatability with source-area treatment being preferable. This is a rapidly developing science and data gaps remain before it can be incorporated effectively into models.

7.5 Groundwater Contamination Potential

Appendix J describes several case studies (both in the laboratory and in the field) on stormwater infiltration through a variety of media. These case studies highlight that well-sited (even if it was unintentional) devices may treat many pollutants stormwater runoff for at least several decades without substantial migration to the groundwater. However, the case studies also show that monovalent ions, such as chloride and nitrate, are poorly treated in the soil under most conditions. Vegetation remains the only effective method of treatment of nitrate (through plant uptake), assuming that the water is retained in the root zone. The potential for contamination especially must be a concern in areas with well-drained soils, typically sands with low organic content. This contamination potential also is highest in areas where the water table is shallow or where two heterogeneous soil types intersect, e.g., where a sand and a separate gravel layer may abut each other. Goutaland et al. (2007) noted that these preferential flow paths had very high hydraulic conductivities, which may increase the likelihood of rapid groundwater contamination, even in areas where the soil chemistry indicates that removal should occur. Ives (1989) also noted preferential flow paths in sand filters used for water treatment. In some cases, groundwater contamination has occurred, especially in areas with shallow groundwater tables, inadequate pollutant removal ability, preferential flow paths existing in or under the infiltration system.

Infiltration and artificial recharge has its advantages and disadvantages. Even though disadvantages exist, they can be lessened through careful site and source water selection. This section describes two levels of modeling that can be used to evaluate a site and its runoff for groundwater contamination potential.

7.5.1 Simple Model to Predict Vadose Zone Treatability and Groundwater Contamination Potential

Unless an infiltration device is installed with an underdrain, stormwater will percolate to the groundwater with only the soil profile (either an engineered or natural soil) providing treatment. At some point in time, this treatment capacity may become exhausted. Therefore, methods are needed to predict the lifespan of infiltration devices. In addition, questions of finding a suitable site during the design phase have to be addressed. The prediction of groundwater contamination potential can be very complex, and it depends on the concentration and form of the pollutant, the characteristics of the soil, and the rate at which water moves through the soil. Mobility is compound-specific and depends on the soil matrix.

This section focuses on a simplified method that links, in a chart, the mobility of the pollutant, the fraction in the filterable (dissolved) phase, and the concentration of the pollutant. This information is combined with the information on the soil type and general soil reactivity to provide a mobility class depending on the type of infiltration device used.

Table 7-4 summarizes some of the pollutants found in stormwater that are of concern for groundwater contamination. Pitt et al. (1995) and Clark and Pitt (2007) used this information to examine risks associated with discharging stormwater to the subsurface and associated potential groundwater contamination. Characteristics that affect potential groundwater contamination include the following:

- ◆ High mobility (low sorption potential) in the vadose zone,
- ◆ High abundance (high concentrations and high detection frequencies) in stormwater, and
- ◆ High soluble fractions (small fraction associated with particulates that could be removed at the soil surface by straining, or by common sedimentation treatment).

The mobility classes are described in Tables 7-5 and 7-6 with Class I including mobile compounds. The mobility classes are based on the partitioning coefficients, k_D , between the pollutant and the soil. These mobility classes have wide ranges of k_D values because these soils have a range of values for their chemical properties, as described in Section 7.3.

Compounds that are very mobile should not be infiltrated if their concentrations are high, or pre-treatment and source control should be used to reduce the influent concentration. For example, sediment control is critical for long-term infiltration success since solids will clog infiltration devices, resulting in frequent maintenance or failure. In addition, solids' pretreatment will reduce the loading of particulate-bound pollutants (common) to the infiltration device. Pre-treatment that can remove dissolved fractions of the contaminants (rare) also increases the duration that the vadose zone soils can capture or sorb filterable pollutants by ion exchange, or other processes.

Table 7-4. Groundwater Contamination Potential for Stormwater Pollutants.

Compound Class	Compounds	Mobility (Worst Case: sandy/low organic soils*)	Abundance in stormwater	Fraction filterable (dissolved)
Nutrients	Nitrate	I	Low/moderate	High
Pesticides	2,4-D	I	Low	Low/moderate
	γ -BHC (lindane)	II	Moderate	Low/moderate
	Atrazine	I	Low	Low/moderate
	Chlordane	II	Moderate	Very low
	Diazinon	I	Low	Low/moderate
Other Organics	VOCs	I	Low	Very high
	1,3-dichlorobenzene	III	High	High
	Benzo(a)anthracene	II	Moderate	Very low
	Bis (2-ethylhexyl) phthalate	II	Moderate	Low/moderate
	Fluoranthene	II	High	High
	Naphthalene	II/III	Low	Moderate
	Phenanthrene	II	Moderate	Low/moderate
	Pyrene	II	High	High
Pathogens	Enteroviruses	I	Likely present	Moderate
	<i>Shigella</i>	II/III	Likely present	Moderate
	<i>P. aeruginosa</i>	II/III	Very high	Moderate
	Protozoa	II/III	Likely present	Moderate
Heavy Metals	Cadmium	III	Low	Moderate
	Chromium	III/IV	Moderate	Very low
	Lead	IV	Moderate	Very low
	Zinc	III/IV	High	High
Salts	Chloride	I	Seasonally high	High

NOTE: The mobility of pollutants such as organics and metals should decrease if the soil is clayey and/or has a higher organic content because these soils are more reactive with the passing pollutants compared to sandy soils. The mobility classes are described in Tables 7-5 and 7-6.

Modified from Pitt et al. 1994

Table 7-5. Mobility Classes for Organic Contaminants. (Modified from Armstrong and Llana, 1992)

Class	K_d	M_i
I – Mobile	< 0.1 to 1.0	0.1 to 1.0
II – Intermediate mobility	1.0 to 10.0	0.01 to 0.1
III – Low mobility	10.0 to 100.0	0.001 to 0.01
IV – Very low mobility	> 100.0	< 0.001

NOTE: K_d is the soil adsorption coefficient, mL/g

M_i is the mobility index (ratio of pollutant's migration velocity to migration velocity of water under saturated flow).

This simplified method (as summarized in Table 7-7) is based on the following assumptions. The contamination potential is the most critical rating of the influencing factors. As an example, if no pretreatment was to be used before percolation through surface soils, the mobility and abundance criteria are most important. The filterable fraction would not be important since no pretreatment for the removal of particulate pollutants is being used. If sedimentation pretreatment is to be used before surface infiltration, then some of the pollutants will likely be removed before infiltration. In this case, all three influencing factors (mobility, abundance in stormwater, and soluble fraction) are important. If subsurface injection (with minimal pretreatment) is used, then only abundance is important. If the pollutant is present in

high concentrations, it will likely have an adverse effect on the groundwater; attenuation through the vadose zone would be insignificant as the water would bypass it if using direct injection.

Table 7-6. Metal Mobility Classes. (Modified from Armstrong and Llena, 1992)

Inorganic Pollutant	Mobility Class* for:	
	Sandy Loam	Silt Loam
Arsenic	III and IV	III and IV
Cadmium	III	III and IV
Chromium	III and IV	II and III
Copper	IV	IV
Lead	IV	IV
Nickel	III	III
Zinc	III	III and IV

*Mobility Class Definitions:

I: mobile

II: Intermediate mobility

III: low mobility

IV: very low mobility

Table 7-7 is only appropriate for initial estimates of contamination potential because of the simplifying assumptions, such as the likely worst case mobility conditions using sandy soils having low organic content. If the soil was clayey and/or had a high organic content, then most of the organic compounds would be less mobile than shown on this table. The abundance and filterable fraction information is generally applicable for warm weather stormwater runoff at residential and commercial area outfalls. The concentrations and detection frequencies would likely be greater for critical source areas (especially vehicle service areas) and critical land uses (especially manufacturing industrial areas), with greater groundwater contamination potential.

7.5.2 Vadose Zone Computer Model for Predicting Groundwater Contamination Potential and Basin Lifespan

Many vadose zone water quality models were developed initially to predict plume migration beneath leaking landfills. They typically focused on the behavior of either organic or inorganic pollutants in the vadose zone. They may be adaptable to predicting contamination potential below infiltration basins. Clark et al. (2006) used one model, SESOIL (Seasonal Soil compartment model), for predictions because it is capable of modeling both organic and inorganic pollutants and allowed the user to modify chemical parameters as needed. The goal was not just to evaluate contamination potential but also to determine the data needs for using the model to predict lifespan and pollutant accumulation in the vadose zone.

SESOIL calculates mass balances and assumes equilibrium partitioning between phases. It contains three submodels to simulate contaminant fate and transport: the hydrologic cycle, sediment washload cycle, and pollutant fate cycle. The hydrologic cycle models the impact of rainfall, groundwater flow, surface runoff, capillary rise, soil moisture retention, infiltration, and evapotranspiration on the pollutant behavior. Next, the sediment washload cycle estimates the amount of erosion and sediment yield to predict the amount of contaminant removed from the system. Finally, the pollutant fate cycle combines natural attenuation of the compound with the values from the hydrologic and sediment washload cycles in a mass balance approach to predict the final fate of the contaminant. The natural degradation processes considered by SESOIL

include diffusion, volatilization, hydrolysis, adsorption, and biodegradation to its pollutant fate cycle (RISKPRO, 2003). However, the limitation of SESOIL was the inability to input detailed rain information and kinetics information for the chemical reactions.

Table 7-7. Groundwater Contamination Potential for Stormwater Pollutants Post-Treatment.

Compound Class	Compounds	Surface Infiltration and No Pretreatment*	Surface Infiltration with Sedimentation*	Subsurface Injection with Minimal Pretreatment
Nutrients	Nitrates	Low/moderate	Low/moderate	Low/moderate
Pesticides	2,4-D	Low	Low	Low
	γ -BHC (lindane)	Moderate	Low	Moderate
	Atrazine	Low	Low	Low
	Chlordane	Moderate	Low	Moderate
	Diazinon	Low	Low	Low
Other organics	VOCs	Low	Low	Low
	1,3-dichlorobenzene	Low	Low	High
	Benzo(a) anthracene	Moderate	Low	Moderate
	Bis (2-ethyl-hexyl) phthalate	Moderate	Low?	Moderate
	Fluoranthene	Moderate	Moderate	High
	Naphthalene	Low	Low	Low
	Phenanthrene	Moderate	Low	Moderate
	Pyrene	Moderate	Moderate	High
Pathogens	Enteroviruses	High	High	High
	<i>Shigella</i>	Low/moderate	Low/moderate	High
	<i>P. aeruginosa</i>	Low/moderate	Low/moderate	High
	Protozoa	Low	Low/moderate	High
Heavy metals	Cadmium	Low	Low	Low
	Chromium	Low/moderate	Low	Moderate
	Lead	Low	Low	Moderate
	Zinc	Low	Low	High
Salts	Chloride	High	High	High

NOTE: Overall contamination potential (the combination of the subfactors of mobility, abundance, and filterable fraction) is the critical influencing factor in determining whether to use infiltration at a site. The ranking of these three subfactors in assessing contamination potential depends of the type of treatment planned, if any, prior to infiltration.

* Even for those compounds with low contamination potential from surface infiltration, the depth to the groundwater must be considered if it is shallow (1 m or less in a sandy soil). Infiltration may be appropriate in an area with a shallow groundwater table if maintenance is sufficiently frequent to replace contaminated vadose zone soils.

Modified from Pitt et al., 1994 and Clark and Pitt 2007.

The list of reactions above require a tremendous amount of data, much of which is not available in the literature. Mikula (2005) performed a full factorial experiment with the model to determine which factors in the model were controlling the calculations and results. The purpose of this activity was to provide guidance as to where to focus data gathering and which parameters could be obtained from the literature. The literature identified three main soil properties that affect infiltration and pollutant removal: intrinsic permeability, organic content, and pH. Other factors beyond the soil itself also affect pollutant movement and groundwater contamination potential, including pollutant concentration, rainfall, and vadose zone thickness. Zinc and sodium chloride were chosen as representative pollutants of interest because of their prevalence in

stormwater, solubility, and differing migration rates. Results indicated that the rainfall amount was a common factor controlling zinc, sodium, and chloride migration. Since the zinc and sodium chloride were assumed to be dissolved in infiltrating stormwater, higher rainfall amounts would naturally allow the pollutants to migrate deeper in the vadose zone. In addition, concentrations were influential in Zn^{2+} migration. Higher concentrations of Zn^{2+} reduced the zinc sorption in any soil layer because the available sorption sites in the upper layers were filled before the zinc in the stormwater was completely removed. Therefore, while this was a simulation, it indicated that more effort should be spent on characterizing the rainfall amounts and runoff concentrations and less effort should be spent on determining partitioning coefficients.

This research used in-situ soil information for calculations. It did not address the substantial parameter differences seen in infiltration basins using engineered soils. In addition, as with most chemical computer models readily available, equilibrium was assumed and non-neutral hydrolysis could not be evaluated because no coefficients were available for the model. Therefore, soil pH was not a recognized significant factor in zinc migration because non-neutral-pH hydrolysis could not be modeled. In reality, zinc should be more mobile in acidic and alkaline soils because of its higher solubility during extreme pH conditions, although zinc is more soluble and more mobile in alkaline conditions only if organic matter is present (Shuman, 1999). For the narrow pH range of typical soils, pH may not be a significant factor. Organic matter also was not a significant controlling factor, even though filtration work has shown that organic matter affects zinc migration, as has other modeling of the soil's ability to trap organic pollutants (Kumar, 2008). The Mikula (2005) result is likely due to the lack of organic matter in the soils below the top layer.

7.6 Predicting Lifespan Based on Soil Chemistry Changes

The following section addresses three issues of concern regarding the lifespan of infiltration devices: the significance of clogging from the capture of sediment on the bioretention facility device, cation exchange capacity (CEC) consumption (a common measure of dissolved pollutant retention to protect groundwater), and sodium adsorption ratio (SAR) (to identify adverse infiltration rate effects due to destabilized clay fractions in the soil). The steps presented here have been previously published in Pitt et al. (2008).

The following tables summarize typical data for different soils, amendments, and plants that may be used in bioretention facilities. Table 7-8 shows the following characteristics, compiled from numerous stormwater treatability and urban soil projects (Clark and Pitt, 1999 with an extensive literature review; Pitt et al., 1999; Pitt and Lantrip, 2000; Pitt et al., 2008; Johnson et al., 2003). The critical soil characteristics for these evaluations include the following:

- ◆ Infiltration rate of the soil,
- ◆ Saturated hydraulic conductivity,
- ◆ Cation Exchange Capacity,
- ◆ Dry density of the soil (assumed to be slightly compacted)

The infiltration rates and saturated hydraulic conductivity for the mixtures should be based on the amount of amendment added (if 10% or greater), as shown in Table 7-9. Table

7-10 shows the anticipated properties for soil/amendment mixtures suggested for bioretention facilities.

The following paragraphs describe the calculations that can be used to estimate the approximate CEC capacity of infiltration media and potential SAR problems associated with the water and soil chemistry. These calculations are intended only to indicate the relative magnitude of the problem associated with these major issues in the operation of an infiltration device and should be confirmed by initial laboratory tests, followed by actual long-term field monitoring of similar facilities in the area.

Table 7-8. Typical Soil Properties for Different Soil Textures and Organic Amendments.
(Clark and Pitt, 1999; Pitt et al., 1999; Pitt and Lantrip, 2000; Pitt et al., 2008; Johnson et al., 2003)

Soil Texture	Infiltration Rate (in/hr) ¹	Saturated Hydraulic Conductivity (in/hr)	CEC (cmol/kg or meq/100 gms)	Dry density (grams/cm ³) ²
Coarse Sand and Gravel	40	500	1	1.6
Sands	13	50	2.5	1.6
Loamy Sands	2.5	5	5	1.6
Sandy Loams	1	2.5	8	1.6
Fine Sandy Loams	0.5	0.5	10	1.6
Loams and Silt Loams	0.15	0.005	12	1.6
Clay Loams and Silty Clay Loams	0.1	0.01	20	1.6
Silty Clays and Clays	0.05	0.015	30	1.6
Peat as amendment	3	3	300	0.15
Compost as amendment	3	3	15	0.25

¹ assumed to be slightly compacted

Table 7-9. Infiltration Rates and Saturated Hydraulic Conductivities for Amendment Mixtures. (Pitt et al., 1999)

Organic amendment (% of total mixture)	Infiltration rate (in/hr), assumed to be slightly compacted	Saturated hydraulic conductivity (in/hr) (same as infiltration rate)
10	1	1
33	2.1	2.1
50	2.5	2.5
100	3.0	3.0

Table 7-10. Example Characteristics for Bioretention Mixtures.

Soil Texture	Infiltration Rate (in/hr) assumed to be slightly compacted	Saturated Hydraulic Conductivity (in/hr)	CEC (cmol/kg or meq/100 gms)	Dry density (grams/cm ³), assumed to be slightly compacted
33% compost amend. to loam	2.1	2.1	13	1.15
10% compost amend. to loam	1	1	12	1.47
50% peat amend. with sand	2.5	2.5	150	0.88

The total cation content of a water sample can be directly calculated knowing the major ion content of the water and the associated equivalent weights, as shown on Table 7-11. The sum of the cations must equal the sum of the anions (expressed in equivalent weight).

Table 7-11. Example Total Cation Content Calculation for Stormwater. (Adapted from Johnson et al., 2003).

Component	mg/L	Equivalent weight	meq/L
Ca ²⁺	13.3	20.0	0.67
Mg ²⁺	3.3	12.2	0.27
Na ⁺	3.9	23.0	0.17
K ⁺	2.3	39.1	0.06
		Total cations:	1.17
HCO ₃ ³⁻	36.7	61.0	0.60
SO ₄ ²⁻	22.4	48.0	0.47
Cl ⁻	3.7	35.5	0.10
		Total anions:	1.17

The above example only lists the major ions in the water. However, the concentrations of the dissolved heavy metals in stormwater are rarely more than about 0.10 mg/L and therefore contribute little to the total cation content of the water. The total (unfiltered) heavy metal concentrations of some metals can be much higher, but only the ionic forms affect the CEC. The total hardness of the above sample (the sum of the divalent cations) is 0.94 meq/L, and with an equivalent weight of 50 meq/L per mg/L as CaCO₃, the resulting hardness concentration is about 47 mg/L.

The maximum consumption of the CEC in the soil can be calculated by dividing the soil total CEC by the total cation content of the water. If the soil is ½ meter thick, and the soil density is about 1.5 grams/cc, the total CEC of a soil having a CEC of 10 meq/100 grams, per m², is approximately 75,000 meq. If the stormwater has a total cation content of about 1.2 meq/L, then the total maximum water treatment capacity of the soil, per square meter, is about 64,000 L, or a column of water about 64 m high. If the soil is only receiving runoff with a cation content of 1.2 meq/L and 1 m of rain falls per year, then the CEC content of the soil would be exhausted in about 60 to 70 years. The natural soil building process, and accumulating layers of organic material, would continue to “recharge” the soil CEC in an undeveloped setting, with very slow changes in the soil CEC with time. In an urban infiltration device, where substantial amounts of runoff are directed to the device, the CEC of a soil would be exceeded much faster.

As described earlier, the sodium adsorption ratio can affect the stability of the soil structure and thus, the infiltration rate. The SAR is calculated by using the soil concentrations of sodium, calcium, and magnesium (in meq) in the following formula:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{(Ca^{+2} + Mg^{+2})}{2}}}$$

Even when soils have SAR values well below the critical values, if the runoff water contains high levels of sodium in relationship to calcium and magnesium (such as snowmelt in areas using salt for de-icing control), an SAR problem may occur in the future, necessitating the addition of gypsum to the infiltration area. Again, these calculations indicate the direction and relative severity of the potential problem.

7.7 Selecting an Engineered Soil Media

As the case studies in Appendix J illustrate, natural soils can provide treatment of stormwater runoff. In addition, as Treese et al. (2009) showed, disturbing soils can increase their tendency to leach pollutants such as nutrients. These studies also, however, illustrate that increasing certain soil properties, such as hydraulic conductivity and sorption/ion-exchange potential, can improve pollutant treatment. New media, and media combinations, are proposed regularly for installation in stormwater infiltration devices. However, many of these media are not screened properly prior to use, resulting in decisions regarding lifespan and maintenance intervals that are based on incomplete information. This section addresses the concerns and the steps required to evaluate properly infiltration media.

7.7.1 Properties that Affect Media Performance

Prior filter and soil amendment media tests have shown that the hydraulic flow rate and particulate solids loadings on the surface greatly affect the performance of the system. A medium with high filtration rates does not provide adequate contact time, thus resulting in reducing pollutant removals. However, a medium that has a very low infiltration rate creates extended surface ponding or requires large surface areas or deep freeboard space above the media. Therefore, a balance between hydraulic capacity/contact time and pollutant removal is critical for a successful system. In addition, clogging of the surface, or pores, of the media often causes premature failure of the system. Particulate solids (and their particle size distribution) are critical parameters in determining the longevity of a filter run and how the flow rate decreases with time and use. Other fouling constituents (such as oil and grease) also affect performance and need to be evaluated. These constituents need to be monitored as part of a media evaluation study, in order to supplement the data gathered on the behavior of the targeted pollutants. These other issues that affect media removal of stormwater pollutants include the following. These characteristics were described earlier in this chapter (Sections 7.3 and 7.4).

- ◆ Stormwater salinity,
- ◆ Oxidation-reduction potential (ORP) and dissolved oxygen (DO) concentrations of the potential stormwater,
- ◆ pH,
- ◆ Phosphorus content on the soil/infiltration media
- ◆ Cation exchange capacity (CEC) and concentrations of major cations and certain metals,
- ◆ Sodium adsorption ratio (SAR).

Additional constituents should/must be monitored when evaluating media in order to understand the removal mechanisms, and how the media may change if the stormwater characteristics change. Some of these additional issues include the following:

- ◆ Exchangeable cations and anions. Major cations and anions need to be monitored to evaluate which are being exchanged as targeted pollutants are being removed. If major ions are being removed by the media, the space available for targeted pollutant removal is reduced. The targeted pollutants, if they are loosely bound through ion-exchange, also may be lost if an ion is preferentially attracted to the same site in the media.

- ◆ Organic compounds. The presence of organic compounds adds to the CEC of the mixture and also provides a basis for organometallic compounds to form stable complexes. However, organic toxicants may also be present and their behavior in the media needs to be considered.
- ◆ Metallic compounds. Total metal removal typically is of interest to treatment professionals and regulators. However, it is the filtered forms of the metals are usually of most interest considering harmful effects on humans and wildlife. The filtered forms also are those exchanged by ion-exchange processes in the media.
- ◆ Bacteria. Stormwater indicator bacteria are normally critical contaminants, but the presence and retention of bacteria should be evaluated in media used for capturing stormwater pollutants as increased indicator bacteria in the media are a good indicator of beneficial bacteria that are needed to assist in the degradation of captured organic material. In addition, bacterial activities in media may aid in pollutant removal through several mechanisms, including creation of additional sorption capacity, creation of exopolymers that attract positively-charged pollutants, etc. A brief summary of bacterial removal mechanisms is given in Clark (2000) and Clark et al. (2006).
- ◆ Nutrients. Nitrogen and phosphorus compounds are also often critical stormwater constituents and their retention in media filters can also indicate replenishment of plant nutrients needed to support plant growth.

7.7.2 Tests Required for Complete Media Evaluation

Four tests are recommended for evaluating potential stormwater infiltration media, including 1) clogging, breakthrough, and removal tests; 2) contact time/media depth tests; 3) batch capacity and kinetics tests; and 4) pollutant retention under aerobic versus anaerobic conditions. These tests are summarized below.

7.7.2.1 Clogging, Breakthrough, and Removal Tests

The purpose of these tests is to simultaneously determine several important stormwater filter media characteristics, including pollutant removal and effluent quality, treatment flow rates, and losses in both pollutant removal and flow rate performance associated with clogging and breakthrough as the media becomes exhausted. The evaluation should be performed to mimic field conditions to the maximum extent possible. Prior testing (Johnson et al., 2003) showed that stormwater, with its intermittent flows and relatively low concentrations (compared to industrial wastewater where traditional media evaluation has been performed), is not as easily treated as industrial wastewater. The low concentrations reduce the concentration gradient for sorption/ion-exchange and the intermittent flows often result in variable pore water chemistries that affect both the quality of the first flush from the filter in a new storm event and the potential availability of removal sites in the media. Therefore, application of high-concentration, continuous-flow testing results to predicting the life of stormwater filters rarely has been successful. Laboratory testing, both batch and continuous flow, has been most successful when the test solution and concentrations most resemble the actual runoff.

7.7.2.2 Contact Time – Media Depth Tests

A significant factor affecting stormwater pollutant removal in infiltration devices is treatment flow rate and the associated contact time. The treatment flow rate can be adjusted by

modifying the media with other materials, such as sand. Contact time also is affected by the depth of the media in the column with deeper media, obviously, having greater contact times.

7.7.2.3 Media Capacity Tests

These traditional isotherm and kinetics batch tests are used to determine the amount of contaminant that can be retained by the media and the rate at which the pollutant is retained. Contact time should be based on the kinetics of the pollutant removal. While traditional batch testing often is only a moderate predictor of performance in stormwater filter columns, knowledge of the parameters allows comparisons of these media to traditional filter media. Also, as modeling improves, many modelers are relating traditional parameters to actual field performance. The results are applied in situations where the desired effluent concentration and given influent concentrations, as well as the flow rates, are known, and the mass of pollutant requiring removal can be calculated as the difference. The amount of media required for pollutant removal then is predicted based on the desired effluent concentration and the amount of pollutant requiring removal.

7.7.2.4 Aerobic and Anaerobic Effects on Contaminant Retention in Media

These tests are used to determine whether pollutant retention is permanent in filter media when the chemical conditions inside the filter change. While most stormwater, and therefore its filtration, occurs under aerobic (> 1 mg/L DO) conditions, stormwater filters only treat flows periodically. Clark (2000) showed that filters do not dry out completely between storm events, with water retention occurring for several months after active flow events. Drying only occurs within the first 1-2 inches of the media exposed to the atmosphere (if free draining, drying may occur at both the surface and at the interface with the drainage layer). Therefore, these wet/damp areas have the potential to develop anaerobic conditions in parts of the media. Because anaerobic conditions often are associated with reducing environments and the prevalence of anaerobic/anoxic bacteria, pollutant retention may be changed. Clark (2000) and Clark and Pitt (2009) showed in a series of preliminary tests that permanent retention of nutrients and metals such as iron that are not strongly bound to the media was a concern. Organic media were a particularly concern for pollutant retention. This is particularly a concern as certain research is indicating that creating an internal storage zone (ISZ), where water is deliberately retained in the gravel drainage layer between storms, reduces nitrate in the effluent through denitrification (Sharkey and Hunt, 2005). The question not addressed in the literature is whether creation of an anaerobic zone in the filter results in unacceptable releases of other pollutants.

CHAPTER 8.0

SURFACE TREATMENT OF STORMWATER — SEDIMENTATION AND FILTRATION

8.1 Introduction

While infiltration is becoming the preferred stormwater treatment mechanism because of its ability to provide groundwater recharge, there are sites where infiltration either cannot treat the entire flow for the range of storms requiring treatment or where infiltration cannot be used due to the potential for groundwater contamination. Therefore, the use of surface-based devices such as detention/sedimentation ponds and filters must remain part of the stormwater management toolbox.

In Chapter 5.0, the user was guided through the process of considering/describing the quality of stormwater runoff on the site and identifying/listing the problem pollutants requiring treatment. Now, these pollutants and flows that cannot be treated by infiltration need to be attributed to sources and the surface control practices that will be expected to treat them. Sedimentation is discussed in Section 8.3 and filtration in Section 8.4.

8.2 Known Stormwater Treatment Ability of Detention and Filtration Systems

Many studies have evaluated the pollutant removal of stormwater detention/wetland and filtration systems. One such project that has evaluated existing control practice performance (based on reported monitoring data) is the International Stormwater BMP Database (www.bmpdatabase.org). The BMP Database contains the results of multiple studies around the world on these treatment devices. Table 8-1 highlights the results of the 2007 statistical summary for these devices (bmpdatabase.org 2007 Performance Summary).

Table 8-1. Median Influent and Effluent Concentrations of Stormwater Control Practices.

		Suspended Solids (mg/L)	Nitrate-Nitrogen (mg/L)	TKN (mg/L)	Nitrogen, Total (mg/L)	Phosphorus, Dissolved (mg/L)	Phosphorus, Total (mg/L)	Cadmium, Total (µg/L)	Cadmium, Dissolved (µg/L)
Detention Pond	Influent	73	0.70	1.5	1.3	0.09	0.19	0.71	0.24
	Effluent	27	0.48	1.5	2.2	0.09	0.19	0.47	0.25
Wet Pond	Influent	38	0.36	1.3	1.5	0.09	0.21	0.41	0.19
	Effluent	10	0.20	1.0	1.3	0.05	0.10	0.27	0.11
Wetland Basin	Influent	31	0.37	1.1	1.5	0.08	0.27	0.34	NA
	Effluent	13	0.13	1.1	1.2	0.08	0.11	0.24	NA
Media Filtration Device	Influent	43	0.41	1.5	1.3	0.09	0.20	0.25	0.16
	Effluent	11	0.66	1.2	0.74	0.08	0.11	0.19	0.13
Hydrodynamic Separator	Influent	41	0.40	1.1	1.3	0.06	0.24	0.74	0.33
	Effluent	23	0.29	1.2	1.6	0.05	0.20	0.57	0.31

Table 8-1. Median Influent and Effluent Concentrations of Stormwater Control Practices (cont.).

		Copper, Total (µg/L)	Copper, Dissolved (µg/L)	Chromium, Total (µg/L)	Lead, Total (µg/L)	Lead, Dissolved (µg/L)	Zinc, Total (µg/L)	Zinc, Dissolved (µg/L)
Detention Pond	Influent	20	5.9	7.4	25	1.3	110	24
	Effluent	16	8.3	3.2	15	1.3	59	28
Wet Pond	Influent	9.5	7.3	6.0	14	3.0	61	39
	Effluent	5.6	4.4	1.4	3.4	1.9	22	29
Wetland Basin	Influent	5.6	NA	NA	4.5	0.50	47	NA
	Effluent	3.4	NA	NA	2.5	0.76	29	NA
Media Filtration Device	Influent	15	7.8	2.2	11	1.4	92	69
	Effluent	7.6	7.0	1.5	2.6	0.86	32	32
Hydrodynamic Separator	Influent	15	14	4.1	18	1.9	120	36
	Effluent	12	12	3.5	5.1	1.7	75	34
Pervious Pavement	Influent ^b	NA	NA	NA	NA	NA	NA	NA
	Effluent	2.8	NA	NA	7.9	NA	17	NA

One pollutant of concern in urban runoff that these devices are not designed to treat is temperature. Studies on temperature and surface-treatment devices can be found in Appendix K. Kieser et al. (2006), for example, researched stormwater thermal enrichment of urban streams. They developed a heat transfer model to evaluate the thermal mechanisms leading to increased temperature.

The user should note that, while this chapter focuses on treatment prior to surface discharge of the water to a receiving body or to a separate storm sewer system, treated water also may be clean enough to discharge directly to the groundwater, if allowed, through underground injection wells. The treated water also could be directed to an infiltration area. Depending on the effluent water quality, this infiltration area may be in a location where the soils cannot provide substantial treatment, e.g., sandy soils with very low CEC.

8.3 Sedimentation

8.3.1 Basic Design Guidance

If well designed and properly maintained, suspended solids removals of 70-90% can be obtained in wet ponds, while dry ponds provide less than 30% suspended solids reductions. Therefore, there are a number of basic design issues to be addressed to ensure that sediment removal is maximized while potential problems are minimized.

- ◆ Permanent standing pool needed for improved stormwater treatment. Generally, 1 m of standing water is recommended to prevent the scour of previously-captured sediments. Additional depth is needed for sediment storage between cleanout operations.
- ◆ The pond length should be about three to five times the width for maximum detention efficiency. The inlets and outlets need to be widely spaced to minimize short-circuiting.
- ◆ Correct pond side slopes are very important to improve safety and to minimize mosquito problems. An underwater shelf near the pond edge needs to be planted with rooted aquatic plants to hinder access to deep water.

- ◆ Outlet structures should be designed for low outflows during low pond depths to maximize particulate retention. Place underwater dams or deeper sediment trapping forebays near pond inlets to decrease required dredging areas.
- ◆ Protect the inlet and outlet areas from scour erosion and cover the inlets and outlets with appropriate safety gratings.
- ◆ Provide an adequate emergency spillway.

Basic pond design guidelines must also be followed to provide the expected level of sediment removal. The following list is a typical example of these guidelines:

- ◆ Engineering design guidelines (covering such things as foundations, fill materials, embankments, gratings, anti-seep collars, and emergency spillway construction), such as published by the U.S. Natural Resources Conservation Service and the Corps of Engineers (SCS, 1982) must be followed.
- ◆ Desired particle size control. Pond size is dictated mostly by desired particle control and water outflow rate. This can be calculated using Stoke's Law and then accounting for potential short-circuiting or can be estimated as a fraction of drainage area based on land use and desired particle size for control (Section 8.3).
- ◆ Safety Issues (Marcy and Flack, 1981; Jones and Jones, 1982; Eccher, 1991)
- ◆ Maintenance

8.3.2 Design Fundamentals

The two basic design approaches for wet detention ponds consider either slug flow or completely mixed flow. Martin (1989) reviewed these flow regimes and conducted five tracer studies in a wet detention pond/wetland in Orlando, FL, to determine the actual flow patterns under several storm conditions. Historically, wet detention ponds have been designed using the plug flow concept, probably because it agreed with the logical thought that water entered at one end of the pond and traveled across the pond as a slug with the water becoming cleaner throughout its travels. In reality, detention ponds exhibit a combination flow pattern that Martin terms moderately mixed flow. He found that the type of mixing that actually occurs is dependent on the ratio of the storm volume to the pond storage volume (the flushing ratio).

This section will describe the upflow velocity design concept for pollutant control. Other methods, such as NRCS TR-55's Chapter 6, can be used to size detention ponds based on the desired volume of water requiring temporary storage.

This section will not describe the routing methods used to describe water transport through the pond. The user is referred to a fundamental hydrology textbook. Routing of the water through the pond is a function of the outlet structure and its allowable flow rate. Therefore, the routing methods should be referenced when designing outlet structures to mimic pre-development hydrographs.

8.3.2.1 Upflow Velocity Design Concept

This discussion is based on design concepts found in any fundamental water treatment textbook (e.g., Viessman et al., 2008). In an ideal system, particles that do not settle below the elevation of the bottom of the outlet will pass through the sedimentation pond, while particles

that do settle below/before the outlet will be retained. The path of any particle is the vector sum of the water velocity (V) passing through the pond and the particle settling velocity (v). Therefore, if the water velocity is slow, slowly falling particles can be retained. If the water velocity is fast, then only the heaviest (fastest falling) particles are likely to be retained. The critical ratio of water velocity to particle settling velocity must therefore be equal to the ratio of the sedimentation pond length (L) to depth to the bottom of the outlet (D) (Figure 8-1).

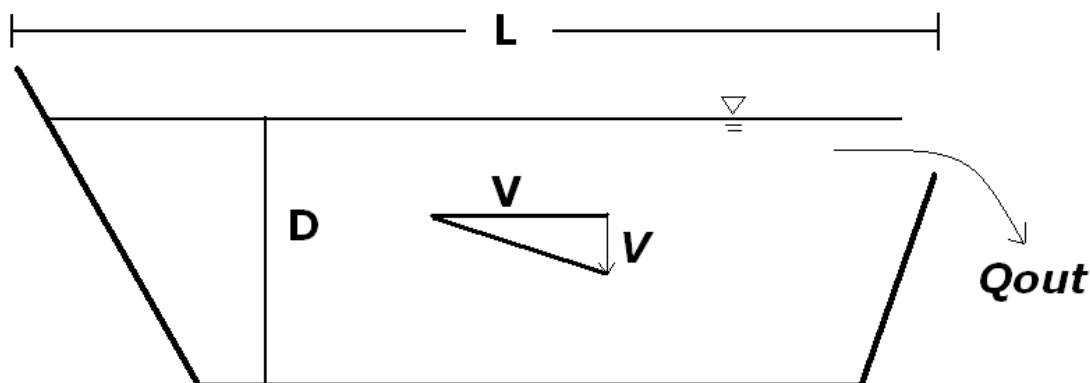


Figure 8-1. Critical Velocity and Pond Dimensions.

The water velocity is equal to the water volume rate (Q , such as measured by cubic feet per second) divided by the pond cross-sectional area (A , or depth multiplied by width: DW). The pond length (L) times pond width (W) equals pond surface area (A). Substituting leaves the definition of upflow velocity:

$$v = \frac{Q_{out}}{A} \quad \text{Equation 8-1}$$

where Q_{out} = pond outflow rate (cubic feet per second),

A = pond surface area (square feet: pond length times pond width), and

v = upflow velocity, or critical particle settling velocity (feet per second).

Therefore, for an ideal sedimentation pond, particles having settling velocities less than this upflow velocity will be removed. Only increasing the surface area, or decreasing the pond outflow rate, will increase pond settling efficiency. Increasing the pond depth does lessen the possibility of bottom scour, decreases the amount of attached aquatic plants, and decreases the chance of winter kill of fish. Deeper ponds may also be needed to provide sacrificial storage volumes for sediment between dredging operations.

8.3.2.2 Settling Velocity for the Critical Particle Size

Ideal settling in a sedimentation pond is modeled typically assuming spherical particles that do not interact with each other. Each particle is assumed to settle discretely, and electrostatic charges are assumed not to exist on the particles to such an extent as to affect sedimentation predictions. If these assumptions do not hold true (such as for waters with a high clay content),

the reader is referred to fundamental water treatment books for information on predicting sedimentation in those cases.

Stoke's Law (Equation 8-2) is used to predict the critical particle settling velocity.

$$v = \frac{gd^2(\rho_w - \rho_p)}{18\mu} \quad \text{Equation 8-2}$$

Where v = critical settling velocity

g = gravitational constant

d = diameter of the particle of the critical size to be captured

ρ_w = density of water

ρ_p = density of particle

μ = absolute viscosity of water

The critical settling velocity for the particle size of interest then is inserted into Equation 8-1 with the known stormwater design flow to calculate the pond surface area.

8.3.3 Short-Circuiting in Detention Ponds

The calculations in Sections 8.3.2.1 and 8.3.2.2 assume “ideal” conditions. However, detention ponds do not operate “ideally.” Therefore, it has to be accepted that the performance will be less than what is predicted using Equations 8-1 and 8-2. The question is the amount of non-ideality. Some sedimentation guidance suggests that efficiencies are as low as 60%; however other studies have found efficiencies, compared to ideal, to be much higher because these ponds are typically operating at velocities much lower than the critical settling velocity for the design storm. Short-circuiting can be predicted using the basic Hazen theory described in Fair and Geyer (1954) or assumed using a correction factor. In general, short circuiting has not significantly reduced the effectiveness of the pond (measured as the percentage of suspended solids captured). Therefore, care should be taken in locating and shaping ponds to minimize short circuiting problems. Poor pond shapes probably cause greater problems by producing stagnant areas where severe aesthetic and nuisance problems originate. Good pond designs have simple shapes (typically rectangular, but may have flared openings on the inlet and tapering to the outlet to reduce the development of stagnant areas alongside the inlet and outlet structures), with minimal side areas where water may stagnate. Water-quality ponds use primary outlet structures, such as V-notch weirs, which provide good flow rate control. They have trash racks or slightly submerged outlets so that floatable debris does not exit the pond. One example of a poor pond shape, with the inlet and outlet are side-by-side, is shown in Figure 8-2. This pond also has no trash screens.

Many researchers have published results of detention pond studies, including studies of both dry and wet ponds. For example, Anderson et al. (2002) summarized a series of research studies on existing ponds and highlighted critical factors in pond design and operation that lead to success or failure. Barrett (2004) summarized the pond results in the International BMP Database. Many of these studies are listed in Appendix K. In addition, several authors have written about the design of good detention ponds and of outlet structures. A few of the references

on this topic include McCuen (2004), Minton (2005), Pitt et al. (2007); plus the additional references on Pitt's website at <http://unix.eng.ua.edu/~rpitt/Publications/Publications.shtml>.



Figure 8-2. Poorly Designed Detention Pond (Distance and Close-Up View).

8.3.4 Enhancements to Sedimentation and Evaluations of Manufactured Sedimentation Devices

Sedimentation devices require the commitment of large land areas, which may not be desirable. Therefore, enhancements to sedimentation have been explored by manufacturers of underground, in-line stormwater settling devices. The goal is to reduce the footprint of the sedimentation device. The two methods commonly used by these manufacturers are swirl concentrators and inclined plates. The ASCE Task Committee on Manufactured Treatment Devices has developed both laboratory and field protocols for these devices to ensure that they are evaluated in a similar manner so that device performances can be compared. This work will be published in 2009. Early work in device comparisons and evaluations has been performed by Dr. Guo of Rutgers University, Dr. Clark of Penn State Harrisburg, Dr. Gulliver of the University of Minnesota, plus the activities of Dr. Stenstrom of the University of California at Los Angeles and the California Department of Transportation (CALTRANS).

8.4 Filtration

Physical filtration is a straining mechanism. Particles are trapped when they are too large to flow through the connected pores of a medium or when they end up in a pore that is not connected to the filter exit. One example of a filter that operates primarily through physical straining of pollutants is a new sand filter. Chemical and biochemical reactions that may occur in filters typically improve stormwater pollutant removal. These may occur through the addition of a medium that has removal potential such as an ion-exchange resin, a sorption media, or the buildup of biologically and chemically active biofilms. Stormwater filters also have been well-studied and can provide excellent removals of heavy metals and phosphorus, depending on the media used. The parameters controlling their behavior are identical to those used in infiltration devices. The reader is referred to Chapter 7.0 and in particular to Section 7.7.1. These properties are briefly summarized here.

8.4.1 Properties that Affect Media Performance

Prior filter and soil amendment media tests have shown that the hydraulic flow rate and particulate solids loadings on the surface greatly affect the performance of the system. Particulate solids (and their particle size distribution) are critical parameters in determining the longevity of a filter run and how the flow rate decreases with time and use. Other fouling constituents (such as oil and grease) also affect performance and need to be evaluated. These constituents need to be monitored as part of a media evaluation study, in order to supplement the data gathered on the behavior of the targeted pollutants. These other issues that affect media removal of stormwater pollutants include the following. These characteristics were described earlier (Sections 7.3, 7.4, and 7.7).

- ◆ Stormwater salinity,
- ◆ Oxidation-reduction potential (ORP) and dissolved oxygen (DO) concentrations of the potential stormwater,
- ◆ pH,
- ◆ Cation exchange capacity (CEC) and concentrations of major cations and certain metals,
- ◆ Sodium adsorption ratio (SAR),
- ◆ Stormwater exchangeable cations and anions,
- ◆ Organic compounds,
- ◆ Metallic compounds,
- ◆ Bacteria,
- ◆ Nutrients.

8.4.2 Characteristics of Media Previously Evaluated for Stormwater Treatment

Clark (2000) and Johnson et al. (2003), after an extensive literature review, evaluated several filtration media for their potential to treat stormwater pollutants. The media were commercially available, with the exception of the two fibrous materials. The primary characteristics of the media that was anticipated to affect pollutant removal were grain size and CEC. The grain size distributions of the media are given in Table 8-2 and Figure 8-3. The CECs of the selected media are presented in Table 8-3. The uniformity coefficient (calculated as d_{60}/d_{10}) values indicate that, for sand, carbon, and zeolite, most of their particles are in a narrow size range, while, for the compost and the peat, there are a wide range of particles in the mixture. Traditional filter design in water and wastewater treatment encourages the use of media with a small uniformity coefficient because the pores in the filter would then tend to be more evenly sized and also the fine particles in the media are much less likely to be washed through the filter during operation.

Table 8-2. Sieve Size Analysis of Non-Fibrous Media.

Media	d_{10} (mm)	Uniformity Coefficient
Sand	0.27	2.52
Activated Carbon	1.3	2.54
Peat	0.08	14.4
Compost	0.11	9.09
Zeolite	1.6	2.31

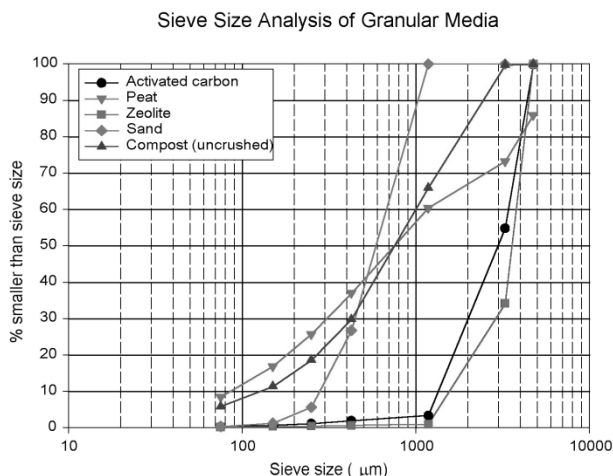


Figure 8-3. Sieve Size Analysis of Granular Media (Clark, 2000). Reprinted with permission.

Table 8-3. Cation Exchange Capacity of Filtration Media.

Medium	Cation Exchange Capacity (meq/100 g)
Peat Moss	21.47
Compost	18.83
Agrofiber	9.36
Zeolite	6.87
Activated Carbon	5.40
Cotton Waste	3.77
Lightweight Sand (used in Jacuzzi Filter)	3.20
Sand	3.49

As expected based on the literature review, the media with the highest CECs were the compost and the peat. All of the selected media, even the cotton textile waste, had CECs greater than the sand. This indicated that the use of a mixed media filter, rather than a pure sand filter, would provide greater removal of cations, such as metals. The CECs determined for peat and compost are in the range given by Watts (1998) for a silt loam soil, as would be expected with their organic content. The other media are generally in the range of sandy soils, also as would be expected.

Other media have been evaluated for their potential to remove stormwater pollutants both in the laboratory and in field applications. For example, Johnson et al. (2003) and Gill (2004) investigated several zeolites, in addition to the media listed above, for their behavior in stormwater filters. Long, et al. (2008) investigated expanded shales, slates and clays for their pollutant removal ability as part of green roof media systems. Smith (2008) proposed a dual filter setup to improve denitrification. The Contech Stormwater Solutions library has an extensive series of publications on the use of compost and perlite in their manufactured filter devices.

8.4.3 The Media as a Source of Pollutants

One concern with the use of filtration/sorption/ion exchange media is that the media itself can contribute undesirable pollutants to its effluent water. Treese et al. (2008) documented the

effect of disturbing a natural soil profile on effluent quality. The research noted initial nitrogen concentrations in the effluent of greater than 50 mg/L with several storms required before the nitrogen levels approached those in the same soil, but undisturbed, after the same time period. A summary of the potentially leachable pollutants for each media is given in Table 8-4.

Table 8-4. Summary of Potentially Leachable Compounds from Media.

Media	Compounds Potentially Leached
Sand	Turbidity, ammonium
Granular Activated Carbon	Sulfate, dissolved copper
Peat-Sand mixture	Turbidity, ammonium, potassium, color, dissolved copper
Compost-Sand mixture	Turbidity, carbonate, bicarbonate, phosphate, ammonium, potassium, magnesium, calcium, hardness, color, total copper, dissolved copper
Kenaf Agrofiber-Sand	Turbidity, carbonate, ammonium, potassium, total copper, dissolved copper
Cotton Waste-Sand	Turbidity, carbonate, ammonium, potassium, total copper, dissolved copper

8.4.4 Modeling the Pollutant Removal Ability of Stormwater Filters (Adapted from Clark, 2000)

Pollutant removals by filter media have a long modeling history. However, much of the research has been performed in the water and industrial wastewater industry where influent concentrations are high, consistent, and well-characterized. Stormwater's high variability in loadings, flow rates and pollutant concentrations greatly affects modeling.

Johnson et al. (2003) and Gill (2004) investigated batch testing as a method to predict the kinetics of metals removal by stormwater media, plus the capacity of the media for the various pollutants. Their results (Figure 8-4a for capacity using industrial waste concentrations; Figure 8-4b for capacity using typical stormwater concentrations) showed that media such as bone char and industrial resins have large capacities at high challenge concentrations, but their adsorption isotherms are unfavorable and their capacities are low at the low concentrations typical of stormwater. Therefore, for modeling, it is important to ensure that the constants in the equations are derived using concentrations typical of stormwater (preferably the challenge solution will be stormwater or a spiked stormwater).

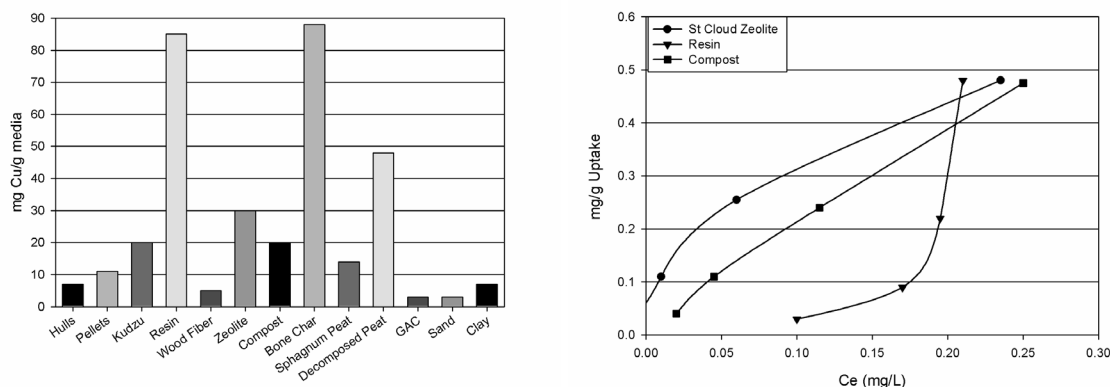


Figure 8-4. a. Capacity of Various Potential Stormwater Filtration Media Using High-Concentration Solution. b. Capacity of Three Media Using Typical Stormwater Concentrations. (Johnson, et al. 2003. Reprinted with permission).

Ideally, a column filtration model would be used to predict pollutant removal in stormwater filters. While several models exist for modeling pollutant removal in industrial waste filters, this brief discussion will focus only on the Bed-Depth Service Time (BDST) model developed by Bohart and Adams (1920) and applied to stormwater filtration in Clark (2000) and Johnson, et al. (2003). The concerns raised in this exercise apply generally to stormwater filtration modeling. The equation results in a traditional S-shaped breakthrough curve.

This model was applied to the prediction of pollutant removal in several stormwater filters during a pilot-scale study. Figure 8-5a shows the pilot-scale results for copper and Figure 8-5b for magnesium. The field results, however, show that rarely did the data follow the S-shaped curve and therefore, the model could not be calibrated to predict pollutant removal in the filters. It is likely that there are two reasons why the modeling did not work. First, the stormwater runoff had very low initial concentrations of pollutants, resulting in a very weak concentration gradient between the water and media. This leads to poor removals since there are few pollutant ions and therefore, a reduced chance of successful interactions between appropriate media sites and the pollutants. In addition, there is a very weak driving force for the reactions, and equilibrium between the concentration of pollutants on the media and in the water may be occurring with little removal. The media which had the best fit to the model was the peat-sand media for removing magnesium from the water. This is likely because peat moss typically is deficient in divalent cations such as magnesium. Even then, the laboratory-predicted constants, when used in the BDST model, were not able to predict the removals seen in the field.

Two lessons were learned from this modeling exercise. First, preliminary predictions regarding media capacity and reactions kinetics must be made using test solutions containing concentrations and pollutant speciations typically of stormwater runoff. Second, traditional column models will not work if the influent concentration is near the irreducible concentration of the pollutant. Additional research is needed to refine these models and to determine their application limits.

8.5 Microorganism Removal in Sedimentation and Filtration

Microorganism treatment is addressed separately from the particulate and chemical pollutant removal because the organisms' biological activity affects the pollutant removal. In both sedimentation and filtration systems, microorganisms are separated from the water matrix primarily by physical mechanisms although chemical processes such as adsorption may also contribute. It is important to note that all of the treatment systems discussed in this chapter are fundamentally systems which simply remove the microorganisms from the flowing water. None of these systems are designed to inactivate or destroy microorganisms. Rather, they simply concentrate and immobilize the microorganisms.

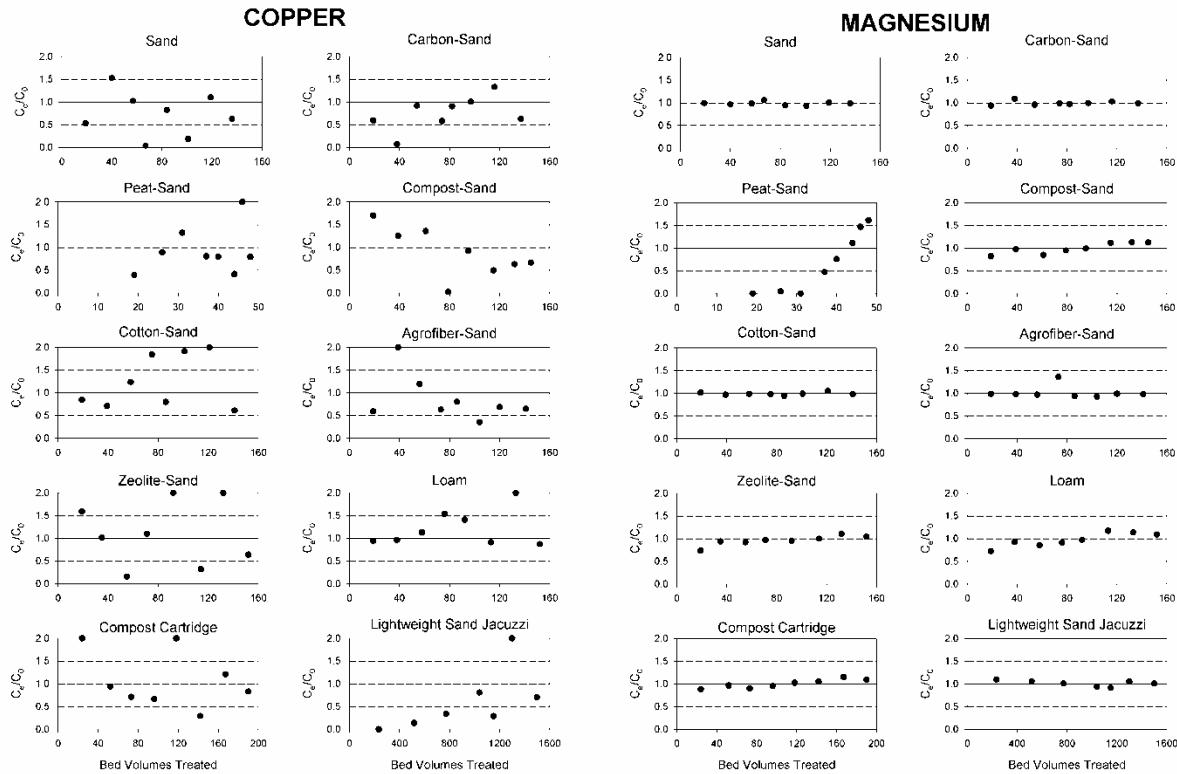


Figure 8-5. Ratios of Effluent to Influent Concentrations as a Function of Bed Volumes Treated for 10 Stormwater Media: Copper (left); Magnesium (right). (Clark, 2000. Reprinted with permission).

The question then is how are pathogenic microorganisms and indicator organisms removed from the environment. The vast majority of the microorganisms that are pathogenic to humans are not normally found in the natural environment. Instead, they are introduced into the environment, typically through contamination with fecal material (see Appendix G.4.5). Most human pathogens are adapted to living within the human body – a warm, moist, dark, and nutrient-rich environment. When these organisms enter filtration media, soil, and water, they usually die-off rapidly. Factors such as sunlight (UV), temperature, lack of nutrients, and predation by other organisms (e.g., insect larvae) all contribute to the rapid elimination of organisms from natural systems.

The characteristics of microorganisms most important in governing their removal by physical mechanisms are the density of the organism, its size and its shape. All microorganisms, regardless of whether they are viruses, bacteria, or protozoa, have a density slightly greater than water. In addition, their size is in the range of less than one micron (μm) for viruses to tens of microns for some of the larger protozoa. Finally, because many microorganisms have a surface charge, they are frequently associated with fine ($< 2 \mu\text{m}$) particles. Thus, transport of microorganisms in stormwater treatment systems often can be modeled using the same equations as those applied to the transport of suspended sediments on colloidal particles.

Both constructed wetlands and detention ponds rely on sedimentation as the dominant physical process for the removal of particle-associated pollutants such as microorganisms. Because constructed wetlands typically have more rooted vegetation than detention ponds and

because this vegetation effectively slows the flow of water, removal of microorganisms, and other fine particles, is often better in constructed wetlands than in unvegetated detention ponds. Both constructed wetlands and detention ponds have been shown to be capable of removing microbial contaminants from stormwater; however, the efficiency of removal with these systems is extremely variable. Removal efficiencies ranging from < 0 (negative removal due to regrowth or resuspension) to $> 100\%$ have been reported for both detention ponds and constructed wetlands depending on a variety of geological, hydrological, and biological factors.

In all treatment devices, the removal of microorganisms from the water column is associated with an increase in microorganisms in the sediments (detention systems) or in the media (infiltration and filtration devices). This is because the microorganisms removed from the water usually are attached to solid particles such as clays. Microbial attachment to particles is the result of multiple processes including electrostatic attractions and the formation of sticky exopolymers (biofilms) by microorganisms. Interestingly, microorganisms which are attached to particles are protected to a certain extent from adverse conditions and may survive for a longer time than non-attached microorganisms. These microbes are also harder to detect than free microorganisms. If sediments are resuspended, the associated microorganisms can be released into the water and can pose a health risk.

8.6 Vector Concerns in Surface Treatment Devices

The majority of water-associated human diseases are transmitted via some type of direct contact with contaminated water, such as by ingestion or recreational exposure. A less-obvious association between water and human disease is the impact of water, particularly standing water, on vector-borne diseases.

A vector-borne disease is transmitted to susceptible individuals as a result of a bite, wound, or other interaction with an animal which carries the disease. In the case of water-associated diseases, the most important vectors are invertebrates which spend at least a portion of their life cycle in aquatic habitats. These invertebrates include snails, biting flies, and mosquitoes. In the U.S., the most important vectors are mosquitoes. These organisms transmit a variety of parasitic and viral diseases, including malaria, West Nile virus, and other viral infections. In the continental U.S., the most common mosquito-borne diseases are the arboviral encephalitides: eastern equine encephalitis (EEE), western equine encephalitis (WEE), St. Louis encephalitis (SLE), and La Crosse encephalitis (LAC).

In most cases, infection with any of the arboviral encephalitides is either asymptomatic or manifests itself as a non-specific flu-like condition. In a small minority of cases, however, the disease may progress to an encephalitis with the potential for severe neurological damage or even death.

Since there are no vaccines against any of these viruses, the accepted approach to prevention involves preventing contact between susceptible hosts (humans) and vectors (mosquitoes). This is done by eradicating suitable habitat for mosquito breeding and by using personal protection methods (long sleeves, insect repellent).

Concerns about vectors and stormwater management focus on the possibility that stormwater management technologies may enhance mosquito populations by providing suitable breeding habitat. Most of the mosquitoes which transmit arboviral diseases to humans are capable of developing quickly in small volumes of standing water. Some, such as *Culex pipiens*,

routinely breed in water that collects in old tires, bird feeders, and discarded flower pots. The majority of mosquitoes breed in shallow (< 0.3 m) waters if there is adequate food (organic debris) present and the water temperature is adequate. These organisms reproduce rapidly and many species complete an entire life-cycle within two weeks or less.

Stormwater management facilities may increase mosquito breeding habitats by increasing areas where there is shallow standing water, although research by Irwin et al. (2008) indicated that most of the stormwater facilities in Madison, WI, did not produce mosquitoes and, of those that did, most did not produce *Culex* spp. However, there were a few ditches and ponds that were “super-producers” *Culex*. They noted that these ditches and detention ponds tended to cycle wet-and-dry, but those that had permanent pools of water were less likely to support mosquito larvae populations. Temporary erosion and sediment control basins, retention ponds and even poorly-draining infiltration facilities can all provide suitable habitat for mosquitoes to breed. The closer the facility is to a natural pond state, the less likely the formation of good mosquito habitat becomes. State-by-state guidelines concerning vector control are available through the state health or environmental protection department. General guidelines for vector control are as follows:

- ◆ Temporary erosion and sediment control basins/traps require frequent maintenance, especially if organic debris (such as wood and grass clippings) are disposed of in the pond.
- ◆ Infiltration systems should not hold water for more than 24 hours. If they begin to retain water for more than 48 hours, maintenance is required to restore infiltration rates in the soil.
- ◆ If dry detention basins retain water for more than approximately 30 hours, maintenance is required.
- ◆ Unvegetated basins should have grass clippings and other organic debris cleaned out regularly since the debris will provide food for the mosquito larvae.,
- ◆ Vegetated basins should have the weeds removed and the vegetation restricted to the basin periphery. Mosquito fish can be used in the pond to reduce the larvae populations.
- ◆ During construction and maintenance activities, avoid producing ruts since they may become habitat.
- ◆ Whenever possible, maintain the natural drainage channels so as not to increase the number and size of areas of unplanned standing water.
- ◆ Use pesticides judiciously and only as a last resort.

CHAPTER 9.0

PREDICTING THE EFFECTIVENESS OF STORMWATER MANAGEMENT PRACTICES

9.1 Introduction

The final step of any design is predicting whether the design will achieve its objectives. In stormwater management, the only way to confirm this would be to install the devices and then monitor their performance. Since this is not feasible, predictive tools such as models should be used to evaluate the final site design.

This chapter focuses on techniques for predicting the treatment performance of single devices, devices in series and parallel, and site modeling where the sources, hydraulic routing, and treatment can be evaluated together. Many guidance documents refer to the Simple Method of predicting performance for devices in series. However, the method is fundamentally flawed because it does not account correctly for reduced influent concentrations reaching the second device after treatment in the first. Therefore, the Simple Method is not included in this guidance document. The methods presented in Sections 9.2 through 9.4 also are simple and designed to address the performance of two treatment technologies connected in series or operating in parallel at a single location on a site. The methods are not designed to evaluate the cumulative performance of devices dispersed throughout the watershed. Several authors (e.g., Emerson et al., 2005; Perez-Pedini et al., 2005a,b; and Gilroy and McCuen, 2009) have modeled and monitored the cumulative impacts of control practices in a watershed, but as noted in Section 9.5 also, the state of the research regarding impacts of multiple control practices in a watershed on downstream health is not as advanced as the state of the research on individual control practices.

9.2 Predicting the Performance of a Single Treatment Device

Many guidance documents and literature studies discuss treatment performance in terms of percent removals (efficiencies of capture). The assumption is that if certain pollutants can be reduced by a certain percentage, then receiving waters would be protected. However, further research (see Appendix E and the summaries in Jones et al. 2008) has shown that this is not necessarily the case. It is more important that treatment be seen in terms of effluent quality and, if the device reduces water, in terms of effluent volume and loads. Lenhart and de Ridder (2006) describe the problems with percent removals as a means of specifying stormwater practices.

This section (Table 9-1) outlines a procedure for estimating the treatment performance of a single device. Working from left to right, the user would input the known influent concentration (whether from site measurements, experience on the type of site, or the literature) and then would enter the data from the literature or theory (or from the manufacturer, if a manufactured treatment device is used) on effluent quality by concentration of the critical constituents and/or percent removal. The critical particle size, the size for which 100% control is needed, is entered in the table since it can be used to predict the effectiveness of sedimentation devices. The literature in drinking water treatment also can be used to determine the particle size in a filter for which nearly 100% control may be feasible. Then the user can calculate the effluent

quality based on the percent removal reported in the literature or by the manufacturer. The effluent quality from the literature, such as from the International BMP Database, is entered next. The user then has the data needed to predict the long-term effluent quality from a particular treatment device. It will be in the range of the higher of the calculated/reported effluent concentrations.

Table 9-1. Predicting Effluent Quality from Stormwater Treatment Devices.

Device	Influent Quality (mg/L) for Critical Constituent(s)	Individual Device Estimated Effluent Quality (mg/L) for Critical Constituent(s)*	Individual Device Performance (% Removal)	Critical Particle Size (μm), typically d_{50}	Effluent Concentration based on Percent removal*	Predicted Effluent Quality (mg/L) – Use greater value from % removal calculation or literature
Sedimentation*						
Filtration						
Infiltration						

* For sedimentation devices, removal efficiency and effluent concentration can be predicted from sedimentation theory if discrete particle settling and ideal behavior can be assumed, or a correction factor should be applied to account for short-circuiting (for example, inclined plate settlers are assumed to be 60% efficient compared to ideal discrete particle settling).

9.3 Predicting Treatment Performance for Devices Connected in Series

For devices connected in series, the flow rate is constant for the two devices, unless one device encourages infiltration of water to the ground and, thus, removes water from the treatment train. Examples of treatment trains include manufactured devices such as the Multi-Chamber Treatment Train (Pitt et al. 1999), two detention ponds in series, using a filter to polish detention pond effluent, or using a detention facility as a last treatment for runoff treated first in smaller, dispersed devices on the site. Table 9-2 highlights the calculations for treatment devices installed in series. The effluent quality of interest then in the receiving water evaluation is the effluent from Device B.

9.4 Predicting Treatment Performance for Devices Connected in Parallel

For devices connected in parallel, the flow rate is split between the two devices, and each device treats the divided flow assuming the same influent quality. Examples of parallel treatment would be the splitting of flows into ponds or multiple infiltration basins to reduce the amount of flow treated by a single device. Table 9-3 highlights the calculations for treatment devices installed in parallel. The effluent quality of interest then in the receiving water evaluation results from the blending of the effluents from Devices A and B.

9.5 Predicting the Effectiveness of Multiple Devices on a Site Using Computer Modeling

As noted in Section 9.1, the state of the research in evaluating the cumulative impacts of multiple devices on a site or in a watershed is not as advanced as the knowledge about the performance of a single control practice. Currently, these evaluations are performed by selecting an appropriate model, inputting the control devices selected and/or already installed, and then running the model under a variety of storm conditions. With the computing power readily

available, this often is performed using a continuous simulation based on historical rainfall records. Then, if monitoring data is available, the modeling and monitoring results are compared.

Table 9-2. Predicting Treatment Performance for Devices Installed in Series.

Pollutant:	Effluent Quality (mg/L μ g/L cfu/100 mL)
Sketch the treatment train used at the site (Device A is the first device in series and Device B is the second device):	
Calculate the performance for the Device A in series (using the calculations described in Table 9-1 and repeated here)	
Flow Rate or Water Quality Volume Being Treated (note units)	
Influent Quality to Device A	
Calculate effluent quality based on removal efficiency: Influent Concentration – (Percent Removal)(Influent Concentration) = Effluent Quality	
Predict effluent quality from literature (such as the International BMP database):	
Predict effluent quality from theory for sedimentation devices.	
Use greater of Effluent Quality based on Percent Removal and Literature Effluent Concentrations.	
Calculate the performance for the Device A in series (using the calculations described in Table 9-1 and repeated here)	
Influent Quality to Device B (= Effluent Quality from Device A)	
Calculate effluent quality based on removal efficiency: Influent Concentration – (Percent Removal)(Influent Concentration) = Effluent Quality	
Predict effluent quality from literature (such as the International BMP database):	
Predict effluent quality from theory for sedimentation devices.	
Use greater of Effluent Quality based on Percent Removal and Literature Effluent Concentrations.	

One limitation of the current state of monitoring is the lack of stream health data. Typically, monitoring involves only water quality (chemical) data and possibly flow data, but no data exists on the stream channel stability, biological habitat, and biodiversity. This section will describe the use of computer models to evaluate larger-scale performance than what is described in Sections 9.2 through 9.4. However, because the state of research is still limited in this area, no evaluation of the ability of these models to predict downstream cumulative impacts is given. It is anticipated that, within the next five years, the results of several long-term modeling+monitoring activities will be published.

Computer models have a long history of use in stormwater management. The earliest models predicted flow patterns, but these have been upgraded in the last decade to include water quality estimations. Other models have been developed strictly to address low impact development and prediction of effluent quality from a variety of control devices installed on a

site. This section is not designed to provide detailed explanations of the variety of models available, but instead to provide guidance about some of the models and their applicability.

There are three types of models commonly used in stormwater management: *hydrologic*, *hydraulic* and *water quality* models. There are also a number of other specialty models to simulate ancillary issues, such as sediment transport, channel stability, lake quality, dissolved oxygen, and evapotranspiration.

Table 9-3. Predicting Treatment Performance for Devices Installed in Parallel.

Pollutant:	Effluent Quality (mg/L μ g/L cfu/100 mL)
Sketch the layout of the devices in parallel (Device A is the first device in series and Device B is the second device):	
Flow Rate or Water Quality Volume to Treatment Area (note units):	
Calculate the performance for the Device A in parallel (using the calculations described in Table 9-1 and repeated here)	
Flow Rate or Water Quality Volume to Device A (note units)	
Influent Quality to Device A	
Calculate effluent quality based on removal efficiency: Influent Concentration – (Percent Removal)(Influent Concentration) = Effluent Quality	
Predict effluent quality from literature (such as the International BMP database):	
Predict effluent quality from theory for sedimentation devices.	
Use greater of Effluent Quality based on Percent Removal and Literature Effluent Concentrations.	
Calculate the performance for the Device B in parallel (using the calculations described in Table 9-1 and repeated here)	
Flow Rate or Water Quality Volume to Device B (note units)	
Influent Quality to Device B (= Effluent Quality from Device A)	
Calculate effluent quality based on removal efficiency: Influent Concentration – (Percent Removal)(Influent Concentration) = Effluent Quality	
Predict effluent quality from literature (such as the International BMP database):	
Predict effluent quality from theory for sedimentation devices.	
Use greater of Effluent Quality based on Percent Removal and Literature Effluent Concentrations.	
COMBINE the Effluent Qualities from Devices A and B	
Effluent Quality from Device A	
Flow Rate or Water Quality Volume from Device A	
Calculate the Effluent Load from Device A (Flow Rate x Time x Concentration) or (Water Quality Volume x Concentration)	
Effluent Quality from Device B	
Flow Rate or Water Quality Volume from Device B	
Calculate the Effluent Load from Device B	
Add the Effluent Loads from Devices A and B	
Calculate the Weighted Average Effluent Quality (Load Sum divided by Sum of Volumes from Devices A and B)	

Hydrologic models simulate the rainfall-runoff process (see Chapter 3.0). Their outputs may include peak flow, flood hydrograph and flow frequencies. Hydrologic models can be described as one or more of the following:

- ◆ *Deterministic* – giving one answer for a specific input set, or
- ◆ *Stochastic* – involving random inputs giving any number of responses for a given set of parameters.
- ◆ *Continuous* – simulating many storm events over a period of time, or
- ◆ *Single Event* – simulating one storm event.
- ◆ *Lumped* – representing a large area of land use by a single set of parameters, or
- ◆ *Distributed* – land areas are broken into many small homogeneous areas each of which has a complete hydrologic calculation made on it.

Hydraulic models take a known flow amount (typically the output of a hydrologic model) and provide information about flow height, location, velocity, direction and pressure. Hydraulic models may be applied to overland flow, channelized flow, and/or pipe flow and can be used to describe the routing of the flow from an upstream to a downstream location. Hydraulic models share some of the differing characteristics of hydrologic models (continuous vs. single event) and add the following:

- ◆ *One-dimensional* – calculating flow information in one direction (e.g. downstream) only, or
- ◆ *Multi-dimensional* – calculating flow information in several dimensions (e.g. in and out of the channel and downstream).
- ◆ *Steady* – having a single unchanging flow velocity value at a point in the system, or
- ◆ *Unsteady* – having changing flow velocities with time.
- ◆ *Uniform* – assuming the channel slope and energy slope are equal, or
- ◆ *Non-uniform* – solving a more complex formulation of the energy and momentum equations to account for the dynamic nature of flows.

Water quality models simulate the various processes and interactions of stormwater pollution. They predict loadings of various types of stormwater pollutants and can become very complex if the complete cycle of buildup, wash-off and impact are determined. These models share the various features of hydrologic and hydraulic models in that it is the runoff flow that carries the pollutants. Water quality models tend to be targeted toward specific pollutants, source types or receiving waters. Some models involve biological processes as well as physical and chemical processes.

While calibration data is not always needed in hydrologic or hydraulic models for an acceptably accurate answer, in water quality models the non-calibrated prediction could be off by orders of magnitude. Site-specific calibration and validation is required.

Stormwater computer models can also be categorized by their use or application. *Screening-level models* are typically equations or spreadsheet models that give a first estimate of the magnitude of urban runoff quality or quantity. *Planning-level models* are used to analyze multiple scenarios to compare in a general way design alternatives or control options. They can be used to establish flow frequencies, floodplain boundaries, and general pollution loading values. *Design-level models* provide a detailed simulation of a single storm event for the purposes of urban stormwater design. Their results provide a more complete description of flow or pollution values anywhere in the system of concern. *Operational models* are used to produce actual control decisions during a storm event.

Table 9-4 lists several widely used computer programs and modeling packages (as approved by the State of Georgia). The programs were described in the Georgia Stormwater Management Manual (2001) for their applicability to both system-wide and localized issues, the methodologies used for computations, and ease-of-use. For the purposes of this table, major drainage systems are defined as those draining to larger receiving waters. These are typically FEMA-regulated streams, or lakes or reservoirs. Minor drainage systems are smaller natural and man-made systems that drain to the more major streams. Minor drainage systems can have both closed and open-channel components and can include, but are not limited to, neighborhood storm sewers, culverts, ditches, and tributaries. Most of these models can provide predictions as to the impacts on flow and/or water quality of multiple control practices in a watershed.

Other models potentially available for use in evaluating one or more aspects of stormwater management, such as the impact of multiple control practices dispersed on a site or throughout a watershed, include the following (in alphabetical order):

- ◆ Delaware Urban Runoff Model (DURM)
- ◆ Low Impact Feasibility Evaluation (LIFE™) – proprietary by CH2M Hill
- ◆ MIKE SHE and MIKE URBAN – proprietary by the Danish Hydraulics Institute
- ◆ Model for Urban Stormwater Improvement Conceptualization (MUSIC)
- ◆ Model of Urban Sewers (MOUSE)
- ◆ P8/Urban Catchment Model
- ◆ Probabilistic Urban Rainfall and Wastewater Reuse Simulator (PURRS)
- ◆ Precipitation-Runoff Modelling Systems (PRMS)
- ◆ Runoff Quality From Development Sites (RUNQUAL)
- ◆ Simple Lumped Reservoir Parametric (SLURP)
- ◆ Snowmelt Runoff Model (SRM),
- ◆ Streamflow Synthesis and Reservoir Regulation (SSARR)
- ◆ SWRRB (Watershed Scale Model for Soil and Water Resources Management)
- ◆ Urban Volume and Quantity (UVQ)
- ◆ Virginia Tech/Penn State Urban Hydrology Model (VT/PSUHM)
- ◆ Water Balance Model (WBM)
- ◆ Watershed Analysis Risk Management Framework (WARMF)
- ◆ Watershed Management Model

The System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) model, sponsored by the U.S. EPA, is scheduled for release in 2009.

Elliott and Trowsdale (2007) reviewed several of the models available for Low Impact Development. Their evaluation included MOUSE, MUSIC, P8, PURRS, RUNQUAL, SLAMM, Storm Tac, SWMM, UVQ, and WBM. First, they evaluated the models for their defined purposes. No model was specifically designed for public education. Only MOUSE and SWMM were able to model detailed designs of regional drainage systems and the hydraulic routing based on the site layout. However, these detailed designs were not the primary purpose of the model.

Table 9-4. Stormwater Modeling Programs and Design Tools.

	Developer (website)	Major System Modeling	Minor System Modeling	Hydrologic Features	Hydraulic Features	Water Quality Features
Hydrology Software						
HEC-HMS (Hydrologic Modeling System)	U.S. Army Corps of Engineers	X		X		
TR-55 (Win TR-55)	U.S.D.A. Natural Resource Conservation Service			X		
Pond Pack	Bentley/Haestad Methods		X	X	X	
WMS - Watershed Modeling System	Engineering/Computer Graphics Laboratory of Brigham Young University	X		X		
Hydraulics Software						
HEC-RAS (River Analysis System)	U.S. Army Corps of Engineers	X			X	
EPA SWMM (Storm Water Management Model)	U.S. Environmental Protection Agency	X	X	X	X	X
CulvertMaster	Bentley/Haestad Methods		X		X	
FlowMaster	Bentley/Haestad Methods		X		X	
Water Quality Software						
HSPF (Hydrologic Simulation Program – FORTRAN)	U.S. Environmental Protection Agency	X		X		X
BASINS (Better Assessment Science Integrating Point and Nonpoint Sources)	U.S. Environmental Protection Agency	X		X	X	X
QUAL-2EU (Enhanced Stream Water Quality Model with Uncertainty Analysis)	U.S. Environmental Protection Agency	X			X	X
WASP 5 (Water Quality Analysis Simulation Program)	U.S. Environmental Protection Agency	X			X	X
WinSLAMM (Source Loading and Management Model)	PV Associates, Inc.	X		X		X

Given the publication date of 2007, the reader can assume that this information was current as of early 2006. That is important because many of these models are undergoing rapid revisions to address items that were not available when this analysis was performed. For

example, several of these models are incorporating on-site routing of water between practices or to the outlet, plus the list does not address treatment trains of devices. Table 9-5 lists the potential uses for the models investigated by Elliott and Trowsdale (2007) and a slightly updated list of the models' ability since publication. Table 9-6 shows the contaminants included in each model. This list also has been revised as many models are addressing pollutants other than solids. No model yet addresses temperature; however, the newer heat models for urban surfaces may be soon linked into these models.

As noted in Table 9-5, most of the models are used for sizing of devices (obtaining the water quality volume or flow control volume) through the preliminary design. They are generally not suitable for larger-scale, watershed-level modeling. The ability to model the impact of practices, as discussed earlier, is substantially more limited.

Table 9-5. Potential Uses for Specified Models.
(Dark gray indicates an intended use; Light Gray indicates that the model is marginally suitable).

Model	Research	Sizing of Devices	Landuse Planning	Preliminary Design of Regional Controls	Preliminary Design of Subdivision of Site
MOUSE					
MUSIC					
P8					
PURRS					
RUNQUAL					
WinSLAMM					
StormTac					
SWMM					
UVQ					
WBM					

Table 9-6. Contaminants Included in the Model Predictions.

Model	Sediment	Nutrients	Heavy Metals, Other Toxicants	BOD, Dissolved Oxygen	Pathogens	Temperature
MOUSE						
MUSIC						
P8						
PURRS						
RUNQUAL						
WinSLAMM						
StormTac						
SWMM						
UVQ						
WBM						

As noted above, at the time of publication, PURRS and WBM did not address water quality issues. The final analysis in Elliott and Trowsdale regarded the types of low impact development practices addressed by the models (Table 9-7).

Table 9-7. Control Practices Addressed by the Models.

Model	Impervious Surface Reduction	Ponds and Wetlands	Soil Protection	Reduction of Contaminant Generation	(In)filtration Devices	On-site Detention Tanks	Swales	Run-on	Rain Tanks	Bioretention	Permeable Pavement	Green Roofs
MOUSE												
MUSIC												
P8												
PURRS*												
RUNQUAL												
WinSLAMM												
StormTac												
SWMM												
UVQ												
WBM*												

* Not a water quality model.

CHAPTER 10.0

PREDICTING THE CAPITAL AND OPERATIONS AND MAINTENANCE (O&M) COSTS OF STORMWATER MANAGEMENT PRACTICES

10.1 Introduction

While some stormwater management decisions are made based on the required pollutant and water removals and not on cost, cost can be a deciding factor when choosing between two or more acceptable management practices. For the site developer, the interest may be in the capital costs of installation. However, for the municipality or organization assuming responsibility for these devices, it is the O&M costs that are most important.

This chapter focuses on providing the user with references that have studied stormwater costs. It is not to present the actual costs of the construction and maintenance of these devices, since they are anticipated to differ significantly from place to place and to change over time.

10.2 Types of Costs and Methods of Predicting Costs

This section is based on the cost report prepared by Narayanan and Pitt (2006). The total cost includes capital (construction and land) and annual operation and maintenance costs. Capital costs are incurred at installation and if retrofitting or up-sizing occurs. Capital costs also include added financing costs that are amortized over the life of the project. The operation and maintenance costs occur periodically throughout the life of the stormwater control device or practice.

Capital cost consists primarily of land cost, construction cost, and related site work. Capital costs include all land, labor, equipment and materials costs, excavation and grading, control structure, erosion control, landscaping, and appurtenances. It also includes expenditures for professional/technical services that are necessary to support the construction of the stormwater control device. Capital costs depend on site conditions, size of drainage area and land costs that vary greatly from site to site.

Design and permitting costs include costs for site investigations, surveys, design, and planning for the stormwater controls. Contingency costs are the unexpected costs incurred during the development and construction of a stormwater control practice. They are expressed as a fraction of the base capital cost and have been considered uniform for all stormwater controls. During the calculation of capital costs, an additional 25% of the calculated base capital cost should be added to cover design, permitting, and contingency fees (Wiegand et al., 1986; U.S. EPA 1999). An additional 5% to 7% of the calculated base capital cost should be added to cover the cost of erosion and sediment control (Brown and Schueler, 1997; U.S. EPA, 1999; and CWP, 1998).

Operation and maintenance relate to post construction activities that ensure the effectiveness of an installed stormwater control practice. They include labor; materials; labor, energy and equipment for landscape maintenance; structural maintenance; sediment removal from sediment control devices and associated disposal; and litter removal. Similar to the design, permitting and contingency costs, the operations and maintenance costs can either be expressed as an annual

percentage of capital costs, or the actual costs can be determined. For example, total annual O&M costs for both routine activities (periodic site inspections, grass mowing, litter and debris removal, bank stabilization, and maintenance of site vegetation for erosion control) and sediment removal may range from 3 to 5% of base construction costs for pond stormwater controls (Wiegand, et al. 1986).

Life cycle costs are all the costs that occur during the life time of the stormwater control device. These costs include design, construction, O&M, and closeout activities. These costs are divided across the anticipated lifespan of the device (typically normalized to present worth value using the appropriate accounting formulas to normalize the anticipated rises in costs over time). Life cycle costs can be used to help select the most cost-effective stormwater control option (Sample, et al. 2003).

The five common methodologies of cost estimation are as follows (DOD, 1995):

- ◆ Bottom-Up Method – involves identifying and estimating the costs of individual components and then combining the costs.
- ◆ Top-Down Method – costs of the entire project are estimated by partitioning the project into lower-level components starting from the top-down.
- ◆ Analogy Method – use cost data from another site to extrapolate the cost on the current site.
- ◆ Expert Judgment – solicit cost estimates from experts in the field.
- ◆ Algorithm/Parametric Method – develop equations relating historical costs to known variables, such as size of the device, anticipated life between maintenance, etc.

10.3 Costs of Stormwater Management

Table 10-1 is a list of references regarding the costs of stormwater management. This list is by no means complete, but it has been developed to aid managers and planners in locating further information on life cycle costs. Detailed information on stormwater management costs has been presented at a number of conferences. The U.S. EPA reference listed first in the table is frequently cited as providing baseline cost information for stormwater practices. Then, these costs are adjusted through the use of R.S. Means' factors for regional differences and for inflation since the original cost lists were created.

A variety of researchers, regulatory agencies and other organizations have reported on the costs of designing, installation and maintaining urban drainage systems. One group that currently houses links to an array of references on these topics is <http://www.urbanwater.info/index.cfm>. Another group, which focuses on research and implementation in the United Kingdom is SUDSNet. In the U.S., the agencies that have funded stormwater cost research are the U.S. Environmental Protection Agency and the U.S. Department of Transportation. Both of their websites house relevant publications. Publications from these agencies related to cost issues are given in Table 10-1.

Table 10-1. Cost References.

Author	Year	Title	Location
U.S. EPA	1999	Preliminary Data Summary of Urban Storm Water Best Management Practices, Chapter 6: Costs and Benefits of Storm Water BMPs.	U.S. EPA
Hoey, Girts	2000	Appendix D: Technical Memorandum – Stormwater Management Cost Information	http://www.ecy.wa.gov/programs/wq/stormwater/commentdocs/AppendixD.pdf
Landphair	2001	Cost to performance analysis of selected stormwater quality best management practices	http://repositories.cdlib.org/jmie/roadeco/Landphair2001a
Taylor, Wong	2002	Nonstructural stormwater quality best management practices: value and life cycle costs	http://www.catchment.crc.org.au/pdfs/Technical200213.pdf
Sample, Heaney, Wright, Fan, Lai, Field	2003	Costs of Best Management Practices and Associated Land for Urban Stormwater Control. EPA 600/JA-03/261	http://www.epa.gov/ORD/NRMRL/pubs/600ja03261/600ja03261.pdf
Wossink, Hunt	2003	An evaluation of cost and benefits of structural stormwater best management practices	http://www.bae.ncsu.edu/stormwater/PublicationFiles/BMPCost&Benefit2003.pdf
Taylor, Fletcher	2004	Structural Stormwater Quality BMP Cost-Size Relationship Information from the Literature	
Lampe et al.	2005	Performance and Whole Life Costs of Best Management Practices and Sustainable Urban Drainage Systems	http://www.werf.org/AM/Template.cfm?Section=Search&Template=/CustomSource/Research/ResearchProfile.cfm&ReportId=01-CTS-21-TA&ID=01-CTS-21-TA
Weiss, Gulliver, Erickson	2005	The Cost and Effectiveness of Stormwater Management Practices	Minnesota Department of Transportation Report 2005-23
Narayanan, Pitt	2006	Costs of Urban Stormwater Control Practices	http://rpitt.eng.ua.edu/Publications/StormwaterTreatability/Arvind%20and%20Pitt%20stormwater%20cost%20report.pdf
Hathaway, Hunt	2007	Stormwater BMP Costs	http://www.bae.ncsu.edu/stormwater/PublicationFiles/DSWC.BMPCosts.2007.pdf
Federal Highway Admin.	2008 (accessed)	Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring	http://www.fhwa.dot.gov/environment/ultraurb/uubmp6p4.htm
Kang, Weiss, Gulliver, Wilson	2008	Maintenance of Stormwater BMPs: Frequency, Effort and Cost (summarizes the Minnesota survey on O&M costs to municipalities)	Stormwater Magazine

10.4 Life-Cycle Analysis of Stormwater Management Practices

Life-cycle analysis (LCA) is used to quantitatively evaluate the environmental impacts of a process or a device from design, through implementation and operation (including maintenance), and to eventual decommissioning, if appropriate. It is a “cradle-to-grave” assessment of the impacts and costs, both direct and indirect, of human actions. In the realm of stormwater management, it can be used to attempt to quantify the benefits and to compare

alternatives in watershed and stormwater management. It also can be used to investigate the impacts of alternative stormwater strategies on conventional infrastructure (Mithraratne and Vale 2007). Several groups of researchers are developing tools to assist in LCA for stormwater management. Taylor and Fletcher (2004) describe the work at the Cooperative Research Centre for Catchment Hydrology in Australia to incorporate LCA into the MUSIC model. Landcare Research in New Zealand also has been using an LCA analysis to evaluate stormwater management projects (Mithraratne and Vale 2007). Kirk (2006) investigated suburban stormwater management using an LCA approach using data generated by the University of New Hampshire Stormwater Research Center.

Hellstrom et al. (2000) describes the framework used in Sweden entitled “Sustainable Urban Water Management” and the indicators used to assess the effectiveness of the program. Bardin et al. (2002) provided a list of 17 indicators that can be used to evaluate the sustainability and long-term performance of stormwater management practices. The paper illustrates the application to infiltration systems, but they can be generalized to other practices. The following are the indicators proposed by Bardin et al. (2002).

- ◆ Flooding reduction – both frequency of flooding and volume of floodwaters
- ◆ Pollutant reduction of water resources (downstream surface water and groundwater)
- ◆ Encouragement/facilitation of groundwater recharge and maintenance of pre-development hydrology
- ◆ Use of few raw materials
- ◆ Prevention/reduction of soil contamination or cause little contamination of soils
- ◆ Trapping of solid waste/litter
- ◆ Durable and easily maintainable
- ◆ No disturbance to other technical systems
- ◆ Safe and secure to prevent harm to users of the system
- ◆ Safe and secure to prevent harm to personnel who are installing or maintaining the system
- ◆ Inexpensive
- ◆ Preservation and/or encouragement of economic activity
- ◆ Adaptable to other uses and treatment of multiple pollutants
- ◆ Provision of other functions (e.g., wildlife habitat)
- ◆ Perception to the general public of providing a benefit
- ◆ Recyclability of system materials

Whole Life Cost models were developed for detention basins, retention ponds, swales, and permeable pavements as part of a joint project between WERF and United Kingdom Water Industry Research. The project description and models can be found in Lampe et al. (2005). A second phase of the research will be released in 2009, including tools for bioretention, green roofs, and cisterns. The new products have been developed as part of a collaboration between WERF and the U.S. EPA.

CHAPTER 11.0

CONCLUSIONS AND DATA GAPS

11.1 Conclusions

Appropriate stormwater management is a difficult process – one that has many constraints on it, not all of which are controllable by the design engineer. For example, stormwater management has to address the water quality problems associated with small, frequent storms, plus protect human health and safety from flooding events. Current guidance typically addresses these as two separate issues, and the lack of integrated guidance to achieve both objectives has resulted in a focus in one area or the other, but rarely in an integrated management plan that addresses both issues. In addition, the science to support the decision-making is not readily available to the practitioners.

This document (starting in Chapter 5.0) proposes that stormwater control be focused on the broad range of storms requiring management/treatment. It starts with the smaller storms, often known the water quality storms, and proposes that most of those can be treated through infiltration practices (where allowed and where the water is relatively clean and/or easily treatable by the soils/engineered media). These storm depths then can be considered “removed” from the traditional drainage system. Then the document reminds the user to address the larger volumes and flow rates associated with the larger storms. These storms may require treatment and transport in surface devices and water from highly-polluted areas may require diversion to a treatment plant. This document has attempted to tie together what is known about stormwater treatment devices with the theory behind treatment process design and efficiency and behind surface and ground water movement. The purpose of the document is to support the development of stormwater plans for sites, starting at the regulatory level and progressing through calculating flows and pollutants to the design of treatment devices and predictions of their effectiveness. This document was not designed to replace the regulatory and guidance provided for stormwater managers and designers by the appropriate regulatory authorities, but instead to outline the process logically and guide the user in determining the types of data needed to design devices that met the goal of stormwater management. Flow charts and checklists were developed to provide guidance and to record the data supporting decisions. This document was developed from the literature and existing guidance. The body of the document focuses on the information needed at the design/decision-making level. The appendices then are provided for supplemental information for those users who are not familiar with the principles and literature supporting the document itself. Case studies and a literature database are provided in the appendices so that the user can locate the original studies and reports that are relevant to their projects and designs.

A review of the extensive literature in Appendix K plus the studies cited in the document and the other appendices highlight the depth and breadth of knowledge that the profession has about the design and performance of surface sedimentation devices. The same depth of knowledge, however, does not exist for filtration/infiltration systems and low-impact development or for the integration of practices for multiple objectives. The data gaps listed

below are meant to identify where additional research is needed to isolate the factors that may be affecting the performance of these systems and their ultimate effect on surface and ground water.

11.2 Data Gaps

Pollutants of Concern. The chemical quality of stormwater has been well-documented over the years. Current research is focusing on identifying potential sources and predicting source loadings in order to improve modeling. However, much still remains unknown regarding microbiological pollution. While there have been a considerable number of studies published that examine the microbiological quality of recreational water, there is essentially no data beyond the California studies that directly addresses the relationship between urban stormwater runoff and RWIs. Instead, the information available seems to address the areas of RWIs and stormwater runoff as entirely separate issues.

There is ample evidence indicating an association between land-use patterns (degree of urbanization) and the presence of indicator organisms in receiving water. Even with these studies, there is very little information available concerning the source – urban stormwater runoff, CSO, SSO, wastewater discharge, etc. – of the indicator organisms. Rather, the relationships between wet-weather flows and higher concentrations of indicator organisms are used to infer a relationship between urban stormwater runoff and microbiological quality.

The second category of research has focused on the relationship between the presence of indicator organisms and adverse health outcomes. While statistically significant relationships have been documented in some studies, the majority of these studies also highlight the limitations of indicator organisms in monitoring recreational water quality.

Effects of Pollutants. As mentioned previously, data gaps exist in both effects of water quality on stream integrity as well as stream restoration. Some questions include: When does it become more than an episodic event, leaving a permanent mark on stream integrity? Does ISC really worsen urban runoff and thus ruin the water quality in an urban stream. Is water quality ever bad without ISC and physical habitat modification? And when, in implementing these changes does it become a problem? Finally, what role does water quality play in stream restoration? Does restoration work? On what kind of time scale do we see improvements? Are some methods more successful than others? Do different streams (cold water versus warm water) need different restoration practices to achieve success? Future research should address these issues. A potential research project would investigate, in a headwaters watershed, whether the installation of BMPs or whether using LID for design was able to protect the receiving water.

Design of Infiltration Facilities. In terms of infiltration, even using the quality-control-checked information in the International BMP database, no site provided complete information to confirm the use of SESOIL and its predictive pollutant depth. Future research should use real data (as planned by Villanova University on their traffic bioretention island data set) and use this model, or a comparable one, to predict pollutant migration depth. These predictions could then be compared with actual pollutant migration data to determine the effectiveness of the model. One concern with the model, as it currently is used, is the determination of the coefficients required to more accurately predict the pollutant migration depth. The model is primarily designed to predict organic movement in the subsurface. However, many stormwater pollutants are inorganic and have substantially different soil interactions. It is recommended that these coefficients for the reactions be determined in the laboratory for several soils to determine their

range. In addition, monitoring of installed devices for better prediction of performance given the theory is recommended.

Impacts on Downstream Health of Multiple Control Practices in a Watershed. The purpose of installing treatment devices on a site is to prevent post-development damage to downstream waters. However, the impact of multiple control practices in a watershed, if they are not planned correctly, may be minimal or negative. For example, suppose that multiple detention ponds were installed in a watershed, each designed to control its effluent flow rate to no more than the 1.5- to 2-year (bankfull) storm during the selected design storm. During a runoff event, each pond stores water and releases it at that bankfull rate into the receiving water at only very specific locations rather than distributed along the streambanks as it likely was in pre-development conditions. It is possible that if these discharge peaks overlap, bankfull flows or greater could be occurring in the stream and increasing streambank instability, plus washing out habitat. Research is needed on the cumulative impacts of multiple control practices in a watershed. This research should focus both on the impacts of water quality and quantity and should measure flow, and the parameters that characterize stream health.

Maintenance and Long-Term Performance of Infiltration Practices. Many regulatory agencies have begun to prescribe “mimicking pre-development hydrology” as the goal of stormwater management in their jurisdictions. This has been translated as not only reducing the peak flow rate to pre-development levels, but also reducing the total volume entering the urban streams to pre-development levels. These goals can only be accomplished by removing some, if not all, stormwater runoff from the storm drainage system. Several methods exist to accomplish this – on-site infiltration, water capture/retention/evapotranspiration by green roofs, and evaporation in detention basins. The practice that is currently favored is infiltration. Infiltration is seen as restoring groundwater recharge, while reducing the negative effects of increased stormwater runoff – increased pollutant loads, thermal effects, and stream instability due to increased energy delivered to the stream. However, only recently have datasets on the long-term performance and maintenance requirements of infiltration practices become available. Prior to the last few years, the reporting of long-term performance has been primarily anecdotal, with insufficient data available to provide statistical comparisons of performance over both the short- and long-term. This body of data continues to grow both in terms of number of devices with long-term monitoring and in terms of the geographic distribution of these monitored devices. A future research need will be to address the data gap of analyzing this data to determine general long-term performance trends and the factors that affect both the long-term performance and the need for maintenance on these devices.

Undertaking activities such as these will allow for better refinement of models, which are the most effective way of predicting whether the water quality and quantity objectives can be met. As the models are improved, performance is better predicted and the uncertainties are then reduced to those inherent with the variability and frequency of rainfall.

APPENDIX A

GLOSSARY

303(d) Impaired waterbody: A list of lakes, rivers, and streams that have been designated as impaired or threatened by a pollutant(s) for which one or more TMDLs are needed. Impaired means that the water is not meeting state water quality standards and its designated use.

319: The section of the Federal Clean Water Act that addresses nonpoint source pollution, such as urban runoff

Algal bloom: Rapidly occurring growth and accumulation of algae within a body of water, which usually results from excessive nutrients or sluggish circulation within a waterbody. Persistent and frequent blooms can result in low oxygen conditions which is hazardous to aquatic life.

Annual plant: A plant that completes its entire life cycle in a single growing season.

Aquifer: A geologic stratum containing groundwater. Typically refers to water-bearing geologic layers that provide water for human use.

Baffle: A device to deflect, check or regulate flow.

Base flow: The flow in a stream between storm events. The flow is supplied by groundwater.

Basin: Any area draining to a point of interest (defined as the outlet of the watershed or basin). The term “basin” also may be used instead of “pond” when describing sedimentation and/or infiltration ponds.

Benthic: Relating to or occurring at the bottom of an aquatic ecosystem.

Berm: A constructed barrier of compacted earth.

Best Management Practice (BMP): Actions, behaviors or on-the ground landscaping practices that reduce pollution and/or the amount of storm water runoff flowing into local waterways. BMPs can be *structural*, such as a rain barrel or shoreline buffer, or *non-structural*, such as picking up after your pet or washing your car on the grass.

Biochemical Oxygen Demand (BOD): A measure of the quantity of oxygen used by microorganisms in the oxidation of organic matter.

Biofiltration swale or Bioswale: A long, gently sloped, vegetated ditch designed to filter pollutants from stormwater.

Bioretention: A water quality practice that utilizes landscaping and soils to treat stormwater by collecting it in shallow depressions and then filtering it through a planting soil media.

Buffer: A designated area adjacent to a structure, slope or waterway that should be left in its natural state in order to provide protection and prevent degradation of the object it is protecting.

Catch basin insert: A device installed underneath catch basin inlet and designed to treat stormwater.

Catch basin: Curbside opening that collects rainwater from streets and serves as an entry point to the storm drain system.

Channel: A long, narrow, open-air excavation or surface feature that conveys surface water.

Check dam: A small barrier built across the direction of water flow in a swale to retain excess water during heavy rains and to slow the speed of runoff traveling through the swale.

Combined Sewer Overflow (CSO): The release of untreated wastewater plus stormwater from a combined sewer system prior to its arrival at the treatment plant. CSOs were designed to bypass all flows in the conveyance system in excess of the maximum flows that the wastewater treatment plant can treat.

Culvert: Pipe or concrete box structure which drains open channels, swales, or ditches under a roadway or embankment typically with no catch basins or manholes along its length.

Debris barrier: A metal trash rack.

Deciduous plant: A plant that sheds or loses its foliage at the end of each growing season.

Depression storage: The amount of precipitation that is trapped in depressions on the surface of the ground.

Designated use: Uses specified in water quality standards for a waterbody.

Detention facility: A facility that collects water from developed areas and releases it at a slower rate than it enters the collection system or receiving water. The excess of inflow over outflow is temporarily stored in a pond or a vault and is typically released over a few hours or a few days.

Detention vault: A type of detention facility.

Direct discharge: Undetained discharge from a proposed project to a major receiving water.

Dissolved oxygen (DO): The amount of oxygen that is dissolved in water. It also refers to a measure of the amount of oxygen available for biochemical activity in a waterbody and as indicator of the quality of that water.

Diversión: A change in the natural discharge location or runoff flows onto or away from an adjacent downstream property.

Drainage area: An area draining to a point of interest. An area of catchment contributing runoff to the treatment system.

Drainage facility: A constructed or engineered feature that collects, conveys, stores or treats surface and storm water runoff.

Drainage: Collection, conveyance, containment, and/or discharge of surface water and runoff.

Easement: A right, such as a right-of-way, given to make limited use of another's real property.

Ecosystem: An interactive system that includes the organisms of a natural community together with their abiotic, physical, chemical and geochemical environment.

EIS (Environmental Impact Statement): A document that discusses the likely significant adverse impacts of a proposed activity, ways to lessen the impacts, and alternatives.

Embankment: A structure of earth, gravel, or similar material raised to form a pond bank or foundation for a road.

Energy dissipater: A rock pad constructed at inlets/outlets to prevent erosion, or a constructed percolation trench to disperse outletting flows over a large area, or a catch basin used to slow fast flowing runoff.

Erosion: The displacement of soil by natural processes such as wind and runoff from land surfaces. Erosion may be enhanced as a result of man's activities on the land, such as by removing surface vegetation or by concentrating flow on an unstable soil. The sediment generated by erosion is a pollutant.

ESA: Endangered Species Act

Estuary: Brackish-water area influenced by the tides where the mouth of the river meets the sea.

Eutrophic: A condition of a waterbody in which excess nutrients stimulates the growth of aquatic plant life usually resulting in the depletion of dissolved oxygen.

Evergreen plant: A plant that remains green and retains its foliage throughout the year.

Excavation: The process of removing earth, stone, or other materials from land.

Fecal coliform bacteria: Bacteria that are present in the intestines or feces of warm-blooded animals. Often used as indicators of water quality.

First flush: The initial washoff of water and pollutants from a land surface. First flush of water has been related at some sources to a slug of pollution that is more concentrated than the runoff later in the storm.

Floodplain: Areas that are periodically flooded by lateral overflow, such as river.

Flow control facility: A drainage facility designed to mitigate the impacts of increased surface and storm water runoff. Flow control facilities are designed either to hold water for a considerable length of time and then release it by evaporation, plant transpiration, and/or infiltration into the ground, or to hold runoff a short period of time and then release it to the conveyance system.

Forebay: Stormwater design feature that uses a small basin to settle out incoming sediment delivered in runoff to a stormwater BMP.

General Permit: A permit issued under the NPDES program to cover a certain class or category of stormwater discharges. These permits reduce the administrative burden of permitting stormwater discharges.

Geographic information systems (GIS): A computer system for capturing, storing, checking, integrating, manipulating, analyzing and displaying data related to positions on the Earth's surface.

Grading: The cutting and/or filling of the land surface to a desired slope or elevation.

Groundwater: Water below the earth's surface, often between saturated soil and rock, that supplies drinking wells and springs. Recharged by runoff.

Gutter: The edge of a street (below the curb) designed to drain water runoff from streets, driveways, parking lots, etc. into catch basins.

Habitat: The specific area or environment where a plant or animal lives. A habitat must provide all of the basic requirements for life (food, water, shelter) and should be free of harmful contaminants and pollution.

Hardpan: A cemented or compacted and often clay-like layer of soil that is impenetrable by roots.

Harmful pollutant: A substance that has adverse effects to an organism.

HRT: Hydraulic residence time

Hydrologic cycle: The cycle of water movement from the atmosphere to the earth and return to the atmosphere through various stages or processes such as precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transpiration.

Illicit connection: Any discharge to a municipal separate storm sewer that is not composed entirely of stormwater and is not authorized by an NPDES permit, with some exceptions (e.g., discharges due to fire fighting activities).

Illicit discharges: Discharges of non-stormwater to the storm drainage system.

Impervious surface: A hard surface area which either prevents or retards the entry of water into the soil mantle as existed under natural conditions prior to development; and/or a hard surface area which causes water to run off the surface in greater quantities or at an increased rate of flow from the flow present under natural conditions prior to development.

Impoundment: A natural or man-made containment for surface water.

Invert: Elevation to the inside bottom of the pipe.

Lake: An area permanently inundated by water with certain minimal dimensions (such as in excess of two meters (7 ft) deep and greater than twenty acres in size as measured at the ordinary high water mark).

Large Municipal Separate Storm Sewer System (MS4): An MS4 located in an incorporated place or county with a population of 250,000 or more, as determined by the latest U.S. Census.

Maximum Extent Practicable (MEP): A standard for water quality that applies to all MS4 operators regulated under the NPDES Stormwater Program. No precise definition of MEP exists.

Medium Municipal Separate Storm Sewer System (MS4): MS4 located in an incorporated place or county with a population of 100,000 or more but less than 250,000, as determined by the latest U.S. Census.

Multi-Sector General Permit (MSGP): An NPDES permit that regulates stormwater discharges from eleven categories of industrial activities.

Municipal Separate Storm Sewer System (MS4): publically-owned conveyance or system of conveyances that discharges to U.S. waters and is designed or used for collecting or conveying stormwater, not a combined sewer, and not part of a publically-owned treatment works (POTW).

Native plant: A plant that naturally occurred in an area before disturbance by humans. Native plants are adapted to the weather, temperature and soil conditions of this region. Native plants require less (if any) fertilizers, pesticides or irrigation; tend to be disease and drought-tolerant.

Natural conveyance system: Swales and small drainage courses, streams, rivers, lakes, and wetlands.

Natural onsite drainage feature: Natural swale, channel, stream, closed depression, wetland, lake.

Nonpoint source pollution (NPS): Pollution that comes from many different sources in a watershed and is carried by storm water runoff into local waterways. Sources of NPS pollution are difficult to identify and control. Typical NPS pollutants are pet waste, lawn fertilizer, pesticides, car washing detergents, litter and sediment.

Nonstructural BMP: A preventative action to protect receiving water quality that does not require construction. Nonstructural BMPs rely predominantly on behavioral changes in order to be effective. Major categories of non-structural BMPs include education, recycling, maintenance practices and source controls.

NPDES (National Pollutant Discharge Elimination System): The name of the surface water quality program authorized by Congress as part of the 1987 Clean Water Act. This is EPA's program to control the discharge of pollutants to waters of the United States (see 40 CFR 122.2).

Nutrient: A primary element necessary for the growth of living organisms. For example, nitrogen and phosphorous, are nutrients required for phytoplankton (algae) growth.

Oil/water separator: A vault, usually underground designed to provide a quiescent environment to separate oil from water. Floatables (e.g., Styrofoam) are also removed.

Outfall: The point where runoff discharges from a sewer pipe, ditch, or other conveyance to a receiving body of water.

Oxygen depletion: Deficit of dissolved oxygen in a water system due to oxidation of organic matter.

Peak flow fate: The peak flow rate associated with the design storm of interest.

Percent impervious: The specific portion of the contributing drainage area that does not allow stormwater to infiltrate, usually expressed as a percent.

Perennial plant: A plant that grows and persists for more than one year. Perennial plants persist as vegetation from year to year or re-sprout from their rootstock annually.

Pervious materials: Pervious materials allow water to soak into the surface by virtue of their porous nature or by "void" spaces in the material.

Phase 1 Stormwater Permit Program: Under Phase I, EPA required NPDES permit coverage for storm water discharges from "medium" and "large" municipal separate storm sewer systems (MS4s) located in incorporated places or counties with populations of 100,000 or more; and eleven categories of industrial activity, one of which is construction activity that disturbs five or more acres of land.

Phase 2 Stormwater Permit Program: The Phase II Program requires NPDES permit coverage for storm water discharges from certain regulated small municipal separate storm sewer systems (MS4s); and construction activity disturbing between 1 and 5 acres of land.

Point discharge: The release of collected and/or concentrated surface and storm water runoff from a pipe, culvert, or channel.

Point source pollution: Water pollution entering the environment from a single point (i.e. factory pipe).

Pollutant loading: The total quantity of pollutants in stormwater runoff. Typically calculated as (concentration x flow rate x storm duration) or (concentration x total storm volume).

Pollution: Any substance that exists in the environment that is undesirable or harmful for that environment.

Reach: A length of channel with uniform characteristics.

Receiving waters: Bodies of water where surface runoff is discharged.

Recharge: The flow to groundwater from the infiltration of surface and stormwater runoff.

Regulated MS4: Any MS4 covered by the NPDES Stormwater Program (regulated, small, medium, or large MS4s).

Retention: The process of collecting and holding surface and storm water runoff with no surface outflow.

Retrofit: The modification of an existing development with or without an existing stormwater management system through the construction and/or enhancement of one or more stormwater treatment devices.

Riparian: Pertaining to the banks of rivers and streams, and sometimes also wetlands, lakes, or tidewater.

Riprap: A facing layer or protective mound of stones placed to prevent erosion or sloughing of a structure or embankment due to the flow of surface and storm water runoff.

Runoff coefficient: The percentage of rainfall volume that will become runoff.

Runoff: Drainage or discharge that leaves an area as surface flow or as pipeline flow. Runoff reaches a channel or pipeline by either surface or sub-surface routes.

Sanitary sewer system: The system that collects and transports sanitary wastewater from building plumbing systems to a wastewater treatment plant for treatment (i.e. wastewater from toilets, showers, sinks, water fountains).

Sediment: Soil, sand, and minerals washed from land into water, usually after rain. Sediment can destroy fish-nesting areas, clog animal habitats, and cloud waters so that sunlight does not reach aquatic plants.

Separate storm sewer: A sewer carrying only runoff from storm events.

Sheet flow: The portion of precipitation that moves initially as overland flow in very shallow depths before eventually reaching a stream channel.

Site plan: A graphical representation of a layout of buildings and facilities on a parcel of land.

Small Municipal Separate Storm Sewer System (MS4): Any MS4 that is not regulated under Phase I of the NPDES Stormwater Program and Federally-owned MS4s.

Source control: Action to prevent pollution where it originates.

State Revolving Fund (SRF): A State-managed revolving fund providing loans for specific water pollution control purposes. Under the SRF program, States and municipalities are

primarily responsible for financing, constructing, and managing wastewater treatment facilities. The SRF program is based on the 1987 Amendments to the CWA which replaced the Construction Grants program with the SRF program.

Storm drainage system: The system built to collect and transport runoff to prevent flooding. This system consists of storm drains, drainage ditches, pipes and culverts. Anything that flows into the storm drainage system flows directly into local creeks and waterways. (Storm water runoff is not treated.) Storm drainage systems are completely separate from those that carry domestic and commercial wastewater (sanitary sewer system).

Stormwater runoff: Water from rain, melted snow or landscaping irrigation that flows over land and into local creeks, streams and waterways. Runoff carries pollutants in it.

Stormwater facility: Facilities that control the discharge of stormwater and that remove pollutants. Stormwater facilities included storage facilities (ponds, vaults, underground tanks, and infiltration systems); water quality facilities (wet ponds, biofiltration swales, constructed wetlands, sand filters, and oil/water separators); and conveyance systems (ditches, pipes, and catchbasins).

Stormwater Pollution Prevention Plan (SWPPP): A plan to describe a process whereby a facility thoroughly evaluates potential pollutant sources at a site and selects and implements appropriate measures designed to prevent or control the discharge of pollutants in stormwater runoff.

Structural BMP: Constructed facilities or measures to help protect receiving water quality and control stormwater quantity. Examples include storage, vegetation, infiltration, and filtration.

Surface water: The water that rests on top of the earth in streams, lakes, rivers, oceans and reservoirs and is open to the atmosphere (i.e. rivers, lakes, creeks, streams, etc).

Swale: A shallow drainage conveyance with relatively gentle side slopes, generally with flow depths less than one foot.

Time of concentration: The amount of time it takes a drop of water falling in the hydraulically most distant point in the watershed to reach the outlet of that watershed.

Tool box: A term to describe the activities and materials that regulatory agencies have created to assign people in the stormwater program in an effective and cost-efficient manner. The eight components include: 1) fact sheets; 2) guidance documents; 3) menu of BMPs; 4) compliance assistance; 5) information clearing house; 6) training and outreach efforts; 7) technical research; and 8) support for demonstration projects.

Total Maximum Daily Load (TMDL): The maximum amount of pollutants which can be released into a waterbody without adversely affecting the water quality.

Toxic substances: Those chemical substances, such as pesticides, plastics, heavy metals, detergents, solvents, or any other harmful materials, which are poisonous, carcinogenic, or otherwise directly harmful to human health and the environment.

Tributary: A stream that flows into a larger stream or other body of water.

Turbidity: A measure of the ability of the solids in water to deflect light. Often referred to as a measure of the “cloudiness” or “muddiness” of water.

Urban runoff: Stormwater from urban areas, which tends to contain heavy concentrations of pollutants from urban activities.

Urbanized area (UA): A Bureau of the Census determination of a central place (or places) and the adjacent densely settled surrounding territory that together have a minimum residential population of 50,000 people and a minimum average density of 1,000 people/square mile. This is a simplified definition of a UA, the full definition is very complex.

Wastewater: Usually refers to effluent from a sewage treatment plant.

Water quality: The biological, chemical and physical conditions of a waterbody; a measure of the ability of a waterbody to support beneficial uses.

Water quality criteria: Specific levels of water quality that, if achieved, are expected to render a body of water suitable for its designated use. The criteria are based on specific levels of pollutants that would make the water harmful if used for drinking, swimming, farming, fish production, or industrial processes.

Water quality design flow: The flow which is required or desired to be treated by the structural BMP device. Often times the design flow is associated with a rainfall depth of intensity that has a high probability of occurrence or frequency (e.g., 50-90% of all rainfall events in a given year occur at an intensity of 0.2 in/hr).

Water quality standards: State-adopted and EPA-approved ambient standards for waterbodies. The standards cover the use of the waterbody and the water quality criteria that must be met to protect the designated use or uses.

Watershed: A geographic area in which water, sediments, and dissolved materials drain to a common outlet, typically a point on a larger stream, a lake, an underlying aquifer, an estuary, or an ocean. A watershed is also sometimes referred to as the "drainage basin" of the receiving waterbody.

Watershed: The land area that drains water to a particular stream, lake or river.

Wetland: An area inundated or saturated by ground or surface water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas (U.S. Army Corps of Engineers Regulation 33 CFR 328.3 (1988)).

Wetlands protection: Activities to protect and restore wetlands.

Wet pond: Drainage facilities for water quality treatment that contain a permanent pool of water. They are designed to optimize water quality by providing long retention times (on the order of a week or more) to settle out particles of fine sediment to which pollutants such as heavy metals adsorb, and to allow biologic activity to occur that metabolizes nutrients and organic pollutants.

APPENDIX B

CONSTRAINTS ON THE STORMWATER MANAGER

Over the past 40-50 years, several surveys of stormwater planners, engineers and regulatory authorities have been conducted to determine the state-of-the-practice at the time of the survey. Included in those surveys also have been questions regarding the impediments to the implementation of research results/newer techniques in the design of a modern stormwater plan. This appendix summarizes the results of four survey activities. The first is a comparison of surveys of engineering practice in 1967 and 1997 (based on Pitt et al., 1998) – one conducted in Wisconsin and one nationwide survey (conducted as part of Phase I of this research). The second survey was presented during the Phase I activity of this project. Stormwater regulatory authorities at all levels of government were surveyed about the impediments to stormwater management and, in particular, to the use of infiltration. The full results of this survey are provided in Clark et al. (2006). The third and fourth studies focused on the acceptance by the public of low impact development practices (Nowacek, 2005; KICP, 2009).

In 1967, researchers at the University of Wisconsin surveyed engineers in the state to determine what would define adequate stormwater drainage and primarily focused on design procedures for stormwater conveyance systems (Ardis et al., 1969 as summarized in Lilburn, 1997). A follow-up survey was conducted in 1997 by Lilburn and broadened the focus of the 1967 Wisconsin survey to a national survey of practices and trends. The purpose of this expansion was two-fold: 1) to determine if design procedures had been updated in the intervening thirty years since much research effort had been focused in the field of hydrology, and 2) to evaluate whether the practices that were commonly used in Wisconsin were specific to the state or the region. The primary conclusion reached in the Lilburn survey was that regulations governed acceptable design methods and levels of service for most projects (about 75%). Most of the applicable regulations were established by local or county authorities, indicating a regional focus, based on the regional response to federal and state regulations. The typical design storm for stormwater management was the 10-year storm, although designs depending on land use may use design storms ranging from the 2-year to 100-year design storm. Many engineers that designed stormwater quality devices for the 10-year storm used the 100-year storm to evaluate flooding concerns. The two most common design methods were the rational method and NRCS (SCS) procedures. Time of concentration formulas (such as the Kirpich, Izzard, or TR-55 equations) were used to determine the times of concentration by 65% of the respondents. System failure in 1997 was typically recognized when manhole covers popped off, when water collected in basements, or when water rose above curbs. Usually, occurrences more often than once every 10 years were indicative of system failure.

The 1997 survey respondents also identified the water quality concerns they associate with stormwater runoff. The most widespread were sediment (63%), nutrients (35%) and metals (34%). Other frequent answers were oils and grease, bacteria, toxicants, CSOs, floatables, and salts. A few survey participants answered the question from a different angle and stated their main water quality concerns dealt with permit and discharge limits.

Successful implementation of state-of-the-art stormwater management practices requires an understanding of the constraints faced by planners (engineers, regulatory agencies and the public). The survey conducted as part of the Phase I research was national in its distribution and response. Responses were received from all nine U.S. EPA rainfall zones (Figure B-1). However, the number of responses was limited (37%). For the 46 responding individuals by the end date of the survey, respondents fell into the following categories: state environmental protection agency employees responsible for stormwater management – 11 (24%), county or regional employees responsible for stormwater management – 14 (30%) and city employees responsible for stormwater management – 21 (46%). No observable pattern could be found related to U.S. EPA rainfall region or general area of the country. The responses are summarized below and categorized according to state, regional or local entity. Results were compared to the results of a Wisconsin survey on successful implementation, and barriers thereto, of infiltration practices.

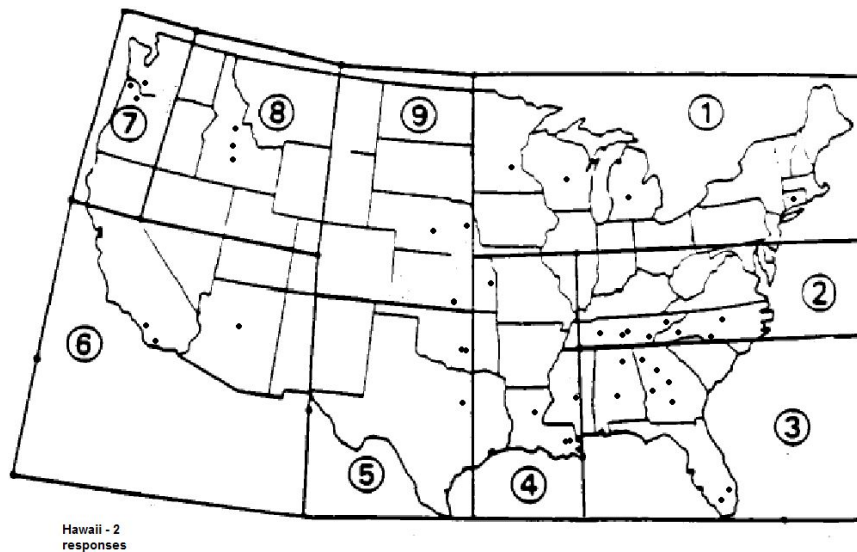


Figure B-1. Survey Respondent Locations (by EPA Rainfall Zone).

Question: In your municipality/agency/federal facility/water management district, who is primarily responsible for setting policy regarding stormwater management decisions and guidance?

The results showed no trend by area of the country. The differences were noted at the level of government (Figure B-2). At the state level, it was always a designated department while at a more local/regional level, the responsibilities were divided among individuals or departments, including having stormwater management's ultimate responsibility resting with elected officials. Having elected officials "in charge" of specific areas of government has the advantage of providing taxpayer representation to the process, but it has two significant drawbacks: 1) potential lack of training/education in engineering, hydrology, and/or water resources, and 2) periodic turnover in elected officials (thus requiring new training). This use of elected officials to head public works departments, however, does not imply that these are the officials making the final design decisions – these people have trained staff working in the appropriate county or local departments.

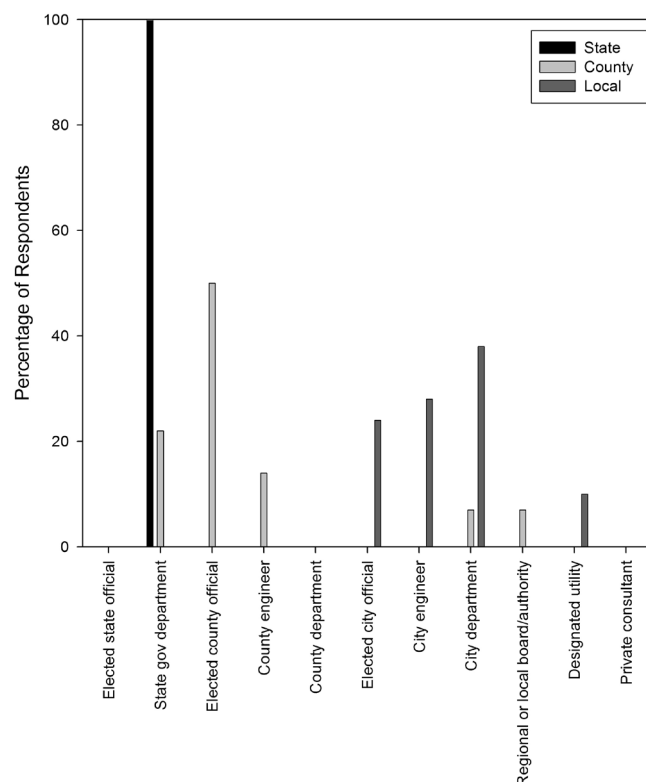


Figure B-2. Where Does the Responsibility for Stormwater Management Rest?

Question: What is your role in the stormwater management process?

This question was designed to evaluate the activities performed by the representative agencies (Figure B-3). The results showed no trend by region of the country or rainfall zone. All differences were noted at the level of government questioned. In general, the state government was concerned with regulatory development, whether through actual development or through providing information and recommendations to those developing the regulations and guidance. In addition, state government did provide public education and in some states, provided inspection and enforcement. At the county and local levels, the obligations/responsibilities were more varied. In many cases, the government agencies were charged with enforcing existing state and federal regulations. Therefore, their regulatory development involved creating or modifying development codes to meet state and federal requirements. The bulk of inspection and enforcement fell to the local governments, with the percentage saying they had responsibility for this increasing as the government came “closer to the people being regulated.” The county and local governments typically also had responsibility for determining effectiveness of the treatment devices, whether it was called “monitoring” or “outcome research.” Public education also mostly fell to the regional levels of government. In addition, for local and regional governments, responsibilities became more varied, including flooding issues, TMDL requirements, erosion control and rainfall data collection.

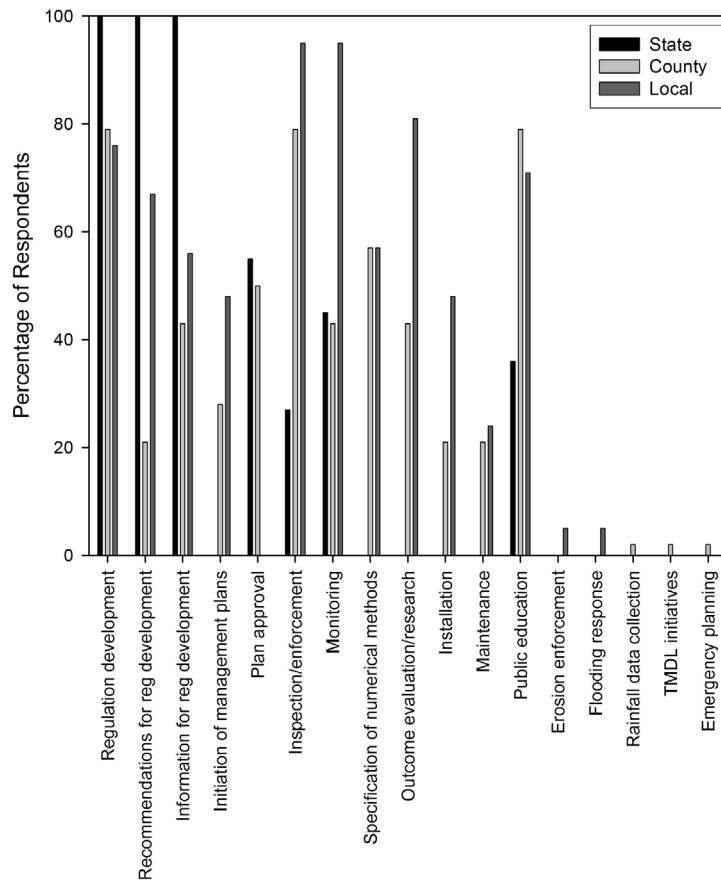


Figure B-3. What Is Your Role in the Stormwater Management Process? What Responsibilities Does Your Job Entail?

Question: Is locally developed guidance document available for stormwater management planning?

As seen in Figure B-4, the states and counties responded that locally developed guidance was available for planning. However, at the local level, approximately two-thirds of respondents stated that locally developed guidance was available, while one-third stated that it was not. The interpretation of locally developed guidance was left to the respondent. A review of the supplied materials indicated that most of the local guidance was related to drainage design, including design storms and drainage system sizes and materials. State and county guidance typically was broader-based and included both drainage design and on-site stormwater management practices. For those states where state-level guidance documents and regulations were available, many regional government requirements required compliance with the state guidance documents.

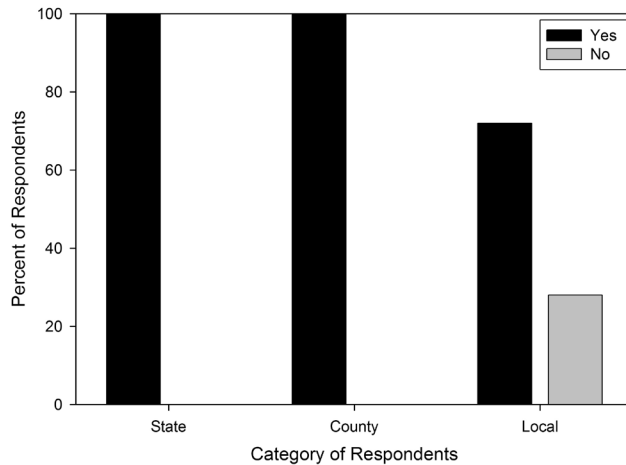


Figure B-4. Is Locally Developed Guidance Available?

Question: Please list guidance documents or databases used in making recommendations or decisions related to stormwater management.

State-level decisions related to stormwater management included state stormwater manuals and guidelines, as well as U.S. EPA regulations and guidance documents. At the county/regional level, drainage design is included with stormwater management in the range of guidance documents used. These include rules related to drainage standards, soil erosion standards and guidelines, and development. Others include subdivision rules and regulations, floodplain ordinances, county stormwater manuals, and receiving water quality requirements and databases. City level guidance came from a wider variety of sources, including U.S. EPA guidance, state stormwater manuals, TMDL and NPDES permit requirements, local watershed plans, water quality management plans, drainage design manuals, flood studies, citizen complaints regarding drainage, flooding, and water quality problems, and city drainage design manuals. Data used to support city-level stormwater management decisions came from stream monitoring databases, river basin assessment reports, water quality monitoring studies, and other research and literature.

Question: When regulations or ordinances regarding stormwater management are considered or modified, what are the steps in the decision making process?

In general, changes to guidance documents and permits at any level of government were performed in response to changes in regulations, typically U.S. EPA regulations. In some cases, changes to the regulations and ordinances also may result from citizen complaints. At the state level, the steps for obtaining and modifying permits, as well as modifying regulations, are outlined in the permits, supporting documentation, and state regulation. At the county and city level, ordinances and regulations were modified usually as a result of one of two actions, either changes in federal and state regulation, or citizen complaints. Changes are approved by the elected officials after a public comment and response period.

Question: Is stormwater infiltration considered along with surface discharge management options in the guidelines?

The results, illustrated in Figure B-5, showed that there are still some municipalities where infiltration is not considered as part of stormwater management, although infiltration is considered for stormwater management at the county and state level. The data does not document why infiltration is not considered an option.

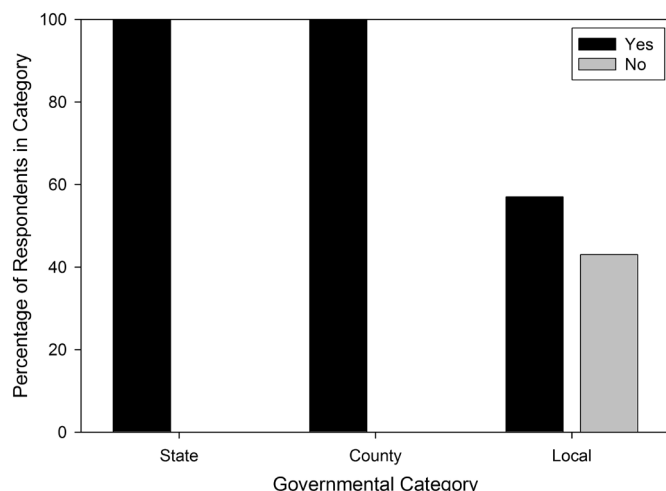


Figure B-5. Is Infiltration a Stormwater Management Option?

Question: If infiltration is considered, what guides the decision process between infiltration and surface discharge?

The results (Figure B-6) showed that, at the state and county level, local site characteristics determined whether infiltration can be considered. Local characteristics, as listed on the survey, included soil type, infiltration ability, shallow groundwater, etc. In addition, anticipated stormwater quality was a factor considered by many state and county managers. This indicates that the potential for groundwater contamination is a factor in allowing or refusing infiltration practices. Development type also was listed by the state government, indicating that the regulations may not allow certain practices at certain sites. At the local levels, a variety of factors influenced the acceptability of infiltration devices, including disease vector control, public acceptance, familiarity, and the existence of other ordinances that would encourage or discourage development. In many locales, ordinances on subdivision of land and the required infrastructure also must be considered and met. The need for specific levels of infrastructure may reduce the ability and the land available for infiltration.

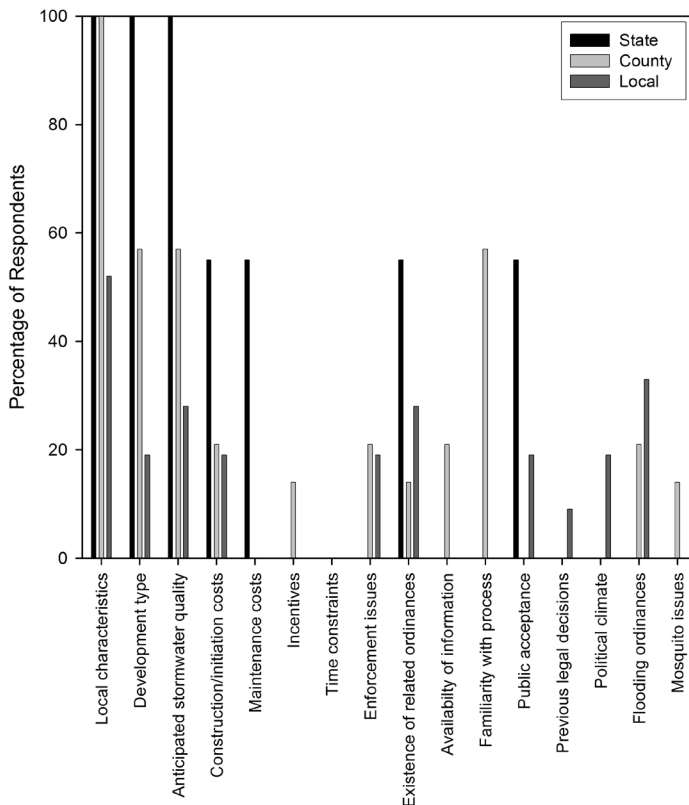


Figure B-6. What Factors Affect the Decision to Use Infiltration as a Part of Stormwater Management?

In summary, the survey indicated that potentially dysfunctional relationships exist between regulatory agencies and stormwater management agencies, depending on the level of government associated with each. It was interesting to note that states thought that cities should be maintaining stormwater management facilities, while the cities wanted to ensure that the developer was able to provide for their proper care and maintenance over their life. Both have the same goal but diverge in the ultimate responsibility for maintenance and function. These divergent views can create barriers, but other surveys (Nowacek et al., 2003) described methods used in some localities to overcome them.

These constraints were seen also in the survey “Social and Institutional Barriers to Stormwater Infiltration” (Nowacek et al., 2003). This survey, conducted in Dane and Milwaukee counties (Wisconsin), interviewed practitioners at all levels of the planning and implementation process: developers, builders, design engineers, municipal engineers, state and local regulators and homeowners (who would be required, in many cases, to maintain lot-based infiltration practices). The Nowacek survey agreed with the primary result of the Phase I survey; the issue of maintenance and the requirements of municipal regulations are often seen as the greatest barriers to the installation of infiltration devices. The Wisconsin survey highlighted the problems of zoning ordinances and/or technology-based regulations. Zoning ordinances often dictated lot sizes and discouraged the use of cluster development with open space set aside in the total development (zoning ordinances often call for the ‘open space’ to be a part of the individual lot by requiring larger lot sizes in areas where the ‘rural character’ is to be preserved). Many respondents criticized regulations as inflexible. The proposal by the authors of that study and

several interviewees was the use of standards, i.e., where a goal would be outlined for all development, which would allow the developer, with the consent of the municipal planner, to determine how to best achieve the community goals.

Several of the barriers to infiltration were practice-dependent. For example, rain gardens were not favored by homeowners who objected to standing water, while narrower streets were not approved by municipalities who saw narrow streets as an impediment to their ability to deliver services. The issue of cluster developments with large open spaces was addressed earlier in this section. One potential solution that was currently available was the Planned Use Development (PUD) section of the zoning ordinances. PUD design differed in that the flexibility allowed under the PUD regulations allowed for the regulatory flexibility to install infiltration devices. (Nowacek et al., 2003). Another dichotomy was noted by several respondents. Current development practices involve dividing the entire site into lots with the developer installing the utility infrastructure. The lots would be sold to individuals who would hire a builder (possibly a different entity) to build their home. The builder and homeowner would develop the plans for the individual lot, yet the developer had obtained the original permits, including or excluding infiltration requirements. The question was raised as to how to ensure development plans and permits were met after the lot was sold and a new construction entity was hired for the individual lot. Deed restrictions were suggested by respondents as one method for ensuring requirements were met.

A recent study in the Denver area (KICP, 2009) highlighted barriers to the use of low-impact development practices for stormwater management. These results reinforce the concerns identified above regarding implementation of innovative stormwater management. The barriers in order of highest concern to lowest included the following:

- ◆ High concern
 - No economic incentive
 - LID not incorporated early in the design process
 - Benefits of LID difficult to measure
 - Perceived design, construction and maintenance costs
 - “Mixed messages” from different governmental departments
 - Soils concerns (swelling, poor infiltration, high groundwater table)
 - Lack of successful demonstration projects in area
 - Maintenance and durability concerns
 - Guidance documents “recommend” LID and do not “require” LID
- ◆ Moderately-high concern
 - Long-term ownership issues (Private versus public)
 - Specialized construction techniques required
 - Familiarity with traditional practices and lack of training in LID
 - Limited, conflicting, and/or potentially confusing technical guidance and ordinances

- Existing requirements for traditional drainage and stormwater management structures even if LID is used
- Other water-quality alternatives easier to design, construct and maintain
- Liability and safety fears
- Water rights issues
- Standing water concerns
- Public perception

While each of these studies is small in size, they do indicate widespread concerns by the development, construction and regulatory community about transitioning to small-scale, dispersed stormwater management at its source. These are barriers that are outside the scope of this project to address, but that will have to be addressed by the appropriate agencies and groups if implementation of dispersed control practices is to be encouraged.

APPENDIX C

REGULATORY ENVIRONMENT

The table in Chapter 2.0 contains the permit information and the link (as of Fall 2008) to the state stormwater agencies. The table in this appendix provides additional information on those programs. However, as noted by several reviewers of this document, many of these regulations and the state guidance documents are undergoing substantial revision and the user should not rely on this information to be current.

Table C-1. Stormwater Management Agencies (www.stormwaterauthority.org).

State	Agency and Program Notes
Alabama	Agency: The Alabama Department of Environmental Management (ADEM), http://www.adem.state.al.us/waterdivision/waterdivisionpp.htm Program Information: closely modeled after the federal NPDES program, which requires that stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established as yet. Permits required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s). Additional permitting requirements exist in the coastal regions of Baldwin and Mobile counties.
Alaska	Agency: U.S. EPA administers NPDES permits in the state, http://dec.alaska.gov/water/wnpspc/stormwater/stormwater.htm Program Information: Stormwater devices shall treat the 2-year, 6-hour rain event and be capable of removing particles $> 20 \mu\text{m}$ during the design event. The Alaska Department of Environmental Conservation (ADEC) reviews and certifies all EPA permits issued in the state, plus ADEC requires that all engineering plans be submitted for review. Permits Required for: construction sites, certain industrial sites, and Municipal Separate Storm Sewer Systems (MS4s) in Alaska.
Arizona	Agency: The Arizona Department of Environmental Quality (ADEQ). EPA Region 9 permits for all Indian lands in Arizona, http://www.azdeq.gov/environ/water/permits/stormwater.html Program Information: AZPDES closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable (MEP). Numeric treatment standards specific to stormwater have not been established at the state level. Permits Required for: industrial activity, construction activity, and municipal separate storm sewer systems (MS4s).
Arkansas	Agency: The Arkansas Department of Environmental Quality (ADEQ), http://www.adeq.state.ar.us/water/branch_permits/general_permits/stormwater/default.htm Program Information: Closely modeled after the federal NPDES regulations, requiring that stormwater be treated to the maximum extent practicable. To date, Arkansas has not established numeric stormwater treatment requirements at the state level. Permits required for: construction sites disturbing $\geq$ one acre must obtain permit coverage, municipal separate storm sewer systems (MS4), and NPDES Phase I communities.
California	Agency: California State Water Resources Control Board (CASWRCB), http://www.waterboards.ca.gov/water_issues/programs/stormwater/ Program Information: The CASWRCB oversees 9 Regional Water Resources Control Boards that develop regional stormwater requirements. Many large municipalities have stormwater programs with additional treatment requirements. To date, most California's stormwater programs require treatment to the maximum extent practicable. Numeric treatment requirements have not been established at the state or regional level. Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s). In addition to state, regional, and local regulations, there are a number of established and proposed TMDLs impacting California's watersheds.

State	Agency and Program Notes
Colorado	Agency: Colorado Department of Public Health and Environment (CDHE), http://www.cdphe.state.co.us/wq/PermitsUnit/stormwater/index.html Program Information: Mirrored after the federal NPDES program, requiring that stormwater be treated to the maximum extent practicable (MEP). No numeric requirements for stormwater pollutant removal have been established at the state level, but many stringent regional and municipal regulations exist. Many municipalities reference the Denver Urban Drainage and Flood Control Manual, which was originally developed for the Denver metro area. Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and designated Municipal Separate Storm Sewer Systems (MS4s).
Connecticut	Agency: Connecticut Department of Environmental Protection (CTDEP), http://www.ct.gov/dep/cwp/view.asp?a=2721&q=325702 Program Information: Closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Treatment devices must be designed to remove 80% of the total suspended solids (TSS) load. There are a number of established and proposed TMDLs on Connecticut's watersheds, which may impact stormwater treatment requirements. Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).
Delaware	Agency: Delaware Department of Natural Resources and Environmental Control (DEDNR), http://www.swc.dnrec.delaware.gov/Pages/SedimentStormwater.aspx Program Information: Stormwater highly regulated because over 90% of Delaware's water bodies are polluted. Many TMDLs exist. Treatment devices shall manage the rate and volume of flow from the two-inch NRCS Type II rainfall event, up to a maximum of one-inch of runoff." Acceptable treatment devices remove at least 80% TSS, address water impairments, and treat specific pollutants if the pollutant is linked to the impairment. In New Castle County north of the Chesapeake and Delaware Canal, treatment devices shall be designed based on the 2-, 10-, and 100-year rain event. Projects in New Castle County, south of the Chesapeake and Delaware Canal, Kent County, and Sussex County, post-development peak discharges cannot exceed pre-development rates for the 2- and 10-year storms. Other impaired water bodies will have restrictions and regulations to guide solutions for stormwater runoff. Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
District of Columbia	Agency: U.S. Environmental Protection Agency. Program Information: Federal NPDES program requirements. A number of D.C. rivers and watersheds, such as the Anacostia and Potomac rivers, Rock Creek, and other area rivers, are impaired and that compliance with an established Total Maximum Daily Load (TMDL) could be required. Permits Required for: construction sites, certain industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Florida	Agency: Florida Department of Environmental Protection (FDEP). FDEP subsequently delegated authority to four of the five regional Water Management Districts (WMDs), http://www.dep.state.fl.us/water/stormwater/npdes/index.htm Program Information: The FDEP and WMDs share implementation of this program, depending on the activity type. Regulations adopted largely to address the specific needs particular to the geographic and hydrologic conditions found in each WMD's jurisdiction. Each WMD and the DEP has adopted either a design manual or handbook that describes treatment devices and criteria for addressing water quality and quantity issues. Devices must remove at least 80% of the average annual pollutant load for stormwater discharges to Class III (recreational) waters. A 95% removal level was set for discharges to sensitive waters such as potable supply waters (Class I), shellfish harvesting waters (Class II), and Outstanding Florida Waters (OFWs). WMDs have established performance standards to minimize flooding by limiting the post-development stormwater peak discharge rate and, in some cases such as closed basins, the stormwater volume. Design storm frequencies, as well as return intervals are specified by the WMDs. Permits Required for: New development, while redevelopment and retrofit projects are largely permitted on a case-by-case basis.
Georgia	Agency: Georgia's Environmental Protection Division (GAEPD), http://www.gaepd.org/Documents/techguide_wpb.html#sw Program Information: mirrored after the federal NPDES program, requiring that stormwater be treated to the maximum extent practicable (MEP). In addition, the Metropolitan North Georgia Water Planning District has developed regional and watershed specific plans for watershed management, wastewater management and water supply and conservation in a 16-county area - Bartow, Cherokee, Clayton, Cobb, Coweta, DeKalb, Douglas, Fayette, Fulton, Forsyth, Gwinnett, Hall, Henry, Paulding, Rockdale and Walton. Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Hawaii	Agency: Hawaii Department of Health's Clean Water Branch (CWB), http://hawaii.gov/health/environmental/water/cleanwater/forms/genl-index.html Program Information: mirrored after the federal NPDES program, requiring that stormwater be treated to the maximum extent practicable (MEP). No numeric requirements for stormwater pollutant removal exist at the state level, but regional and municipal regulations are in place. Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Idaho	Agency: U.S. EPA Region 10 with the exception of Indian country. The Suck Valley Reservation is the only land that is covered under EPA. The Clean Water Act Idaho reviews and certifies all EPA permits issued in the state, http://www.deq.state.id.us/water/prog_issues/storm_water/overview.cfm Program Information: Federal NPDES Program. No numeric requirements for stormwater pollutant removal have been established at the state level, but regional and municipal regulations are in place. For example, the City of Boise has created a sliding scale for stormwater quality requirements based on the percent of impervious surface on the site. Permits Required for: construction sites, certain industrial sites, and Municipal Separate Storm Sewer Systems (MS4s) in Idaho. As described in section 401 of Additional permit requirements are outlined in section 9 of the Construction General Permit.

State	Agency and Program Notes
Illinois	Agency: The Illinois Environmental Protection Agency (IEPA), http://www.epa.state.il.us/water/permits/storm-water/index.html Program Information: mirrors the federal NPDES stormwater requirements, requiring that stormwater be treated to the maximum extent practicable. No numeric requirements for stormwater pollutant removal have been established at the state level, but more stringent requirements do exist, especially in the greater Chicago area and watersheds draining to Lake Michigan. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).
Indiana	Agency: Indiana Department of Environmental Management (IDEM), http://www.in.gov/idem/4899.htm Program Information: mirrored after the federal NPDES program, requiring that stormwater be treated to the maximum extent practicable. No numeric stormwater treatment requirements have been established at the state level, but stringent regional and municipal regulations are in place in some parts of the state. Marion County, for example, requires the removal of 80% of the annual total suspended solids (TSS) load. Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).
Iowa	Agency: The Iowa Department of Water Quality (DWQ), http://www.iowadnr.com/water/stormwater/index.html Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established at the state level. Additional requirements may exist at the municipal level. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Kansas	Agency: Kansas Department of Health and Environment (DHE), http://www.kdheks.gov/stormwater/ Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established at the state level. Permits Required for: all construction sites disturbing $\geq$ one acre, many industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Kentucky	Agency: Kentucky Department of Environmental Protection (DEP), http://www.water.ky.gov/permitting/wastewaterpermitting/KPDES/storm/ Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established at the state level. More stringent treatment requirements exist at the county and local level especially in Lexington-Fayette County where sensitive karst topography drives treatment objectives. Permits Required for: all construction sites disturbing $\geq$ one acre, many industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Louisiana	Agency: The Louisiana Department of Environmental Quality (LDEQ). The LDEQ has established the Louisiana Pollutant Discharge Elimination System (LPDES), http://nonpoint.deq.louisiana.gov/wqa/default.htm Program Information: mirrors the requirements of the federal NPDES Phase II program. Numerical stormwater treatment requirements are not in place at the state level, but stormwater must be treated to the maximum extent practicable (MEP). A number of Louisiana's large municipalities also have stormwater programs in place, and additional treatment requirements are possible at the local level. TMDL compliance will be required when working in a watershed draining to an impaired waterbody. Permits Required for: construction sites $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Maine	Agency: Maine Department of Environmental Protection (MEDEP), http://maine.gov/dep/blwq/docstand/stormwater/index.htm Program Information: Rules address four primary stormwater treatment objectives: effective pollutant removal, cooling of stormwater runoff, channel protection, and flood control. Specific treatment devices and design criteria specified to meet the four management objectives. The State has moved away from using total suspended solids (TSS) as a surrogate pollutant in favor of more stringent standards which result in more effective removal of nutrients, metals and other stormwater pollutants. All proprietary devices must be evaluated under a DEP testing protocol to establish performance capabilities. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Maryland	Agency: Maryland Department of the Environment (DOE), http://www.mde.state.md.us/Programs/WaterPrograms/SedimentandStormwater/home/index.asp Program Information: Regulated sites must comply with design manual requirements. The primary goal is 80% removal of annual Total Suspended Solids (TSS) load and 40% removal of the Total Phosphorus (TP) load. Only devices approved by the DOE and designed in accordance with Maryland's Stormwater Design Manual may be used. Exceptions may exist for retrofits or where the DOE approves a particular device for a unique project. For new developments, treatment devices must safely convey the 100-year storm and provide extended detention of the 1-year, 24-hour storm event. Also, any device without a permanent pool must drain within 48 hours of a storm event. For eastern shore watershed projects, peak discharge rate may not exceed the predevelopment peak discharge rate for the 2-year storm event. For western shore watershed projects, the peak discharge rate may not exceed the predevelopment peak discharge rate for the 10-year storm event. Many counties in Maryland have their own stormwater requirements and approval processes. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Massachusetts	Agency: U.S. EPA Region 1. MADEP reviews the conditions of each permit, and certifies the program unconditionally or with specific conditions. MADEP signs each NPDES permit, creating a separate state and federal permit, http://www.mass.gov/dep/water/wastewater/stormwat.htm Program Information: MADEP has state standards for stormwater discharges (enforced through different MADEP regulations, including, but not limited to, the Mass. Wetlands Protection Act regulations (310 CMR 10.00), Mass. 401 Water Quality Certification regulations (314 CMR 9.00), and Mass. Surface Water Quality Discharge Standards (314 CMR 3.00 and 4.00). Stormwater discharges from new development and redevelopment projects located in regulatory jurisdictional areas must meet the standards contained in the MADEP Massachusetts Stormwater Management Policy. Source controls, pollution prevention measures and treatment devices must be designed to remove 80% of the Total Suspended Solids (TSS) load. Water quality devices must treat the first one-half-inch of runoff. In critical areas, such as shellfish beds, coldwater fish habitats, public swimming beaches, and public drinking water recharge areas and reservoirs, devices must treat the first 1-inch of runoff. Recharge must be provided to offset the recharge lost due to site development to the maximum extent practicable. Peak discharges must be attenuated for the 2-year and 10-year, 24-hour storm, as well as for the 100-year 24-hour storm if flooding is possible. Additional treatment is required for land uses with higher potential pollutant loads. Permits Required for: construction sites disturbing $\geq$ one acre, and for many industrial sites under the Multisector General Permit. The Stormwater General permit for Small Municipal Separate Storm Sewer Systems (MS4s) was issued jointly by EPA and the MA DEP in Massachusetts in 2003.
Michigan	Agency: Michigan Department of Environmental Quality (MDEQ), http://www.michigan.gov/deq/0,1607,7-135-3313_3682_3716---,00.html Program Information: mirrored after the federal NPDES program, requiring that stormwater be treated to the maximum extent practicable (MEP). Numeric treatment requirements specific to stormwater have not been established at the state level. Many of the large municipalities have stormwater programs of their own, such as Wayne County, with additional treatment requirements. Requirements also may exist for watersheds draining to the Great Lakes. Permits Required for: all construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Small Sewer Systems (MS4).
Minnesota	Agency: Minnesota Pollution Control Agency (MPCA), http://proteus.pca.state.mn.us/water/stormwater/index.html Program Information: The MPCA stormwater program incorporates the requirements of both the federal NPDES permits and the Minnesota State Disposal System (SDS) permit into a single permit referred to as NPDES/SDS permit. Currently, Minnesota does not have numeric stormwater treatment requirements at the state level. Treatment devices must treat stormwater to the maximum extent practicable (MEP). The state may impose specific phosphorous removal requirements. The Minneapolis/St Paul stormwater program has specific phosphorus removal requirements typically ranging from 20-42% total phosphorus removal. Local regulations likely in many municipalities, including Minneapolis/St Paul, and specific watershed districts (particularly around Lake Minnetonka). Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Mississippi	Agency: Mississippi Department of Environmental Quality (DEQ), http://www.deq.state.ms.us/MDEQ.nsf/page/NPS_Urban_Stormwater_Construction?OpenDocument Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established at the state level. Mississippi published a draft stormwater guidance manual for MS4's in 2002, but a final draft of the document is still not available. Additional requirements may exist in the coastal regions. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Missouri	Agency: Missouri Department of Natural Resources (DNR), http://www.dnr.mo.gov/env/wpp/stormwater/index.html Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable (MEP). Numeric treatment requirements specific to stormwater have not been established at the state level. The St. Louis Metropolitan Sewer District (MSD) has adopted a program for proprietary products including filtration technologies for General Use Level, and hydrodynamic separation devices for Re-development Use Level and Highway Use Level applications. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Montana	Agency: Montana Department of Environmental Quality (MDEQ), http://www.deq.state.mt.us/wqinfo/MPDES/StormWater/ms4.asp Program Information: Permits developed and issued under the authority of the Montana Pollution Discharge Elimination System (MPDES). Montana's stormwater program requires that stormwater be treated to the maximum extent practicable (MEP). Requirements at the state level do not include numeric water quantity or quality parameters, although the state is concerned about water quality associated with the mining industry. Permits Required for: all construction sites disturbing $\geq$ one acre, many industrial sites, and all designated MS4's.
Nebraska	Agency: Nebraska Department of Environmental Quality (DEQ), http://www.deq.state.ne.us/WaterPer.nsf/Pages/NPDES Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable (MEP). Numeric treatment requirements specific to stormwater have not been established at the state level. The state has delegated authority to Omaha and Lower Platte South Natural Resources District to develop and implement stormwater standards and all projects are required to meet these standards. Be advised that there may be additional permitting requirements at the county and municipal level. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Nevada	Agency: Nevada Department of Environmental Protection (DEQ), http://ndep.nv.gov/BWPC/storm01.htm Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established at the state level. The state has delegated authority to localities to develop and implement stormwater plans, in particular, the areas around Lake Tahoe, Lake Mead, and Truckee River. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
New Hampshire	Agency: U.S. EPA Region 1, http://des.nh.gov/organization/divisions/water/stormwater/index.htm Program Information: As described in section 401 of the Clean Water Act, New Hampshire reviews and certifies all EPA permits issued in the state. New Hampshire's stormwater program requires stormwater be treated to the maximum extent practicable. Numerical stormwater treatment requirements are not currently in place at the state level, but water quality parameters for individual streams and rivers may impose additional requirements. The New Hampshire Department of Environmental Services (NHDES) can require treatment devices in coastal regions. NHDES has created a BMP manual with suggestions. Permits Required for: construction sites disturbing $\geq$ one-acre, certain industrial sites, and designated Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
New Jersey	Agency: New Jersey Department of Environmental Protection (DEP), http://www.state.nj.us/dep/stormwater/ Program Information: Peak post-development runoff rate from the 2, 10, and 100 year storm event cannot exceed 50, 75, and 80 percent of the predevelopment peak runoff rates. Treatment devices must be designed to remove 80% of the total suspended solids (TSS) load on an annual basis. In certain watersheds the state may also require nutrient and/or hydrocarbon removal. Water quality devices must be designed to treat the flow from a water quality storm of 1.25 inches of rain in 2 hours. The state has compiled a list of acceptable devices and assigned a removal credit to each of them. As an incentive for developers to use environmentally conscious site design, the state offers removal credits for various environmental design components. Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all Municipal Separate Storm Sewer Systems (MS4's).
New Mexico	Agency: U.S. EPA Region 6, http://www.nmenv.state.nm.us/swqb/StormWater/index.html Program Information: As described in section 401 of the Clean Water Act, New Mexico reviews and certifies all EPA permits issued in the state. Permits required for: construction sites disturbing $\geq$ one acre, certain industrial sites, and designated Municipal Separate Storm Sewer Systems (MS4s).
New York	Agency: New York Department of Environmental Conservation (NYDEC), http://www.dec.ny.gov/chemical/8468.html Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Treatment devices must be designed to remove 80% of the total suspended solids (TSS) load and 40% of the average annual post development phosphorous load. Treatment devices shall be designed based on the 10-year and 100-year, 24-hour rain event and require extended 24 hours detention of the stormwater for the 1-year, 24-hour storm event. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
North Carolina	Agency: North Carolina Department of Environment and Natural Resources (NCDENR), http://www.ncstormwater.org/ Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. The NCDENR has established specific stormwater treatment requirements for projects that meet designated criteria, including all development in the 20 coastal counties identified by NCDENR and/or any development draining to Outstanding Resource Water (ORW) or High Quality Waters (HQW). The low-density impervious area thresholds are typically between 12 and 30% depending on the project location. In addition projects must maintain vegetated buffers and transport runoff through vegetated conveyances. If projects cannot meet these criteria then they must install structural treatment devices capable of controlling the runoff from the 1 or 1.5 inch rain event. BMPs must also remove 85% of the total suspended solids on an annual basis. Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).
North Dakota	Agency: North Dakota Department of Health & Environmental Division of Water Quality (DHEWQ), http://www.ndhealth.gov/WQ/Storm/StormWaterHome.htm Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established at the state level. Stringent requirements also may be established around lake discharge areas. There are a number of established and proposed TMDLs impacting North Dakota's watersheds. Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Ohio	Agency: Ohio Environmental Protection Agency (OEPA), http://www.epa.state.oh.us/dsw/storm/ Program Information: mirrored after the federal NPDES program, requiring that stormwater be treated to the maximum extent practicable (MEP). The Ohio Department of Natural Resources (ODNR) has identified stormwater treatment devices for use in Ohio. The Ohio Department of Transportation (ODOT) has developed stormwater programs of their own with additional treatment requirements. Numeric treatment requirements have not been established at the state level, although parameters have been established to address more stringent requirements and needs particular to geographic and hydrologic conditions. Ohio's 6217 management area (for the most part, the lake Erie watershed), for example, have very specific requirements including the goal to reduce or maintain the total suspended solids loading by 80% on an average annual basis. Permits Required for: construction sites disturbing $\geq$ one-acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
Oklahoma	Agency: Oklahoma Department of Environmental Quality (DEQ), with the exception of Indian land, which is regulated by EPA region 6, http://www.deq.state.ok.us/WQDnew/stormwater/index.html Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established at the state level. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Oregon	Agency: Oregon Department of Environmental Quality (ODEQ), http://www.deq.state.or.us/wq/stormwater/stormwater.htm Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Currently, numeric treatment requirements specific to stormwater have not been established at the state level. However, specific treatment requirements have been established in local areas. For example, in the City of Portland, all stormwater quality BMPs must be able to safely convey all flow from the 25-year storm, remove 70% of the net annual TSS load and treat all runoff from a 0.83 inch in 24 hours design storm. A number of total maximum daily loads (TMDLs) have been implemented in Oregon, and stormwater discharges must be in compliance. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Pennsylvania	Agency: Pennsylvania Department of Environmental Protection (DEP), http://www.depweb.state.pa.us/watershedmgmt/cwp/view.asp?a=1437&Q=518682&PM=1 Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Currently, numeric treatment requirements specific to stormwater have not been established at the state level, but stormwater is often regulated at the local and watershed level in Pennsylvania. The new manual became available early in 2008. All communities are required to meet the new regulations, but may opt to impose requirements, which exceed the state minimum. Areas draining to the Chesapeake Bay may face additional stormwater requirements in the future. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Rhode Island	Agency: Rhode Island Department of Environmental Management (RIDEM), http://www.dem.ri.gov/programs/benviron/water/permits/ripdes/stwater/index.htm Program Information: modeled after the federal National Pollution Discharge Elimination System (NPDES). The state has established specific treatment requirements. All treatment devices must be designed to remove 80% of the annual total suspended solids (TSS) load. The state also requires extended (24 hours) detention of all runoff from the 1-year 24-hour storm event. Peak flows from the 10, 25, and 100-yr storms must be kept at predevelopment levels, and conveyed so that no erosive velocities occur up to and including the 10-yr event. In addition, treatment may be required in some areas to address Phosphorus and/or Nitrogen discharges. Stormwater discharges must also comply with TMDLs. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
South Carolina	Agency: South Carolina Department of Health and Environmental Control (SCDHEC). The SCDHEC has delegated authority to South Carolina Office of Ocean and Coastal Resource Management to regulate stormwater discharges in the states eight coastal counties, http://www.scdhec.net/environment/water/swnpdes.htm Program Information: Post-development peak discharge rates may not exceed predevelopment peak discharge rates for the 2 and 10-year, 24-hour storm event. Implementing agencies may utilize a less frequent storm event (e.g. 25-year, 24-hour). The discharge from all treatment devices must be restricted to prevent erosive velocities downstream of the structure. All water quality treatment devices must be designed to treat the entire volume of runoff from the first ½-inch of rainfall on a site. Devices must also be designed to remove 80% of the total suspended solids (TSS) load or 0.5 ml/L peak settleable solids concentration. Removal calculations will be based on post development conditions during the 10-year, 24-hour storm. Additional regulations are likely in coastal and sensitive watersheds, as well as at the county and municipal level. Permits Required for: construction sites disturbing $\geq$ one acre, many industrial sites, and all designated Municipal Separate Storm Sewer Systems (MS4's).
South Dakota	Agency: South Dakota Department of Environment & Natural Resources (DENR). http://www.state.sd.us/denr/DES/Surfacewater/stormwater.htm Program Information: closely modeled after the federal National Pollution Discharge Elimination System (NPDES) program, which requires stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established at the state level. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Tennessee	Agency: Tennessee Department of Environment and Conservation (DEC), http://www.state.tn.us/environment/wpc/stormh2o/ Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable (MEP). Numeric treatment requirements specific to stormwater have not been established at the state level. More stringent stormwater regulations are in place at the local and county level. For instance, in Knoxville, water quality BMPs must be designed to remove 75% of the annual total suspended solids (TSS) load. BMPs must also provide 24-hour detention of the first flush (1/2 inch). The peak flow from the 1-, 2-, 5-, 10-, and 100-year storm events must be kept at predevelopment levels. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
Texas	Agency: Texas Commission on Environmental Quality (TXCEQ), http://www.tceq.state.tx.us/nav/permits/sw_permits.html Program Information: closely modeled after the federal National Pollution Discharge Elimination System (NPDES) program, which requires stormwater be treated to the maximum extent practicable (MEP). Numeric treatment requirements specific to stormwater have not been established at the state level. Specific treatment requirements exist for all projects in the Edwards Aquifer recharge zone. All projects in this region must comply with the Edwards Aquifer Technical Guidance Manual. Water quality treatment devices must be designed to remove 80% of the Total Suspended Solids (TSS) load and meet specific volume requirements. In Austin, devices also must be designed to remove 80% of the TSS load. The city of Houston has established specific requirements for stormwater treatment as well. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Utah	Agency: Utah Department of Environmental Quality (UTDEQ), http://www.waterquality.utah.gov/UPDES/stormwater.htm Program Information: closely modeled after the federal National Pollution Discharge Elimination System (NPDES) program, which requires stormwater be treated to the maximum extent practicable (MEP). Numeric treatment requirements specific to stormwater have not been established at the state level. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s). Additional permitting requirements may exist where TMDLs are in place.
Vermont	Agency: Vermont Department of Environmental Conservation (VTDEC), http://www.anr.state.vt.us/dec/waterq/stormwater.htm Program Information: The VTDEC stormwater program requires the site owner to meet both the requirements of the National Pollution Discharge Elimination System (NPDES) and state-specific treatment requirements. The state manual requires that stormwater treatment devices be designed to remove 80% of the total suspended solids (TSS) and 40% of the total phosphorus (TP) on an annual basis. In addition, specific design requirements exist for many types of stormwater BMPs. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Virginia	Agency: Virginia Department of Conservation & Recreation. http://www.dcr.virginia.gov/soil_&_water/stormwat.shtml Program Information: closely modeled after the federal National Pollution Discharge Elimination System (NPDES), which requires stormwater be treated to the maximum extent practicable (MEP). Virginia, plus a number of counties and municipalities, has established specific stormwater treatment requirements. Virginia had established a sliding scale phosphorus removal requirement for stormwater runoff based on the percent imperviousness of the development. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Washington	Agency: Washington State Department Ecology (WADOE), http://www.ecy.wa.gov/programs/wq/stormwater/index.html Program Information: In addition to the federal requirements which require stormwater to be treated to the maximum extent practicable (MEP), Washington has imposed additional stormwater regulations. Many large municipalities plus many counties in western Washington, have stormwater programs of their own with additional treatment requirements. Treatment devices must be designed to remove 80% of the Total Suspended Solids (TSS) load during the peak of the 6-month, 24-hour storm. In addition, devices must be designed so that peak discharges from the 2, 10, and 50-year, 24-hour storm do not exceed predevelopment rates. Proprietary treatment devices must be evaluated prior to use on a project site. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

State	Agency and Program Notes
West Virginia	Agency: West Virginia Department of Environmental Protection (WVDEP), http://www.wvdep.org/item.cfm?ssid=11&ss1id=588 Program Information: closely modeled after the federal NPDES program, which requires stormwater be treated to the maximum extent practicable. Numeric treatment requirements specific to stormwater have not been established at the state level. As required by the State review process, all stormwater treatment devices shall be designed based on the 2-year, 24-hour rain event. All outlets must be designed to ensure that discharges occur at non-erosive velocities. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Wisconsin	Agency: Stormwater runoff is currently regulated at the state level by three agencies: Department of Natural Resources (DNR); Department of Transportation (DOT); and the Department of Commerce (COMM), http://dnr.wi.gov/runoff/stormwater/publications.htm Program Information: DNR and DOT regulations address runoff from developed urban areas within permitted municipalities as well as construction site and post-construction site runoff from new development larger than one acre. COMM regulations address runoff from new development smaller than one acre as well as stormwater managed through plumbing systems. Each Agency rule contains its own performance standards, although in most cases standards are the same. These standards of performance determine how stormwater management practices, including proprietary devices, are evaluated for compliance. Stormwater management must comply with specific treatment objectives including 80% removal of the annual total suspended solids (TSS) load from new development and 40% removal of the annual TSS load from redevelopment and certain in-fill development. Treatment devices used in new development shall ensure that the peak flow rate from the post-development 2-year, 24 hour rain event not exceed predevelopment levels. Technical standards now exist for proprietary hydrodynamic separation devices, and the advisory group soon will be addressing filtration technologies. DNR advocates use of hydrologic models such as P8 and SLAMM for evaluating the efficiency of a BMP design in reducing TSS. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).
Wyoming	Agency: Wyoming Department of Environmental Quality (DEQ), http://deq.state.wy.us/wqd/WYPDES_Permitting/WYPDES_Storm_Water/stormwater.asp Program Information: closely modeled after the federal National Pollution Discharge Elimination System (NPDES) program, which requires stormwater be treated to the maximum extent practicable (MEP). Numeric treatment requirements specific to stormwater have not been established at the state level. Water quality regulations require that stormwater discharges to a live waterbody (such as lakes, streams, and rivers) cannot increase the turbidity level by more than 10-15 NTUs. When discharging to non-live waterways, the goal is to reduce sediment loads in order to avoid aesthetic and habitat degradation. Permits Required for: construction sites disturbing $\geq$ one acre, industrial sites, and Municipal Separate Storm Sewer Systems (MS4s).

APPENDIX D

HYDROLOGY TO SUPPORT THE DESIGN OF STORMWATER CONTROL PRACTICES

D.1 Introduction

Stormwater control practices or treatment devices, also known as Best Management Practices (BMPs), are “all of the practices, techniques, and measures that prevent or reduce water pollution from urban stormwater runoff by using the most effective and practicable means of achieving water quality goals. BMPs include, but are not limited to official controls, structural and nonstructural controls and operation and maintenance procedures.”

This appendix addresses the question of calculating pre- and post-development flows.

D.2 Calculation of Peak Flow Rate and Runoff Volume

The first part of evaluating the impact of increasing flow after development is to estimate the pre- and post-development flows. Many methods are available for predicting the volume of runoff from an area, but the two most commonly used methods are the Rational Method and the methods based on Technical Releases 20 or 55 (NRCS). This appendix will focus on these two methods, their current extensions and models that incorporate them. In addition, guidance for selecting the appropriate method is given at the end of the section. Continuous simulation methods and water quality volumes were discussed in the Chapter 3.0.

It is well known that three primary factors affect the peak rate and volume of runoff. They are the following:

- ◆ Rainfall – The duration of the storm and the distribution of the rainfall during the storm are the two major factors affecting the peak rate of runoff. The length and total volume of rainfall affect the total volume of runoff.
- ◆ Surface cover – the type and condition of the soil surface cover affects the rain energy transferred to the soil surface and can affect the infiltration rate also. Much of this is termed land-use category.
- ◆ Soil conditions – Antecedent moisture conditions generally affect the infiltration rate of the rainfall falling on the ground. Soil texture and compaction (structure) usually have the greatest effect on the infiltration.

D.2.1 Rainfall

D.2.1.1 Rainfall Frequency (and Duration)

The first parameter referred to in a discussion of rainfall is the rainfall frequency. This can be phrased as the following question: how often does a storm of a particular size and duration occur?

By definition, rainfall frequency is commonly expressed as the average return period of the event, or, on average, how long is the gap between storms of this size and duration or greater?

The return period and probability of occurrence (in a specific time period, typically one year) are related through the following equation:

$$\text{Return Period, } T \text{ (yr)} = \frac{1}{\text{Probability of Occurrence (p)}} \quad \text{Equation D.1}$$

$$T = \frac{1}{p} \quad \text{Equation D.2}$$

NOTE: Multiple rare events may occur in any one year, but it is not very likely.

Most drainage design regulations and discussions are based on using the return period in the calculations, although an expression of probability would be preferred (see sample drainage design regulations below – Section 3.02 – from the City of Birmingham, Alabama) (Figure D-1).

In terms of applicability in stormwater device design, often a one-year probability is not useful since the devices will have life spans of more than one year and the designer and/or owner may want to know what the probability is that the design capacity will not be exceeded during the design life. The following equation, Equation D.3 (from McGhee, 1991), can be used to calculate the probability that a rain having a return period of “n” years, will occur at least once in the next “y” years:

$$P = 1 - \left(1 - \frac{1}{n}\right)^y \quad \text{Equation D.3}$$

This equation can be reworked to relate the service life to the needed design return period and probability of exceedence (or failure) (Equation D.4 through the simplification process).

3. STORM SEWERS

3.01 Method of Determining Runoff

- (a) Storm water runoff may be estimated using any accepted method. The two predominant methods presently in use are the Rational Method and the SCS TR55 method, however, runoff estimation is not limited to either method. The owner's engineer shall be responsible for selecting an appropriate method
- (b) Storm sewer systems shall be designed based on future land use.

3.02 Return Periods

- (a) The minimum return period used in the design of storm sewer collection systems shall be the 10 year return period.
- (b) Box culverts and pipes larger than 60" shall be design using the 25 year return period.
- (c) Other return periods may be used as determined by the owner's engineer.

3.03 Storm Sewer Design

- (a) In general, the Manning equation shall be used to size drainage structures.
- (b) A Manning's "n" of 0.013 shall be used to size concrete pipe and box culverts.
- (c) In developed areas, the proposed drainage system shall be compatible with the existing drainage system. The developer may be required to upgrade the existing system to accommodate the proposed development.
- (d) The minimum pipe diameter allowed is 18 inches.
- (e) Storm sewer pipe shall be a minimum of Class 3 reinforced concrete if the storm sewer is to be maintained by the City of Birmingham, is in an easement, and/or passes runoff through a site. Other pipe materials may be used on systems that will not be turned over to the City of Birmingham for maintenance.

Figure D-1. Sample Design Guidelines Specifying Runoff Estimation Methods
(<http://www.informationbirmingham.com/planning/Criteria.PDF>).

$$\begin{aligned}
 P &= 1 - \left(1 - \frac{1}{T_{needed}} \right)^{\text{design life}} \\
 1 - P &= \left(1 - \frac{1}{T_{needed}} \right)^{\text{design life}} \\
 (1 - P)^{\left(\frac{1}{\text{design life}} \right)} &= 1 - \frac{1}{T_{needed}} \\
 (1 - P)^{\left(\frac{1}{\text{design life}} \right)} - 1 &= - \frac{1}{T_{needed}} \\
 1 - (1 - P)^{\left(\frac{1}{\text{design life}} \right)} &= \frac{1}{T_{needed}} \\
 T_{needed} &= \frac{1}{1 - \left[(1 - P)^{\left(\frac{1}{\text{design life}} \right)} \right]}
 \end{aligned}$$

Equation D.4

Figure D-2 is a plot illustrating this relationship, but modified to show the probability of an event not being exceeded during the design period.

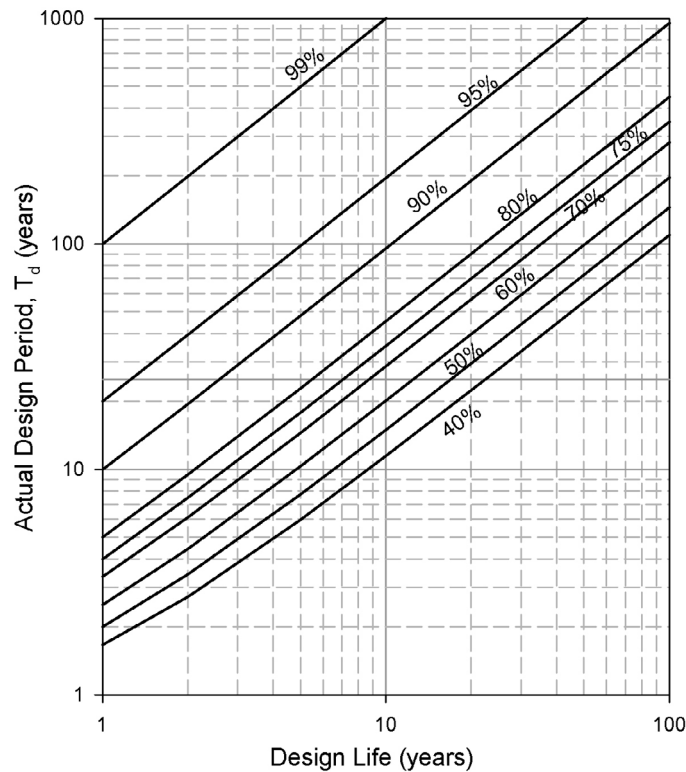


Figure D-2. Probability of Design Storm (Design Return Period) Not being Exceeded During the Project Life (Design Period).

Calculations of this type are important if failure is a concern. The next sections review the common methods for predicting the water flow into a treatment device. While these methods have been typically applied to flood control, they are currently being used in many areas of the country to size smaller treatment devices, including infiltration devices. Therefore, understanding how to apply the methods and the limitations of the methods is crucial to properly designing non-flood-control stormwater quality devices.

D.2.1.2 Rainfall Intensity

The second feature of rainfall information is its intensity, or how fast does the rain occur. Precipitation is expressed as an average intensity over a specified time period (usually as rain depth/unit time). A statistical analysis of rainfall data from the early 1960s to mid-1970s was performed to determine the frequency of storms of a specific depth and duration. This report, Technical Paper No. 40, was called the Rainfall Frequency Atlas of the United States. The maps generated from this analysis ranged from storm durations of five minutes through 10 days and for probabilities of exceedence from 1-50%.

On-line versions of these maps can be found at http://www.srh.noaa.gov/lub/wx/precip_freq/precip_index.htm.

An example map is shown below (Figure D-3). This is the map for the eastern United States for 2-year, 24-hour rainfall, e.g., a storm with a duration of 24 hours and whose total rainfall volume has a probability of occurring or being exceeded in any given year of 50%.

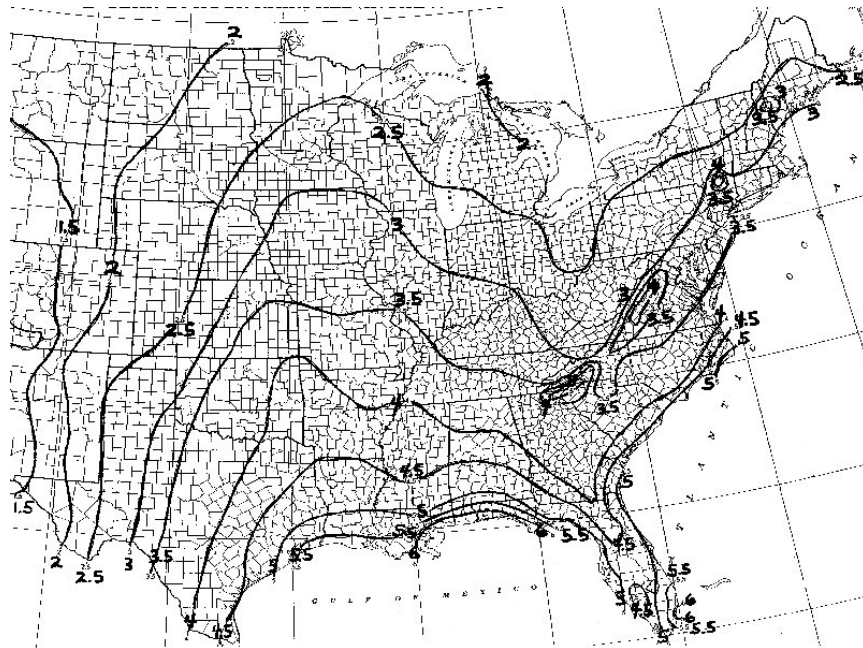


Figure D-3. 2-Year, 24-hour Rain Depth for the Eastern United States (TP-40).

Scanned images of NOAA Atlas 2 for the Western U.S. are available from the Western Region Climate Center or from NOAA directly. The link to the NOAA Climate Center for the rainfall atlas is the following:

<http://lwf.ncdc.noaa.gov/oa/documentlibrary/rainfall.html>

In addition to these on-line resources, several private firms sell compiled rainfall information and copies of these atlases.

For a specific locale, this data has been compiled into a series of curves that relates the storm duration of interest to the rainfall intensity and using the storm's return period as the designator for each line. These curves are called Intensity-Duration-Frequency curves or IDF curves. An example of a city-specific IDF is Figure D-4, the IDF curve for Birmingham, Alabama.

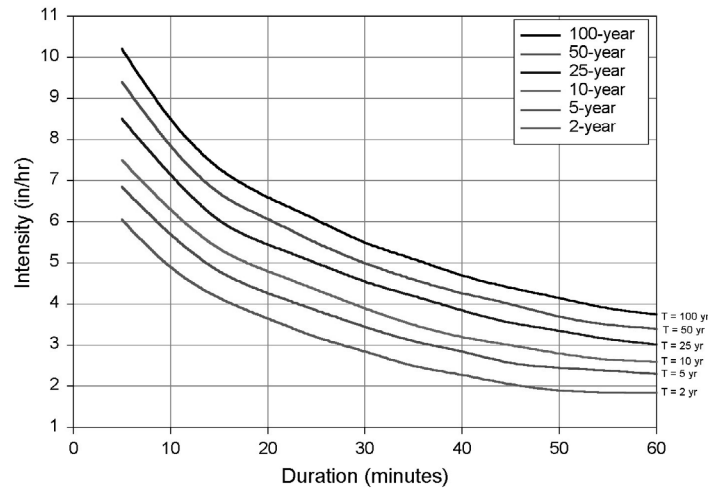


Figure D-4. IDF Curve for Birmingham, Alabama. (based on NWS Hydro-35)

In some states, IDF information is compiled by region and is available through one of the state agencies, typically the state Department of Transportation. Pennsylvania is an example of one such state. Pennsylvania is divided into five regions based on the region's characteristic patterns. Pennsylvania's IDF curve information also provides rainfall depth based on storm duration and return period. The current Pennsylvania manual (Field Manual of the Pennsylvania Department of Transportation, 1986) was updated and replaced the information available in TP-40. These regional rainfall design curves in this Pennsylvania field manual were developed from frequency analyses based on hourly records from 153 climatological stations and 15-minute records from 45 stations in Pennsylvania. The analysis leading to the design curves is fully described in the project report "Pennsylvania Department of Transportation Rainfall Intensity-Duration-Charts," submitted to the Pennsylvania Department of Transportation. Figure D-5 shows the state of Pennsylvania divided into representative rainfall regions, while Figure D-6 is the actual rainfall IDF curve for Region 4 of the state.

Similar to Pennsylvania's update, rainfall data collected since the publication of NWS' Technical Paper 40 and HYDRO-35, and NOAA's Atlas 2 and Atlas 14, and the development of improved statistical methods, motivated several states to initiate update studies of precipitation distributions (Durrans and Brown, 2001).

The study by Durrans and Brown (2001) is an interesting one to highlight for three reasons. One, it uses a substantially longer period of record to perform the statistical calculations. Second, it was based on extreme-event probability calculations. Third, the results are widely disseminated on the Internet and information for several smaller cities is available, based on their historical rainfall record. Since much of the interest in precipitation records has come from state Departments of Transportation as part of their need to calculate runoff peak flow rates for design purposes, it is logical that this study was funded for the Alabama Department of Transportation.

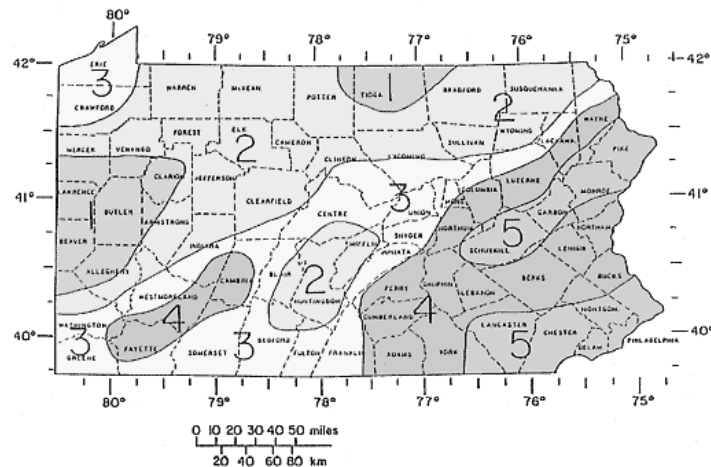


Figure D-5. Rainfall Zones for the State of Pennsylvania.
(Field Manual of the Pennsylvania Department of Transportation 1986).

The Alabama Rainfall Atlas is available at: <http://www.bama.ua.edu/~rain/>. This web site, prepared by Dr. S. Rocky Durrans of the University of Alabama, calculates and presents IDF curves for any location in the state. IDF equation coefficients were calculated based on long-term rain records (in some cases, for over 100 years of rainfall record) for many state locations. This mathematical unit supporting the web site then interpolates the coefficients for any location on the state map and presents graphical and tabular IDF information. IDF information is presented for 2- to 500-year rains and for five minutes to 48 hours durations. The web site will also produce design hyetographs for use in the NRCS methods (explained later in the chapter). The user simply clicks the mouse anywhere an IDF calculation is desired, and selects if a map or table (or both) is desired. In most cases, the “partial duration” option is probably desired in order to be more consistent with historical NOAA IDF curves (not a significant difference for the large, rare, rains, but more of an effect on the smaller events). These IDF curves are likely to vary from the “official” older NOAA IDF curves as they are obtained from more recent data (the Alabama Rainfall Atlas values seem to be slightly smaller than the NOAA values). The bottom button is then clicked to accept the choices and the desired outputs are produced.

Several design methods to calculate runoff have very specific methods for calculating or obtaining rainfall intensity and volume. The rainfall curves and information for the NRCS Technical Release No. 55 methods will be covered in those sections.

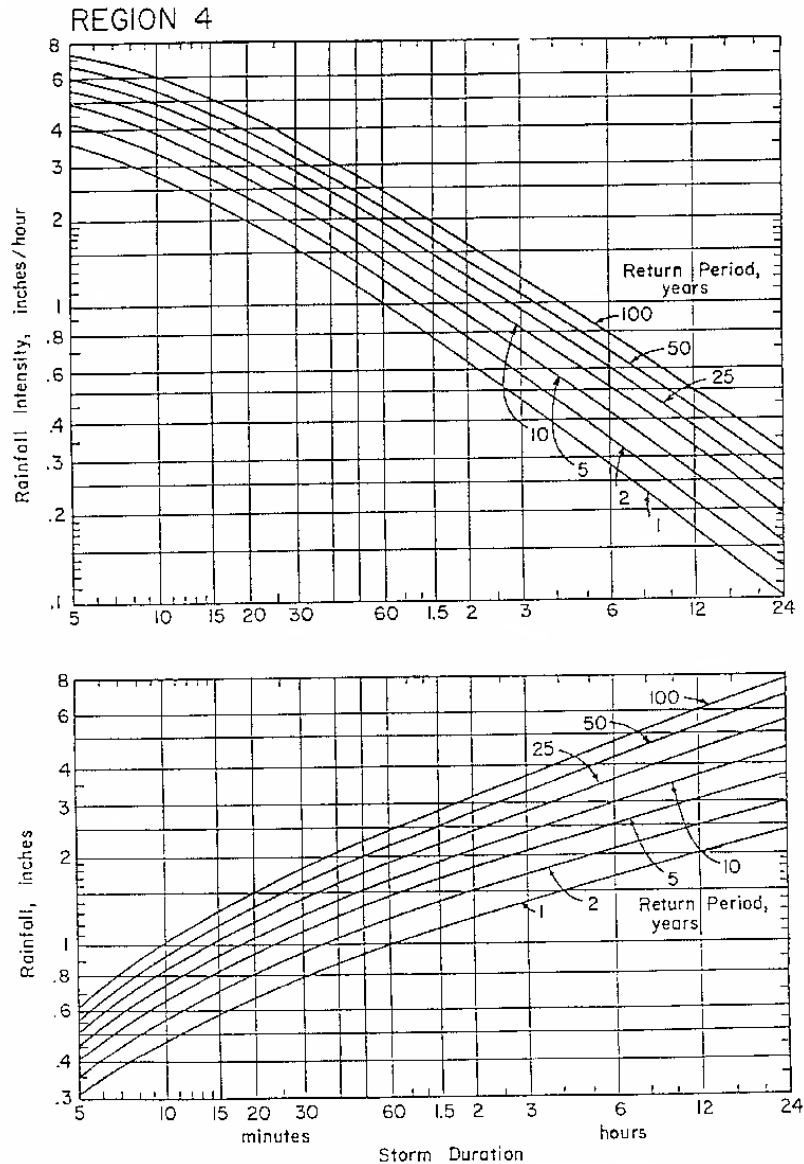


Figure D-6. IDF Curves for Pennsylvania Region 4.
(Field Manual of the Pennsylvania Department of Transportation 1986).

D.2.2 Surface Cover (Land Use Category)

It is well-documented that the type of cover on the land will greatly affect the amount of runoff generated from the site. Land uses may range from natural rangeland or forested through highly-urbanized with substantial pavement and roofing blocking the rainfall's access to the underlying soil structure for infiltration.

One parameter often used to characterize the watershed and the time required for water to flow through the basin is the Time of Concentration (T_c or t_c). Calculation of the Time of Concentration is typically based on the methods outlined in NRCS TR-55 Chapter 3.0.

By definition, the time of concentration is time required for runoff to travel from the most hydraulically distant point in the watershed to a point of interest, typically the drainage/outlet point, within the watershed. It is the sum of the travel times calculated for the flow segments that are included in the flow path of T_c . Travel time is defined simply as the time required for water to travel from one location to any other location in the watershed.

NOTE: T_c is the time from the hydraulically most distant point in the watershed – not the time from the spatially most distant point. In enough cases to warrant checking, T_c should be based on a flow path extending across a flood plain (low sloping area) rather than the path with the steeper slope that reaches the main channel faster (even with a longer main channel travel length).

D.2.2.1 Time of Concentration Estimates

The TR-55 procedures estimate t_c using three flow segment types, each of which may have separate subsegments if land use or slope or channel characteristics change significantly:

- ◆ Sheetflow
- ◆ Shallow concentrated flow
- ◆ Channel flow

Candidate T_c pathways are drawn on the site map and the travel times for the three flow segments are calculated, remembering that flow paths from areas that are not the most-spatially distant should be checked. The T_c for the drainage area is the longest travel time calculated.

Three primary factors affect the calculation of travel time for each of the segments listed above, and ultimately affect the calculation of T_c :

- ◆ Surface Roughness
- ◆ Channel Shape and Flow Pattern
- ◆ Slope

Travel time (T_t) is the ratio of the flow length, L , to the flow velocity, V . The general form of the travel time equation is:

$$T_t(hr) = \frac{L(ft)}{(3600 \text{ sec/hr})(V[ft / \text{sec}])} \quad \text{Equation D.5}$$

There are up to three flow regimes that may be involved in the T_c calculations, remembering that each flow regime can have multiple segments if the slope and/or land cover changes. Two flow regimes potentially occur in overland flow, i.e., flow in areas without definable channels and where flow depth is typically shallow.

- ◆ Sheet Flow: Flow over plane surfaces (generally occurs for less than 300 feet of flow). Water depth is less than 1 inch (< 0.1 ft or 2.5 cm).
- ◆ Shallow Concentrated Flow: Flow that starts when the flow depth exceeds than 1 inch (>0.1 ft or 2.5 cm).

Open Channel Flow is defined as it sounds. For open channel flow, channel dimensions should be definable. Typically, open channel flow is assumed to begin when the water reaches a defined stream on a topographic (or other map). Streams may be constantly flowing or intermittent.

Given the size of reservoirs and lakes, the travel time in TR-55 is assumed to be zero, and for a representative T_c calculation, reservoirs or lakes cannot be in the T_c flow path.

Calculation equations exist for all three flow regimes. The equations reported in this section are the equations given by TR-55 without modification.

Sheet Flow

Sheet flow occurs from the outer boundary of the watershed to the approximate point where the runoff depth would be approximately 0.1 ft (2.5-3.0 cm). This flow is highly affected by friction due to the unevenness of the surface over which it moves. TR-55 says that sheet flow should extend for no longer than 300 ft (100 m). A survey of state and local regulations by the investigators suggest that 100 m is the maximum distance of sheet flow over smooth surfaces (new and/or even pavement, smooth roofing materials). Many agencies recommend that for grassy or dirt-covered surfaces, sheet flow distances be no more than 50-100 ft (15-30 m). At that point, it is believed that friction has slowed the water sufficiently to generate a water depth greater than 2.5 cm.

The equation to calculate sheet flow is as follows. The equation is a simplified form of the Manning's kinematic solution and is based on the following: shallow steady uniform flow, constant intensity of runoff/rainfall excess, rainfall duration of 24 hours, and minor effects of infiltration on travel time.

$$T_{t_{sheet}} = \frac{0.007(nL)^{0.8}}{P_2^{0.5} S^{0.4}} \quad \text{Equation D.6}$$

where

$T_{t_{sheet}}$ = travel time for sheet flow (hr)

n = Manning's n for sheet flow (NOTE: do not use the Manning's n used for channel flow) – see Table D-1

L = length of sheet flow (ft)

P_2 = 2-year, 24-hour rainfall depth (in) – available from IDF curves or from the TR-55 rainfall maps

S = slope of the sheetflow section (ft/ft)

Table D-1. Manning's n Coefficients (Roughness Coefficients) for Sheet Flow.

Surface Description	n ¹
Smooth Surfaces (concrete, asphalt, gravel, bare soil)	0.011
Fallow (no residue)	0.05
Cultivated Soils	
Residue cover ≤ 20%	0.06
Residue cover ≥ 20%	0.17
Grass	
Short prairie grass	0.15
Dense grasses ²	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods ³	
Light underbrush	0.40
Dense underbrush	0.80

¹The n values are a composite of information compiled by Engman (1986).

²Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.

³When selecting n, consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

Shallow Concentrated Flow

Shallow concentrated flow begins after sheet flow ends (once flow depth exceeds 2.5-3.0 cm). At this point, it is assumed that the effects of friction do not occur throughout the entire depth profile in the flow path. An average velocity is typically calculated based on land cover condition and land slope. TR-55's Figure 3.1 (Figure D-7) relates the slope calculated for the shallow concentrated flow segment to the estimated velocity. Land use categories are separated into two simple land-use categories: paved and unpaved. Graphs supplied by the Federal Highway Administration (FHWA) break the unpaved group into several subcategories based on anticipated effect on the flow velocity.

The velocity read from the graph is then inserted into the general travel time equation relating velocity and flow length.

$$T_i(hr) = \frac{L(ft)}{(3600 \text{ sec/hr})(V[ft/sec])} \quad \text{Equation D.7}$$

Figure 3-1 Average velocities for estimating travel time for shallow concentrated flow

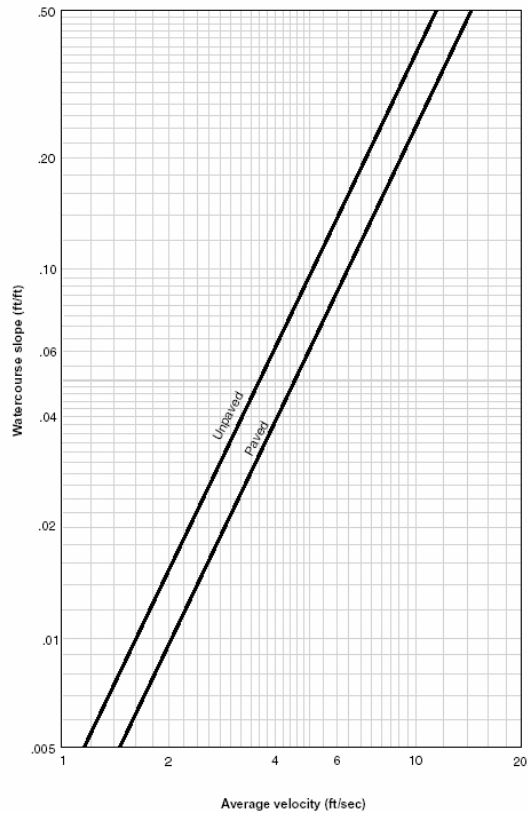


Figure D-7. Velocity Estimation for Shallow Concentrated Flow.

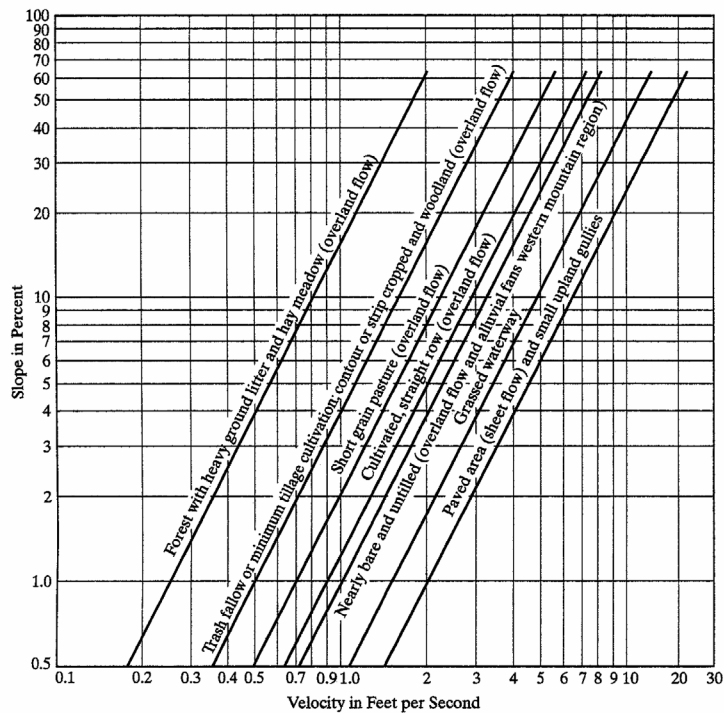


Figure D-8. Velocity Estimation for Shallow Concentrated Flow. (In: FHWA Hydraulic Engineering Circular No. 19)

Open Channel Flow

The final travel-time calculation is for open-channel flow (flow that occurs in a definable passageway). This calculation is based on Manning's equation for velocity and relates channel characteristics (roughness, slope, and cross-sectional dimensions). These calculations are based on bank-full conditions in the channel. Bankfull conditions are assumed to be approximated by the flow depth associated with baseflow plus the volume from the 1.5-year storm. Manning's equation is given below:

$$V = \frac{1.49r^{2/3}s^{1/2}}{n} \quad \text{Equation D.8}$$

where

V = average velocity (ft/sec)

r = hydraulic radius = A/P

P = wetted perimeter (ft)

s = slope of the hydraulic grade line (ft/ft)

n = Manning's roughness coefficient

Manning's roughness coefficients can be obtained from many sources (Table D-2 is an example from the literature of tabulated Manning's n values). The travel times through these segments of flow are then added together to get an estimated time of travel from the selected point to the watershed outlet. The travel times are then compared for the selected flow paths and the time of concentration is the longest travel time. These calculations are summarized in a spreadsheet supplied in TR-55.

D.2.2.2 Soil Conditions

Much of the discussion on soil conditions is based on USDA's Urban Forestry research, which is summarized at <http://www.urbanforestrysouth.org/Resources/Library/Citation.2005-06-02.2748/view?parentObj=Collection.2005-06-02.0039>. The title of the applicable chapter is G: Urban Soils and is part of the Urban Forestry Manual.

The characteristics of the soil affect whether the rainfall becomes runoff. Geologists typically classify soils according to three characteristics: texture, structure and moisture retained. Other characteristics are also important for pollutant movement and will be discussed in the appropriate section on performance of infiltration structures.

Soil Texture Soil texture refers to the relative size (fineness or coarseness) and the proportion of the sand, silt, and clay particles in the soil (Soil Characteristics summarized in Tables D-3 and D-4).

Soil Structure Structure is the way soil particles – sand, silt and clay – are grouped or bound together. These clumps of soil are called aggregates, and between these clumps are pore spaces. A well-structured soil for healthy root growth, which is important if a stormwater treatment device is to be designed to encourage infiltration and groundwater recharge, has adequate pore space for water movement and gas exchange. There are different types of soil structure, such as crumb or columnar, based on the shape of the aggregate. When a soil is disturbed (such as

through clearing or compaction), aggregates are often crushed, resulting in decreased pore space and drainage. One measurement of a soil's structure is through the bulk density measurement (Table D-5), where the higher the bulk density, the higher the compaction.

Table D-2. Values of n to be Used with the Manning Equation.

Surface	Best	Good	Fair	Bad
Uncoated cast-iron pipe	0.012	0.013	0.014	0.015
Coated cast-iron pipe	0.011	0.012	0.013	
Common clay drainage tile	0.011	0.012	0.014	0.017
Glazed brickwork	0.011	0.012	0.013	0.015
Brick in cement mortar; brick sewers	0.012	0.013	0.015	0.017
Cement mortar surfaces	0.011	0.012	0.013	0.015
Concrete pipe	0.012	0.013	0.015	0.016
Wood stave pipe	0.010	0.011	0.012	0.013
Concrete-lined channels	0.012	0.014	0.016	0.018
Cement-rubble surface	0.017	0.020	0.025	0.030
Dry-rubble surface	0.025	0.030	0.033	0.035
Dressed-ashlar surface	0.013	0.014	0.015	0.017
Semicircular metal flumes, smooth	0.011	0.012	0.013	0.015
Semicircular metal flumes, corrugated	0.0225	0.025	0.0275	0.030
Canals and ditches				
Earth, straight and uniform	0.017	0.020	0.0225	0.025
Rock cuts, smooth and uniform	0.025	0.030	0.033	0.035
Rock cuts, jagged and irregular	0.035	0.040	0.045	
Dredged-earth channels	0.025	0.0275	0.030	0.033
Canals, rough stony beds, weeds on earth banks	0.025	0.030	0.035	0.040
Earth bottom, rubble sides	0.028	0.030	0.033	0.035
Natural-stream channels				
Clean, straight bank, full stage, no rifts/deep pools	0.025	0.0275	0.030	0.033
Clean, straight bank, full stage, no rifts deep pools, but some weeds/stone	0.030	0.033	0.035	0.040
Winding, some pools and shoals, clean	0.033	0.035	0.040	0.045
Winding, some pools/shoals, clean, lower stages, more ineffective slope/sections	0.040	0.045	0.050	0.055
Winding, some pools/shoals, some weeds/stones	0.035	0.040	0.045	0.050
Winding, some pools/shoals, clean, lower stages, more ineffective slope/sections, stony sections	0.045	0.050	0.055	0.060
Sluggish river reaches, weedy or very deep pools	0.050	0.060	0.070	0.080
Very weedy reaches	0.075	0.100	0.125	0.150

Data summarized from Metcalf & Eddy, Inc. (George Tchobanoglous). *Wastewater Engineering: Collection and Pumping of Wastewater*. McGraw-Hill, Inc. 1981. (Table 2-1)

Table D-3. Soil Texture Classifications.

Soil Texture Class	Diameter, d (mm)
Gravel	$d > 2$
Sand	$0.02 \leq d \leq 2$
Silt	$0.002 \leq d \leq 0.02$
Clay	$d < 0.002$

Table D-4. Characteristics of Different Soil Textures.

Soil Texture	Characteristics	Infiltration Rate Range (in/hr)
Sand	Typical coarse texture. Good permeability. Good drainage.	Coarse Sand: 0.75 – 2 Fine Sand: 0.5 – 1 Very Fine Sand: 0.25 – 0.75
Silt	Intermediate texture between sand and clay.	Silty Loam: 0.25 – 0.4
Clay	Fine texture. Poor permeability. Poor drainage.	Clay: 0.10 – 0.25

Table D-5. Comparison of Common Bulk Densities.

Material Type	Bulk Density Measurement (g/cm ³)
Normal soils	1.0 – 1.6
Soils with restricted root growth	1.4 – 1.6
Soils commonly found on construction sites	1.7 – 2.2

Soil Moisture Soil moisture and its impacts on potential use of the soil as a treatment mechanism for stormwater are addressed later in the section on infiltration design. This section will briefly cover the basics of soil moisture.

Soil moisture occurs through water retention in the pore spaces, typically by capillary action of water on the individual soil grains. The higher the bulk density, the less pore space is available for water flow. Other measurements of soil that affect soil moisture and the ability of surface water to infiltrate include the following:

- ◆ **Permeability:** Permeability is how easily water moves through the soil. In sandy soils, permeability is usually high because of the coarse texture and large pores. In clay soils it is low because the small pores reduce water's ability to move.
- ◆ **Infiltration rate:** The infiltration rate is how fast water moves through the soil. Typically, the larger the pore size the faster the movement of water. Sandy soils have a high infiltration rate; clay soils have a low infiltration rate.
- ◆ **Retention rate or water-holding capacity:** Retention is how well a soil holds water. The small pores of fine-textured soils (clays) tend to hold more water than coarse-textured soils (sandy).

D.2.2.3 Hydrologic Soil Group

As part of a USDA series of projects, the former Soil Conservation Service (now the NRCS) mapped out the predominant soil types and the extent of those types in each state. Soil scientists observed the steepness, length, and shape of the slopes; the general pattern of drainage; the kinds of crops and native plants; and the kinds of bedrock. Holes were dug to study the soil profile. The profile extends from the surface down into the material in which the soil formed (where the material is devoid of roots and other living organisms and has not been changed by other biological activity). The purposes of these soil surveys were to provide a description of the soil, and their suitability, limitations and management for specified uses. The information typically included in these soils surveys includes:

- ◆ Soil type by general area
- ◆ Descriptions of the various soil types
- ◆ Tables of information regarding the various soil types
- ◆ Soil classification (Hydrologic Group A, B, C, and D)

For the purposes of this project, the most important information included in the soil survey is the hydrologic soil group. This parameter is used in many of the older design methods to describe the infiltration ability of the soils and ranged from A soils (sandy soils that are well-draining) to D soils (poorly draining).

According to NRCS, “**hydrologic soil groups** are based on estimates of runoff potential. Soils are assigned to one of four groups according to the rate of water infiltration when the soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long-duration storms.” The four hydrologic soil groups are (quoted from NRCS):

- ◆ **Group A** Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission.
- ◆ **Group B** Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission.
- ◆ **Group C** Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission.
- ◆ **Group D** Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.

Approximate infiltration rates for these soils have been tabulated by NRCS.

D.2.2.4 Common Soil Problems in Urban Areas

Development in an area changes the soil physical, chemical and biological characteristics. Construction can cause soil problems in urban areas because these activities often alter the soil profile. Potential impacts of construction and post-development activities include, but are not limited to, the following:

- ◆ Impervious surfaces, such as buildings and roads, interrupt the natural exchange of gases, increase soil temperature, and alter drainage patterns.
- ◆ Heavy construction equipment compact the soil.
- ◆ Moving soil, such as grading, clearing, and excavating, influences drainage and aeration and causes erosion. Often, topsoil is removed, reducing the ability of the remaining soil

to support plant life, which increases the time needed to re-establish vegetation and infiltration areas.

- ◆ Chemical spills, such as cement washout areas or painting sites, contaminate the soil.
- ◆ Use of fill dirt influences soil drainage, aeration, and fertility.
- ◆ Dumping or burying waste materials, such as dry wall and garbage, may change drainage patterns and contaminate the soil.
- ◆ Poorly timed irrigation systems can cause soil moisture problems.
- ◆ Removal of organic matter influences soil fertility and moisture.
- ◆ Excessive herbicide or fertilizers contaminate the soil.

The most prevalent of these is compaction due to construction. Compaction, however, is not mentioned in these rainfall-runoff methods as a factor when selecting runoff coefficients.

D.2.3 Calculating Runoff

The best method for calculating runoff is to use real stream flow data to estimate the watershed response to rain storms of varying sizes.

When real data is not available, runoff can be considered to be some fraction of the rainfall and can range from 0% of the rainfall to 100%. Runoff can be related to Rainfall through the following relationship (Equation D.9):

$$\text{Runoff} = (\text{Proportionality Constant}) (\text{Rainfall}) \quad \text{Equation D.9}$$

The proportionality constant is based on two primary factors — the surface slope and the surface's infiltration rate. Increased slopes typically result in higher proportionality constants, simply because the water travels faster when the slope is increased. Faster travel times result in less opportunity/time for infiltration to occur. The infiltration rate is based on the soil characteristics as discussed in the previous section. Many of the methods for calculating runoff are based on the use of the Hydrologic Soil Group as a descriptor of the soil. When site-specific information is not available on the infiltration capacity of a soil, the soil maps from the soil surveys are used to find the predominant soil type on a proposed site and the accompanying tables are used to find the hydrologic soil group.

Two other factors affect the amount of runoff that is generated from a site – depression storage and vegetative interception. In many of the models, these factors are lumped into the infiltration parameter, since it is difficult to estimate their values.

D.2.3.1 Volumetric Runoff Coefficient, R_v : Constant Intensity Design Storm

This is the simplest method for calculating runoff. Land use category is used to predict the fraction of the rainfall that will be returned as runoff. This calculation gives the depth of runoff that will be generated for a pre-specified design storm. The volume is then calculated by multiplying the depth of runoff by the area of the watershed.

The NURP study (U.S. EPA, 1983) recommended the use of average volumetric runoff coefficients as an effective method for calculating runoff. This method was effective when calculating runoff for drainage design, where the concern is removing water from larger storms.

Water quality investigations typically are concerned with storms of all sizes, but in particular, small, frequent storms. When these same procedures are used to estimate the runoff associated with common small storms, the runoff predictions can be highly inaccurate. As an example, the volumetric runoff coefficient (the ratio of the runoff to the rain depth) observed at outfalls varies for each rain depth. This ratio can be about 0.1 for storms of about 0.5 inches (12 mm) but may approach about 0.4 for a moderate size storm of 2.5 inches (65 mm) or greater that is typically associated with drainage events for medium density residential areas. Therefore, common small storms would likely have their runoff volumes over-predicted. Bannerman et al. (1983) plotted the observed runoff depths versus their associated rainfall depths for several land uses (Figure D-9). As can be seen, the volumetric runoff coefficient is not consistent across all storm depths, with the exception of the commercial site (heavily-paved site).

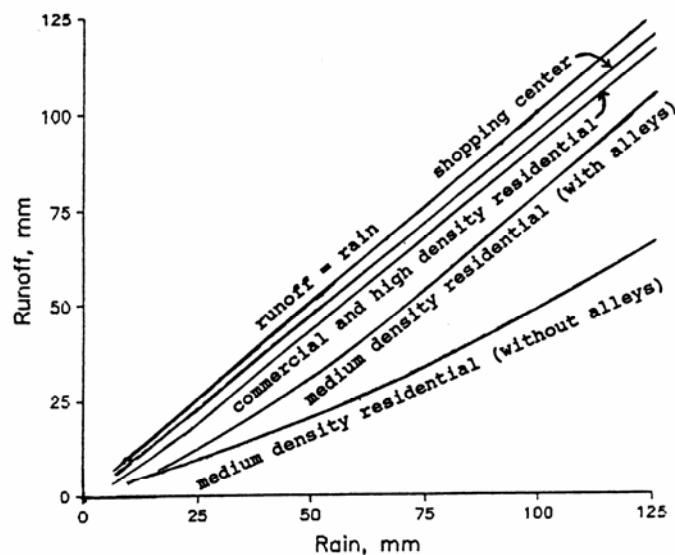


Figure D-9. Runoff Versus Rainfall by Land Use – Monitored Milwaukee, WI.
(From Bannerman et al., 1983, U.S. EPA NURP study)

In addition to the changing R_v with rain depth, this method is limited by the use of the total rainfall depth as the measure of rainfall. When this is used for designing drainage structures, it assumes a constant rain intensity across the entire storm – an unlikely occurrence in reality. When the peak flow is not accounted for in the design, the structure likely is undersized for part of the storm, resulting in temporary flooding.

D.2.3.2 Rational Method: Constant Intensity Design Storm

The Rational Method was proposed by Mulvaney 1851, in Ireland and Kuichling, 1889, in the United States. Similar to the Volumetric Runoff Coefficient Method, the method uses a proportionality constant, the Rational C , to relate runoff to rainfall. Unlike the R_v method, where rainfall is input to the model as a total depth (and is not based on the actual pattern of rainfall), the Rational Method uses the rainfall intensity, i , as the measure of rainfall. This method was originally developed for drainage design, and it addresses the limitation of assuming a constant intensity across the entire storm. The peak intensity of the storm is used as the rainfall design

parameter, based on the assumption that the calculation will predict the peak flow rate and the drainage structure will not flood when the rainfall is equal to or less than the design predictions.

The equation for calculating the peak flow rate using the Rational Method is the following:

$$Q_p = CiA \quad \text{Equation D.10}$$

Where

Q_p = peak discharge (ft³/sec, cfs)

i = rainfall intensity (in/hr) – based on the watershed T_c

A = drainage area (acres)

C = runoff coefficient

When the time of concentration and the rain duration are equal for an area, the maximum runoff rate for that rain intensity is reached because the complete drainage area is contributing runoff to the point of concern. It, in effect, addresses the worst-case scenario – a storm occurring with the design storm's peak intensity that lasts as long as the T_c . If the rain duration exceeds T_c , then the maximum runoff rate is maintained until the rain ends. When the rain ends, the runoff rate decreases according to a recession curve for that surface.

The time of concentration is calculated as described in the Time of Concentration section earlier in this chapter. Then the IDF curve is used to select the appropriate rainfall intensity for the design storm where the duration is equal to T_c .

When the watershed contains several land uses, a weighted Rational coefficient, C_w , is used in the calculation. The weighted Rational coefficient is calculated as follows:

$$C_w = \frac{\sum_i C_i A_i}{\sum_i A_i} \quad \text{Equation D.11}$$

Where: C_w = weighted Rational coefficient

C_i = Rational coefficient for area i

A_i = area for which C_i is applicable

Various authors have summarized the accepted Rational runoff coefficients (range of coefficients), based both on land use and on surface type. Surface-type charts typically are used to size a drainage inlet, such as one in a parking lot where the watershed's runoff response is based on a surface type not an aggregate land use. Three tables of Rational coefficients are given in Tables D-6, D-7, and D-8, in order of increasing complexity. Table D-6 presents the range of coefficients based on land-use category, where these coefficients are independent of land use. The second table (Table D-7) shows the range of Rational coefficients based on surface type. The coefficients in these two tabulations are applicable for storms of five to 10-year frequencies.

Less frequent, higher intensity storms will require the use of higher coefficients because infiltration and other losses have a proportionally smaller effect on runoff. The coefficients are based on the assumption that the design storm does not occur when the ground surface is frozen.

The third table (Table D-8) provides Rational coefficients for land-use categories based on hydrologic soil type and land slope. In addition, the size of the storm is accounted for, as two lines of coefficients are given for each land use. The first/top line is for design storms of less than 25 years, while the bottom line provides coefficients for 25-year or greater storms. This detailed table is designed to improve the accuracy of the prediction of the runoff flow rate. The rational method is typically used to size the flow rates for smaller watershed areas (such as the flow rate that might be diverted to an on-site treatment system).

Table D-6. Runoff Coefficients for the Rational Method.

Description of Area	Range of Runoff Coefficients	Recommended Value
Business		
Downtown	0.70 – 0.95	0.85
Neighborhood	0.50 – 0.70	0.60
Residential		
Single-family	0.30 – 0.50	0.40
Multiunits, detached	0.40 – 0.60	0.50
Multiunits, attached	0.60 – 0.75	0.70
Residential (suburban)	0.25 – 0.40	0.35
Apartment	0.50 – 0.70	0.60
Industrial		
Light	0.50 – 0.80	0.65
Heavy	0.60 – 0.90	0.75
Parks, cemeteries	0.10 – 0.25	0.20
Playgrounds	0.20 – 0.35	0.30
Railroad yard	0.20 – 0.35	0.30
Unimproved	0.10 – 0.30	0.20

Table D-7. Rational Coefficients based on Surface Cover Characteristics.

Character of Surface	Range of Runoff Coefficients	Recommended Value
Pavement		
Asphaltic and Concrete	0.70 – 0.95	0.85
Brick	0.75 – 0.85	0.80
Roofs	0.75 – 0.95	0.85
Lawns, sandy soil		
Flat, < 2%	0.05 – 0.10	0.08
Average, 2 to 7%	0.10 – 0.15	0.13
Steep, > 7%	0.15 – 0.20	0.18
Lawns, heavy soil		
Flat, < 2%	0.13 – 0.17	0.15
Average, 2 to 7%	0.18 – 0.22	0.20
Steep, > 7%	0.25 – 0.35	0.30

The Rational Method, as outlined above as a constant intensity design storm method, is best used for sizing inlets and culverts where the watersheds are small and urban (paved —

where C is less likely to vary with rainfall depth). It is also recommended that it be used in small drainages areas with short times of concentrations.

Many governmental agencies have provided guidance for what their design standards consider the upper limit of the Rational Method applicability. The typical range for the Rational Method is given as 0-200 acres. However, given that it is well-documented that the Rational Method increases in inaccuracy as the size of the watershed increases, some governmental agencies (Pennsylvania Department of Environmental Protection, for example) have strongly suggested decreasing the upper size limit for the use of the method.

Table D-8. Runoff Coefficients for the Rational Formula versus Hydrologic Soil Group (A, B, C, D) and Slope Range.

Land Use	A			B			C			D		
	0-2%	2-6%	6%+	0-2%	2-6%	6%+	0-2%	2-6%	6%+	0-2%	2-6%	6%+
Cultivated Land	0.08 ^a	0.13	0.16	0.11	0.15	0.21	0.14	0.19	0.26	0.18	0.23	0.31
	0.14 ^b	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Pasture	0.12	0.20	0.30	0.18	0.28	0.37	0.24	0.34	0.44	0.30	0.40	0.50
	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Meadow	0.10	0.16	0.25	0.14	0.22	0.30	0.20	0.28	0.36	0.24	0.30	0.40
	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Forest	0.05	0.08	0.11	0.08	0.11	0.14	0.10	0.13	0.16	0.12	0.16	0.20
	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Residential Lot, 1/8 acre	0.25	0.28	0.31	0.27	0.30	0.35	0.30	0.33	0.38	0.33	0.36	0.42
	0.33	0.37	0.40	0.35	0.39	0.44	0.38	0.42	0.49	0.41	0.45	0.54
Residential Lot, 1/4 acre	0.22	0.26	0.29	0.24	0.29	0.33	0.27	0.31	0.36	0.30	0.34	0.40
	0.30	0.34	0.37	0.33	0.37	0.42	0.36	0.40	0.47	0.38	0.42	0.52
Residential Lot, 1/3 acre	0.19	0.23	0.26	0.22	0.26	0.30	0.25	0.29	0.34	0.28	0.32	0.39
	0.28	0.32	0.35	0.30	0.35	0.39	0.33	0.38	0.45	0.36	0.40	0.50
Residential Lot, 1/2 acre	0.16	0.20	0.24	0.19	0.23	0.28	0.22	0.27	0.32	0.26	0.30	0.37
	0.25	0.29	0.32	0.28	0.32	0.36	0.31	0.35	0.42	0.34	0.38	0.48
Residential Lot, 1 acre	0.14	0.19	0.22	0.17	0.21	0.26	0.20	0.25	0.31	0.24	0.29	0.35
	0.22	0.26	0.29	0.2	0.28	0.34	0.28	0.32	0.40	0.31	0.35	0.46
Industrial	0.67	0.68	0.68	0.68	0.68	0.69	0.68	.69	0.69	0.69	0.69	0.70
	0.85	0.85	0.86	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.71	0.71	0.72	0.71	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.89	0.89	0.90
Streets	0.70	0.71	0.72	0.71	0.72	0.74	0.72	0.73	0.76	0.73	0.75	0.78
	0.76	0.77	0.79	0.80	0.82	0.84	0.84	0.85	0.89	0.89	0.91	0.95
Open Space	0.05	0.10	0.14	0.08	0.13	0.19	0.12	0.17	0.24	0.16	0.21	0.28
	0.11	0.16	0.20	0.14	0.19	0.26	0.18	0.23	0.32	0.22	0.27	0.39
Parking	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87
	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97

^a Runoff coefficients for storm recurrence intervals less than 25 years.

^b Runoff coefficients for storm recurrence intervals of 25 years or longer.

D.2.3.3 NRCS TR-55 Methods: Unit Hyetograph Storms (SCS/NRCS 1986; 2002)

Urban Hydrology for Small Watersheds, also known as *Technical Release 55 (TR-55)*, simplifies more complex hydrological prediction procedures so that they are applicable for estimating runoff and peak discharges in small watersheds. While TR-55 emphasizes urban and urbanizing watersheds, the procedures apply to any small watershed in which certain limitations

are met. The calculations are simple and allow for pre- and post-development comparisons. TR-55 includes four regional rainfall time distributions. All four distributions are for a 24-hour period. This period was chosen because of the general availability of daily rainfall data that were used to estimate 24-hour rainfall amounts. The computer model of TR-55 allows for easy comparison of pre- and post-development conditions.

Rainfall Distributions in TR-55 The Rational method uses a constant-intensity design storm for its hydrologic predictions. In reality, in most locations, there is often a peak rainfall that occurs during the storm — a period of brief, and comparably very intense, rainfall. These intense bursts do not usually extended over a large area and intensities vary greatly. Therefore, a constant-intensity storm (unless the rainfall intensity is selected for that peak at T_c) does not reflect actual rainfall distributions. The TR-55 methods use a geographically-specific, synthetic rainfall distribution that has a varying rainfall intensity distribution. It includes a period of intense rainfall surrounded by periods of much lower rainfall intensities. The logic and development of these distributions is described in the following paragraphs, quoted directly from TR-55 (1986).

In the calculation, the length of the most intense rainfall period contributing to the peak runoff rate is related to the time of concentration (T_c) for the watershed. In a hydrograph created with NRCS procedures, the duration of rainfall that directly contributes to the peak is about 170 % of the T_c . For example, the most intense 8.5-minute rainfall period would contribute to the peak discharge for a watershed with a T_c of 5 minutes. ... to avoid the use of a different set of rainfall intensities for each drainage area size, a set of synthetic rainfall distributions having “nested” rainfall intensities was developed. The set “maximizes” the rainfall intensities by incorporating selected short duration intensities within those needed for longer durations at the same probability level.

For the size of the drainage areas for which NRCS usually provides assistance, a storm period of 24 hours was chosen the synthetic rainfall distributions. The 24-hour storm, while longer than that needed to determine peaks for these drainage areas, is appropriate for determining runoff volumes. Therefore, a single storm duration and associated synthetic rainfall distribution can be used to represent not only the peak discharges but also the runoff volumes for a range of drainage area sizes.

The intensity of rainfall varies considerably during a storm as well as geographic regions. To represent various regions of the United States, NRCS developed four synthetic 24-hour rainfall distributions (I, IA, II, and III) from available National Weather Service (NWS) duration-frequency data ... or local storm data. Type IA is the least intense and type II the most intense short duration rainfall. The four distributions are shown in Figure B-1, and Figure B-2 shows their approximate geographic boundaries. [Figure D-10 in this document.]

Types I and IA represent the Pacific maritime climate with wet winters and dry summers. Type III represents Gulf of Mexico and Atlantic coastal areas where tropical storms bring large 24-hour rainfall amounts. Type II represents the rest of the country. For more precise distribution boundaries in a state having more than one type, contact the NRCS State Conservation Engineer.

An example map of the anticipated 24-hour rainfall is shown for the five-year storm (Figure D-10).

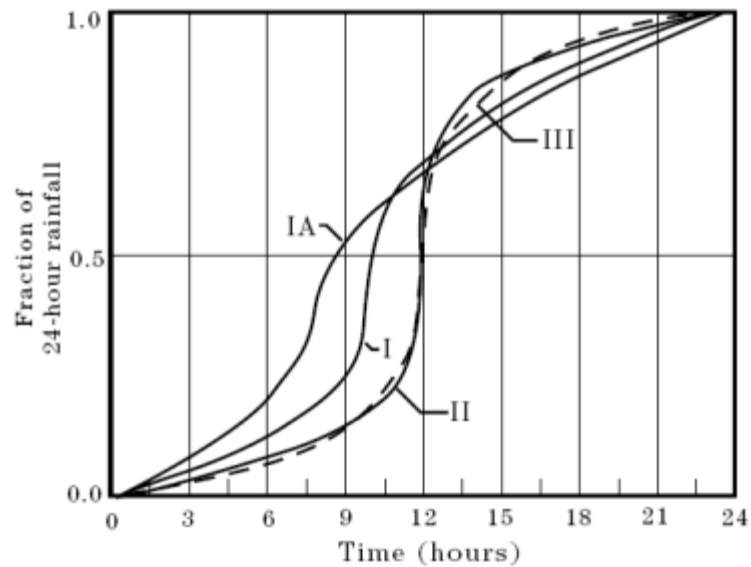


Figure D-10. SCS 24-hour Rainfall Distribution. (USDA NRCS, 1986)

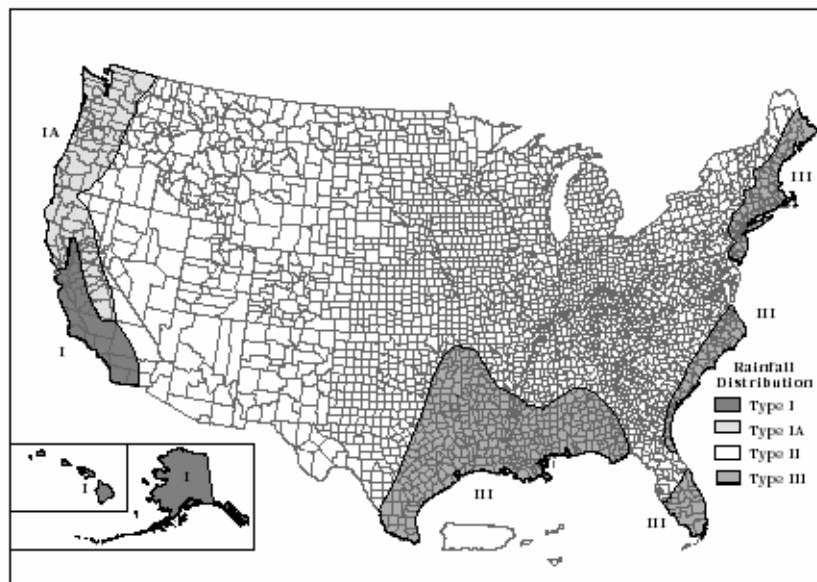


Figure D-11. Approximate Geographic Boundaries for NRCS Rainfall Distributions. (USDA NRCS, 1986)

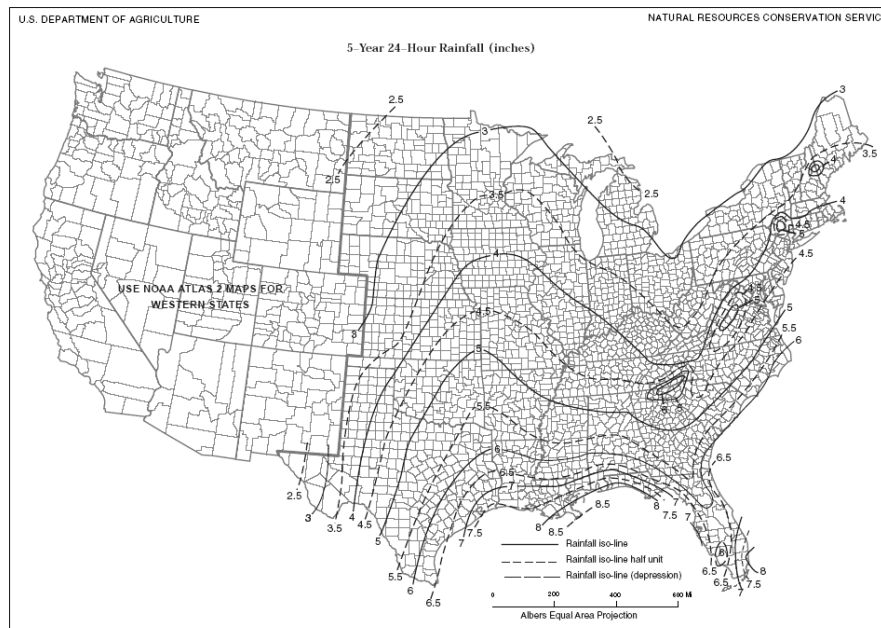


Figure D-12. 5-year, 24-hour Rainfall. (USDA NRCS, 1986)

TR-55 contains two methods for calculating peak flow, the Graphical Peak Discharge Method and the Tabular Hydrograph Method. The flow chart in Figure D-13 assists the user in selecting the appropriate calculation method based on the needs of engineer and designer. The two methods are summarized in this section. Full descriptions of the methods are found in TR-55.

Limitations of the General TR-55 Protocol (based on and quoted from NRCS TR-55 1986).

TR-55 begins with a rainfall amount uniformly imposed on the watershed over a specified time distribution (the rainfall is assumed to occur equally across the entire watershed). Mass rainfall is converted to mass runoff by using a proportionality constant, the runoff curve number (CN). The CN is based on soils, plant cover, amount of impervious areas, interception, and surface storage. Runoff is then transformed into a hydrograph by using unit hydrograph theory and routing procedures that depend on runoff travel time through segments of the watershed.

The procedures in TR-55 are simplified by assumptions about some parameters. These simplifications, however, limit the use of the procedures and can provide results that are less accurate than more detailed methods. The user should examine the sensitivity of the analysis being conducted to a variation of the peak discharge or hydrograph. To ensure that the degree of error is tolerable, specific limitations are given with each method. Additional general constraints to the use of TR-55 are as follows:

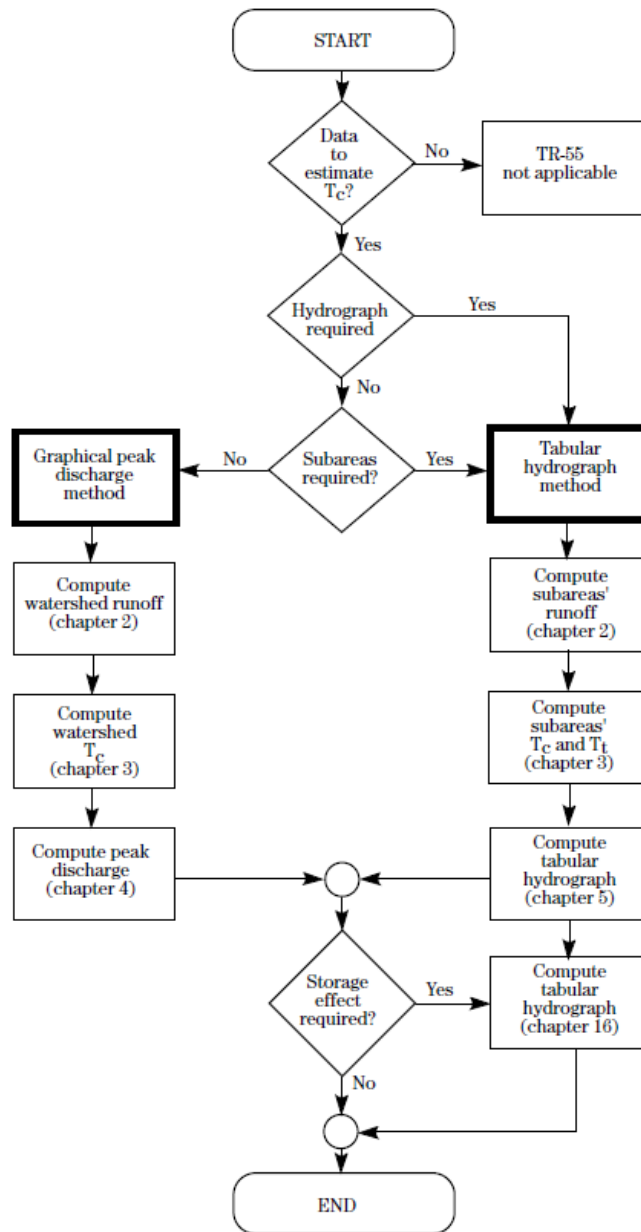


Figure D-13. Decision Flow Chart for TR-55. (USDA NRCS, 1986)

- ◆ The methods in this document are based on open and unconfined flow over land or in channels. For large events during which flow is divided between sewer and overland flow, more information about hydraulics than is presented here is needed to determine T_c . After flow enters a closed system, the discharge can be assumed constant until another flow is encountered at a junction or another inlet.
- ◆ Both the Graphical Peak Discharge and Tabular Hydrograph methods are derived from TR-20 (SCS, 1983) output. Their accuracy is comparable; they differ only in their products. The use of T_c permits them to be used for any size watershed within the scope of the curves or tables. The Graphical Method (Chapter 4) is used only for hydrologically

homogeneous watersheds because the procedure is limited to a single watershed subarea. The Tabular method (Chapter 5) can be used for a heterogeneous watershed that is divided into a number of homogeneous subwatersheds. Hydrographs for the subwatersheds can be routed and added.

Curve Numbers for SCS Graphical Peak and Tabular Hydrograph Methods As stated earlier, the runoff curve number is a measure of the fraction of rainfall that becomes runoff. Similar to the coefficients for the Rational method, tables of curve numbers have been developed for various land uses and hydrologic soil groups.

Equation D.12 used to calculate the curve number is the following:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{Equation D.12}$$

Where

Q = runoff (in)

P = rainfall (in)

S = potential maximum retention after runoff begins (in)

I_a = initial abstraction (in)

The initial abstraction (I_a) includes all the losses that occur before runoff begins: water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally can be correlated with soil and cover parameters. By studying many small agricultural watersheds, I_a could be approximated by the following empirical equation (Equation D.13):

$$I_a = 0.2 S \quad \text{Equation D.13}$$

Substituting into the above equation, the initial abstraction (I_a) is removed as a parameter. By removing I_a as an independent parameter, this approximation allows use of a combination of S and P to produce a unique runoff amount (Equation D.14 – both forms).

$$Q = \frac{(P - 0.2S)^2}{(P - 0.2S) + S} \quad \text{Equation D.14}$$

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN through the following equation:

$$S = \frac{1000}{CN} - 10$$

Equation D.15

Tables D-9 through D-11 show the estimated curve number for various land use categories based on hydrologic soil group.

Table D-9. Runoff Curve Numbers for Cultivated Agricultural Lands¹.

Cover Description			Curve Numbers for hydrologic soil group			
Cover Type	Treatment ²	Hydrologic condition ³	A	B	C	D
Fallow	Bare Soil	--	77	86	91	94
	Crop Residue Cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row Crops	Straight Row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & Terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small Grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or Broadcast Legumes or Rotation Meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

¹Average runoff condition, and $I_a = 0.2S$.

²Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

³Hydrologic condition is based on a combination of factors that affect infiltration and runoff, including (1) density and canopy of vegetative areas, (2) amount of year-round cover, (3) amount of grass or close-seeded legumes in rotations, (4) percent of residue cover on the land surface (good $\geq 20\%$), and (5) degree of surface roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better infiltration and tend to decrease runoff.

Table D-10. Runoff Curve Numbers for Other Agricultural Lands¹.

Cover Description		Curve Numbers for Hydrologic Soil Group			
Cover Type	Hydrologic Condition	A	B	C	D
Pasture, grassland, or range – continuous forage for grazing ²	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow – continuous grass, protected from grazing and generally mowed for hay		30	58	71	78
Brush – brush-weed-grass mixture with brush the major element ³	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 ⁴	48	65	73
Woods-grass combination (orchard or tree farm) ⁵	Poor	57	73	83	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods ⁶	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 ⁴	55	70	77
Farmsteads – buildings, lanes, driveways, and surrounding lots		59	74	82	86

¹Average runoff condition, and $I_a = 0.2S$.

²Poor: < 50% ground cover or heavily grazed with no mulch.

Fair: 50 to 75% ground cover and not heavily grazed.

Good: > 75% ground cover and lightly or only occasionally grazed.

³Poor: <50% ground cover.

Fair: 50 to 75% ground cover.

Good: >75% ground cover.

⁴Actual curve number is less than 30; use CN = 30 for runoff computations.

⁵CNs shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CNs for woods and pasture.

⁶Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.

Fair: Woods are grazed, but not burned, and some forest litter covers the soil.

Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Table D-11. Runoff Curve Numbers¹.

Land Use Description/Treatment	Hydrologic Condition	Hydrologic Soil Group			
		A	B	C	D
Residential ²					
Average lot size:	Average Percent Imperviousness ³				
1/8 acre or less	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
Paved parking lots, roofs, driveways, etc. ⁴		98	98	98	98
Streets and roads					
Paved with curbs and storm sewers ³		98	98	98	98
Gravel		76	85	89	91
Dirt		72	82	87	89
Commercial and business areas (85 percent imperviousness)		89	92	94	95
Industrial districts (72 percent imperviousness)		81	88	91	93
Open spaces, lawns, parks, golf courses, cemeteries, etc.					
Good condition: grass cover on 75 percent or more of the area		39	61	74	80
Fair condition: grass cover on 50 to 75 percent of the area		49	69	79	84
Poor condition: grass cover on less than 50 percent		68	79	86	89
Western Desert Urban Areas					
Natural desert landscaping (pervious areas only) ⁵		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Developing Urban Areas					
Newly developing areas (pervious areas only, no vegetation) ⁶		77	86	91	94

¹Average runoff condition, and $I_a = 0.2S$.

²Curve numbers are computed assuming the runoff from the house and driveway is directed toward the street with a minimum of roof water directed to lawns where additional infiltration could occur. Impervious areas have a CN of 98 and pervious space considered equivalent to open space in good hydrologic condition.

³The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

⁴In some warmer climates of the country, a curve number of 95 may be used.

⁵Composite curve numbers for natural desert landscaping should be computed using the following figures based on the impervious area percentage and the pervious area CN. The pervious area CNs are assumed equivalent to desert shrub in poor hydrologic condition.

⁶Composite CNs to use for the design of temporary measures during grading and construction should be computed using the following figures based on the degree of development (impervious area percentage) and the CNs for the newly graded pervious areas.

The urban area land use categories have a percentage imperviousness associated with them. These percent imperviousness measurements are based on average conditions. In some cases, the average percent imperviousness does not reflect actual conditions. The composite CN is the y-value corresponding to the actual percent imperviousness in the watershed and the CN of the pervious area.

In an urban watershed, not all impervious areas are directly connected to the drainage systems. Runoff from these unconnected impervious areas is spread over a pervious area as sheet flow. If the total impervious area is greater than 30%, TR-55 adjustment methods can be used to adjust for percent imperviousness since the pervious area will not significantly contribute to the volume of runoff or peak flow.

Curve numbers can be weighted based on the percentage of area in the watershed assigned to each land use category. The equation for weighting curve numbers is as follows:

$$CN_w = \frac{\sum_i CN_i A_i}{\sum_i A_i} \quad \text{Equation D.16}$$

Where

CN_w = weighted Curve Number

CN_i = Curve Number for area i

A_i = area for which C_i is applicable

Limitations of Curve Numbers

- ◆ Curve numbers describe average conditions that are useful for design purposes. If the rainfall event used is a historical storm, the modeling accuracy decreases.
- ◆ Use the runoff curve number equation with caution when re-creating specific features of an actual storm.
- ◆ The equation does not contain an expression for time and, therefore, does not account for rainfall duration and intensity.
- ◆ The user should understand the assumption reflected in the initial abstraction term (I_a) and determine that the assumption applies to the situation.
- ◆ Runoff from snowmelt or rain on frozen ground cannot be estimated using these procedures.
- ◆ The CN procedure is less accurate when runoff is less than 0.5 inch. As a check, use another procedure to determine runoff.
- ◆ The SCS runoff procedures apply only to direct surface runoff.
- ◆ When the weighted CN is less than 40, use another procedure.

These curve numbers have been developed for larger, drainage design storms. However, this method is accepted for use in calculating water quality volumes for the design of stormwater treatment devices. What needs to be remembered is that, like volumetric runoff coefficients, curve numbers based on these drainage design storms are often lower than curve numbers observed in the field for small storms. Underpredicted CNs lead to underestimated runoff peak flow rates and runoff volumes. Figure D-14 is from the Milwaukee NURP study (from Bannerman et al. (1983)) and shows the variation in curve number based on the storm size.

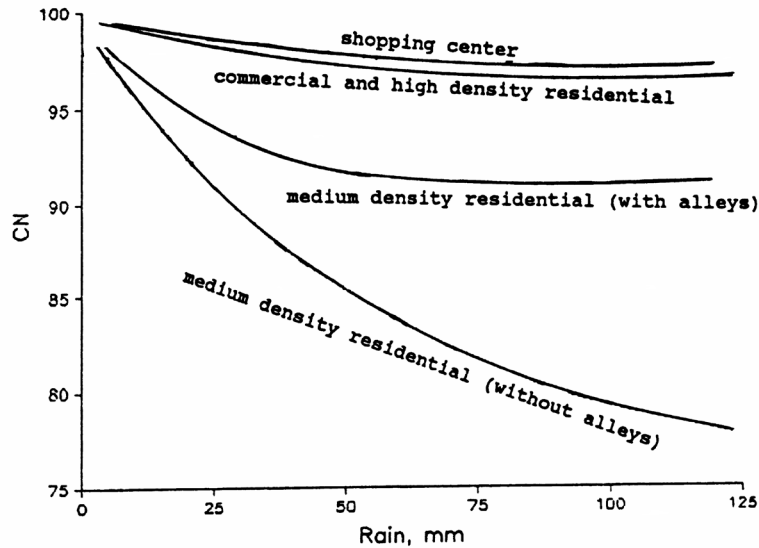


Figure D-14. Relationship Between the Actual Curve Number and the Rainfall Depth.

Graphical Peak Discharge Method (Chapter 4 of TR-55 Manual) The Graphical Peak Discharge Method can be used to predict the peak flow rate from a small watershed. It cannot be used to predict the runoff hydrograph for the watershed based on rainfall that equals the synthetic design storm. The input requirements for the Graphical Peak Discharge Methods are the following:

- ♦ T_c (hr)
- ♦ Drainage area (mi^2)
- ♦ Rainfall distribution (I, IA, II, III)
- ♦ 24-hour rainfall for the design storm
- ♦ Curve Number (weighted and adjusted as needed)
- ♦ Pond and Swamp Adjustment Factor (F_p)

The calculation equation is as follows:

$$Q_p = q_u A_m Q F_p \quad \text{Equation D.17}$$

Where

Q_p = peak discharge (cfs)

q_u = unit peak discharge (csm/in)

A_m = drainage area (mi^2)

Q = runoff (in)

F_p = pond and swamp adjustment factor

For a selected rainfall frequency (Types I, IA, II, and III) and the design storm, the 24-hour rainfall (P) is obtained the rainfall figures in TP-40 or more detailed local precipitation information. The curve number is read from the table and adjusted as needed for the actual percent imperviousness and for the percentage of impervious area that is not directly connected to the drainage system. The total runoff is estimated on the appropriate worksheet, based on the CN, from the 24-hour rainfall depth (P) using the figure or the equations that relate CN and total runoff (Q) for the watershed

Limitations of the Graphical Peak Discharge Method as reported by TR-55

- ◆ Watershed must be hydrologically homogeneous (i.e., one CN).
- ◆ Watershed must have only one main stream, or if more than one, branches must have nearly equal T_c .
- ◆ Method cannot perform valley or reservoir routing.
- ◆ F_p factor must apply only to ponds and swamps not in the T_c flowpath.
- ◆ Accuracy of peak discharge estimated will be reduced if I_a/P is not in the range given by the figure.
- ◆ Weighted curve number must be greater than 40.
- ◆ T_c values must be between 0.1 and 10 hours.

NRCS TR-55 Tabular Hydrograph Method The NRCS TR-55 Tabular Hydrograph Method uses watershed information and a single design storm to predict the peak flow rate, the total runoff volume, and the hydrograph. This method more closely approximates TR-20. It provides partial composite flood hydrographs for the watershed by dividing the watershed into homogenous subareas. This allows the runoff from non-homogeneous watersheds to be estimated. The required information is the following:

- ◆ Subdivision of the watershed into areas that are relatively homogeneous by land uses and have convenient routing reaches.
- ◆ Drainage area of each subarea in square miles.
- ◆ T_c for each subarea in hours.
- ◆ T_t for each routing reach in hours.
- ◆ Weighted CN for each subarea.
- ◆ Appropriate rainfall distribution (Type I, IA, II and III).
- ◆ 24-hour rainfall for the design storm.
- ◆ Total runoff (Q) in inches computed from CN and rainfall.
- ◆ I_a for each subarea from TR-55 Table 4-1.
- ◆ Ratio of I_a/P for each subarea.

This procedure requires the use of two worksheets (named Worksheets 5a and 5b in TR-55). The calculation equation of interest for the peak flow at any time on the hydrograph is as follows:

$$q = q_t A_m Q \quad \text{Equation D.18}$$

Where

q = hydrograph coordinate (cfs) at hydrograph time t

q_t = tabular hydrograph unit discharge from Exhibit 5 (tables) (csm/in)

A_m = drainage area of individual subarea (mi²)

Q = direct runoff based on precipitation P and CN

Limitations of the Tabular Hydrograph Method

The Tabular method is used to determine peak flows and hydrographs within a watershed. However, its accuracy decreases as the complexity of the watershed increases. When comparing present and developed conditions of a watershed, use the same procedure for estimating T_c for both conditions.

Use the TR-20 computer program (NRCS, 2002) instead of the Tabular method if any of the following conditions applies:

- ◆ T_t is greater than 3 hours.
- ◆ T_c is greater than 2 hours.
- ◆ Drainage areas of individual subareas differ by a factor of 5 or more.
- ◆ The entire composite flood hydrograph or entire runoff volume is required for detailed flood routings. The hydrograph based on extrapolation is only an approximation of the entire hydrograph.
- ◆ The time of peak discharge must be more accurate than that obtained through the Tabular method.

The composite flood hydrograph should be compared with actual stream gage data where possible. The instantaneous peak flow value from the composite flood hydrograph can be compared with data from USGS curves of peak flow versus drainage area.

Estimating Runoff using Computer Modeling (*Win TR-20 and WinTR-55*). The TR-55 methodology is available as a freeware computer program at the following website:

<http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models.html>

These models have on-line guidance documents and many have training programs available as PowerPoint presentations.

TR-20 is also available as a freeware program.

APPENDIX E

IMPACTS OF COMPACTION ON INFILTRATION

E.1 Introduction

Hydrologic models contain a component/term called infiltration to account for the loss of rainfall that does not become runoff. The term “infiltration” encompasses what in soil science are the processes of both infiltration (surface penetration of water) and percolation (subsurface transport of water to the groundwater). The rate of infiltration is a function of gravity and porosity of soil. In an unsaturated soil, infiltration usually is rapid initially but declines quickly to a constant value. Concerns about the effects of soil infiltration on earth structure applications have been raised, including effects such as slope instability and landslides resulting from soil hysteresis. It is crucial, therefore, that development engineers better understand infiltration and the parameters that affect it.

E.2 Infiltration Mechanisms

Rainfall infiltration into pervious surfaces is controlled by three mechanisms: the maximum possible rate of entry of the water through the soil/plant surface, the rate of movement of the water through the vadose (unsaturated) zone, and the rate of drainage from the vadose zone into the saturated zone. The surface entry rate of water may be affected by a surface sealing layer of silts and clay particles at the soil surface and/or by vegetation which may or may not enhance water penetration. The movement of water through the soil is highly dependent on the characteristics of the underlying soil. Water cannot enter the soil surface layer faster than it is being transmitted through the underlying layer. During longer storm events, the available storage capacity in the soil is depleted, which affects the transmission and drainage rates. The storage capacity depends on the soil thickness, porosity, and the soil-water content. Many factors, such as soil texture, root development, soil insect and animal bore holes, structure, and presence of organic matter, affect the effective porosity of the soil.

The infiltration capacity of most native, undisturbed soils allows low intensity rainfall to totally infiltrate, unless the soil voids became saturated or the underlain soil was much more compact than the top layer (Morel-Seytoux, 1978). High intensity rainfalls generate substantial runoff because the infiltration capacity at the upper soil surface is surpassed, even though the underlain soil might still be very dry.

The classical assumption is that the infiltration capacity of a soil is highest at the very beginning of a storm and decreases with time (Willeke, 1966). Horton (1939) is credited with defining infiltration capacity and deriving an appropriate working equation. Horton defined infiltration capacity as “...the maximum rate at which water can enter the soil at a particular point under a given set of conditions” (Morel-Seytoux, 1978).

Natural infiltration is significantly reduced in urban areas due to several factors: the decreased area of exposed soils, removal of surface soils and exposing subsurface soils with typically poorer drainage characteristics, importing different soils to a construction site and subsequent compaction associated with soil placement, compaction of the soils during earth

moving and construction operations, and many typical urban activities (such as parking cars on grass, compacted playing fields and walkways, etc.). The decreased areas of soils are typically linked to increased runoff volumes and peak flow rates, while the effects of soil disturbance are rarely considered. Silting of engineered infiltration areas, which were installed to compensate for the loss of natural infiltration areas post-development, often results in early failures of these devices, although compaction from heavy traffic is also a recognized problem.

E.3 Effect of Compaction on Infiltration

The data presented here is based on research performed in the state of Alabama for the U.S. EPA (Pitt et al., 1998). To establish the correlation between soil compaction and infiltration rates, several series of tests, both in the field and in the laboratory, have been conducted throughout the state of Alabama. This paper focuses on the critical effects on soil infiltration caused by compaction of soils as part of urban development. While much of the change of runoff volume has been “blamed” on decreased surfaces available for infiltration, urban soils also undergo major modifications that also result in increased runoff. Specific soil disturbance effects include changing the microstructures of soil materials, inducing soil suction, altering soil friction and cohesion, and ultimately changing the soil strength characteristics. These changes are not included typically, either as individual effects or as a lumped-parameter, in traditional urban hydrology models.

Figure E-1 shows three-dimensional plots of the field infiltration data, illustrating the effects of soil-moisture and compaction, for both sandy and clayey soils. Four general conditions were observed to be statistically distinguishable. As shown in the figures, compaction has the greatest effect on infiltration rates in sandy soils, with little detrimental effects associated with higher soil-water content conditions (the only condition usually considered during runoff modeling). Clay soils, however, are affected by both compaction and soil-water content. Compaction was seen to have about the same effect as saturation on clayey soils, with saturated and compacted clayey soils having very little effective infiltration. Table E-1 summarizes the average infiltration rate for five different soil groups.

The Horton infiltration equation was fitted to each set of individual site data (Figure E-2 for one example) and the equation coefficients were statistically compared for the different site conditions. The data showed a high scatter in the infiltration rates over time – even at the same site. A comparison of sites in the same general category further showed the large variability of the results. Because of the wide range in observed rates for each major category, it may not be important which infiltration rate equation is used. The residuals are all relatively large and it may be much more important to consider the random nature of infiltration about any fitted model and to address the considerable effect that soil compaction has on filtration.

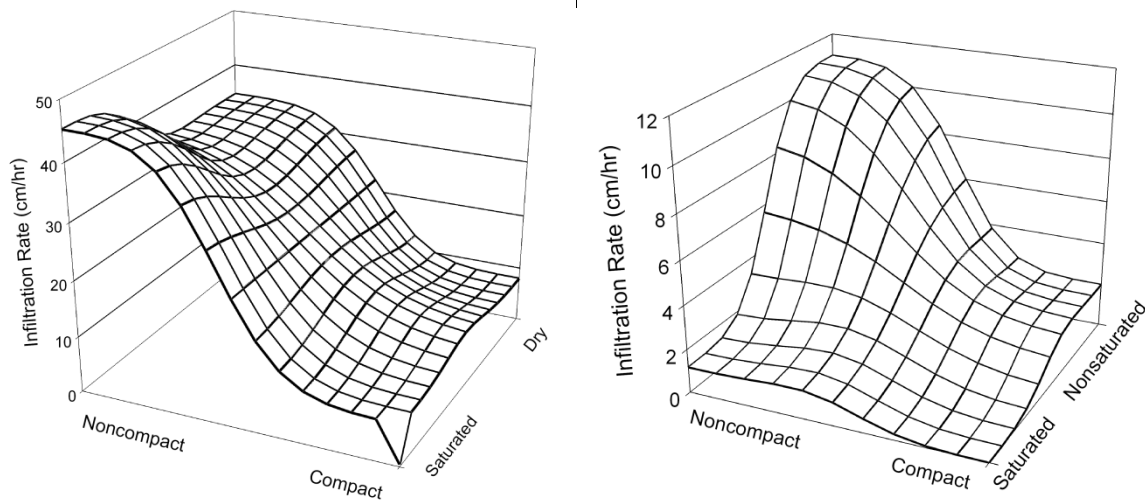


Figure E-1. Infiltration Rates through Sandy (left) and Clayey (right) Soils as a Function of Compaction and Saturation.

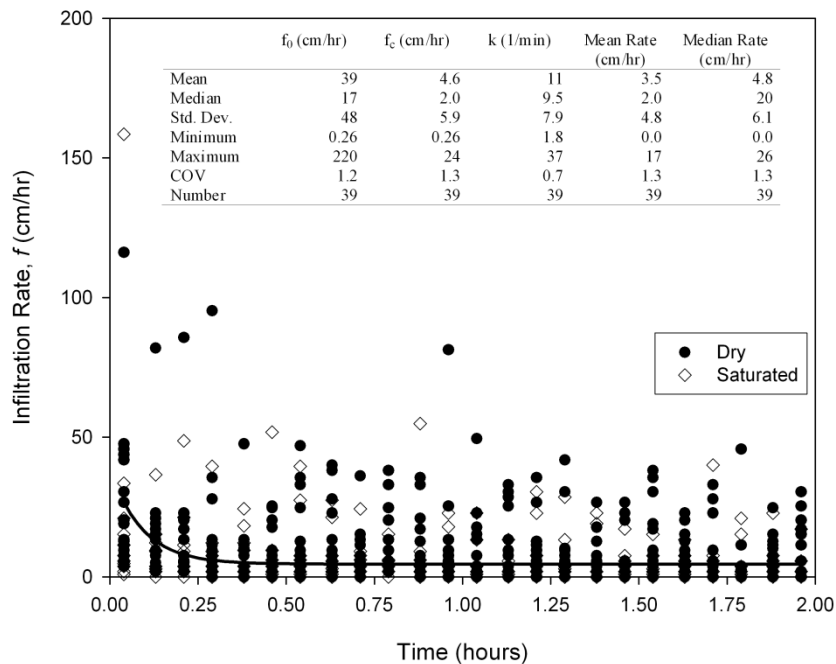


Figure E-2. Horton Infiltration Regression for One Example Site.

Higher infiltration rates were seen for shorter rainfall periods, with infiltration rates becoming relatively steady after 30 to 45 minutes during most tests. Clayey soils would be most affected by the antecedent interevent period which would define the soil-water level at the beginning of the event. Soil texture and compaction are likely not an issue since they would remain fixed for an extended period of time unless the soil underwent a successful recovery operation to reduce soil compaction.

Laboratory tests were performed to examine infiltration under more controlled conditions of compaction and initial soil-water content. Figures E-3 shows typical infiltration plots obtained

during these laboratory compaction tests for silty and sandy-loam soils, respectively. Plots for other soil types can be found in Pitt et al. (2008).

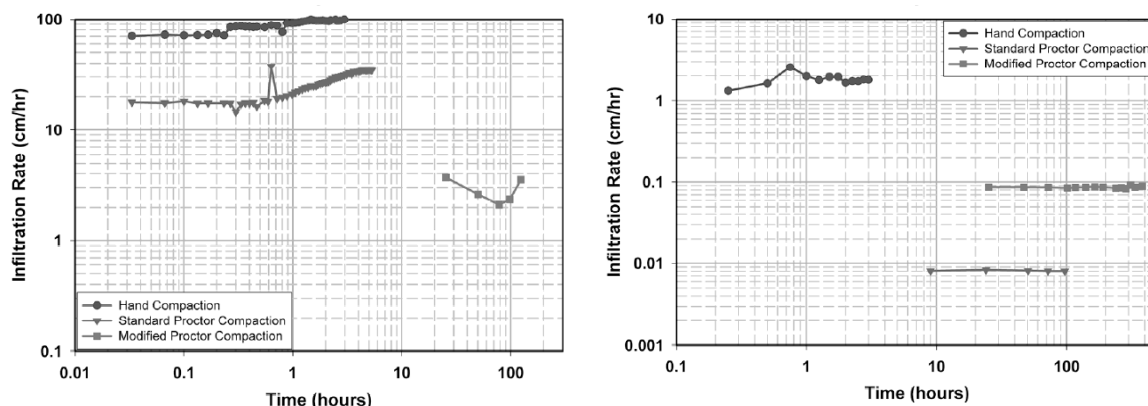


Figure E-3. Effects of Compaction Method on Infiltration (Left: Sandy Loam; Right: Silty Loam).

Table E-1 compares the infiltration test results from these field and laboratory investigations. The low-head laboratory and field results were similar, except for the higher rates observed for the non-compacted clay field tests. These higher results could reflect actual macro-structure conditions in the natural soils, or the compaction levels obtained in the laboratory were unusually high compared to field conditions. In addition, the high-head laboratory test results produced infiltration rates substantially greater than for the similar low-head results for sandy soil conditions, but not for the other soils.

Table E-1. Comparison of Infiltration Rates from Different Test Series.

Group	Field Test Average Infiltration Rates	Low-Head Laboratory Test Results
Noncompacted sandy soils	32.5 cm/hr (13 in/hr)	20 to 24 cm/hr (8 to 9.5 in/hr)
Compact sandy soils	3.5 cm/hr (1.4 in/hr)	7.5 to 12.5 cm/hr (3 to 5 in/hr)
Noncompacted and dry clayey soils	24.5 cm/hr (9.8 in/hr)	1.0 to 1.5 cm/hr (0.4 to 0.6 in/hr)
All other clayey soils (compacted and dry, plus all wetter conditions)	0.5 cm/hr (0.2 in/hr)	0 to 1.0 cm/hr (0 to 0.4 in/hr)
Noncompacted silty and loamy soils	NA	0.25 to 0.6 in/hr
Compacted silty and loamy soils	NA	0 to 0.02 in/hr

NA = not available based on field tested soils.

The field measurements of infiltration rates during these tests were all substantially larger than expected, but comparable to previous standard double-ring infiltrometer tests in urban soils and comparable to the recent measurements in non-compacted sandy soils in Florida by Gregory et al. (2006). The infiltration rates in compacted sandy soils also were comparable to those of Gregory et al. (2006) with the exception of the measurement of compacted soil in a planted forest in Florida, which was an order of magnitude higher than these tests. In their survey of lawn establishment and maintenance, Hamilton and Waddington (1999) found that soil texture was not significant, but that excavation and lawn establishment procedures appeared to be the

controlling factors for soil infiltration rates. Gregory et al. (2006) showed that infiltration was reduced 70-99% on compacted-soil sites, and that the type of equipment did not affect the reduction in infiltration. Instead, simply exposing the soil to construction equipment reduced the infiltration rate. Other researchers have noted the general over-predictions of ponding infiltrometers compared to actual observations during natural rains. In all cases, these measurements are suitable to indicate the relative effects of soil texture, compaction, and soil-water on infiltration rates. Also, the measured values can be directly used to predict the infiltration rates that may be expected from stormwater infiltration controls that incorporate ponding (most infiltration and bioretention devices).

Current infiltration guidance by many regulatory authorities states that infiltration areas should be not be exposed to construction activities. However, this is unrealistic when excavating infiltration basins, areas for permeable pavements, or bioretention areas. What these results show is that construction equipment should not enter the area of infiltration, but instead all excavation should be performed with the base of the backhoe on the basin sides and not in the infiltration area itself.

E.4 Rapid Detection Methods for Compacted Soils

Table E-2, adapted from the Urban Forestry Manual, summarizes methods of quickly determining (without infiltration or percolation testing) if the soil is compacted.

Table E-2. Signs of Compaction.

Sign	Description
Hard soil	Soil is hard to penetrate with a shovel. In previously-agricultural lands, earlier cultivation may have produced a layer of hard soil 10 – 12 inches below the surface.
Standing water	Water standing on top of the soil for a long time may indicate compaction.
Excessive water runoff	This is a sign of low permeability (little movement of water through the soil).
Vegetation loss or poor plant growth	Compacted soil reduces the air circulation and water infiltration into the root zone. A lack of water, nutrients and oxygen causes declining tree health or death. Compaction at depth may be noticed through good grass growth but poor tree establishment.
Bulk density	High soil bulk density indicates compaction. The reduced pore space limits water infiltration, aeration, root growth.
Surface crust	Development of a surface crust sometimes occurs with the compaction of fine-textured soils. This crust limits the infiltration of air and water into the soil, increases runoff and increases erosion. Surface crusts are usually found on soils subject to heavy foot traffic.

E.5 Recovery of Compacted Soils

Recovering infiltration capacity has been proposed by several researchers. This recovery typically only is effective at the near-surface areas. Table E-3 lists the methods recommended by the USDA.

One of the most often proposed techniques for regaining soil infiltration capacity is the addition of an organic material. Pitt et al. (1999) examined the benefits of adding large amount of compost to a glacial till soil (poor infiltration) at the time of development. Compost-amended soils were found to have significantly increased infiltration rates, but increased concentrations of nutrients in the surface runoff. The compost-amended test plots produced superior turf, with little or no need for establishment or maintenance fertilization. Therefore, the use of soil amendments

to improve infiltration capacity, whether in the natural soils of an area or in an infiltration/bioinfiltration area, can increase infiltration, but may reduce water quality. The results of these tests are summarized as a case study in Appendix J.

Table E-3. Techniques for Solving Soil Compaction Problems for New and Existing Planting Sites.

New Sites	
Techniques for Reducing Compaction	Description
Soil Mixing	Compacted soil can be mixed with a fully composted organic mulch to improve the soil quality, but up to 50% of the soil volume is needed.
Rototilling or grading	The compacted soils may be rototilled, disked or graded to improve near-surface infiltration.
Subsoiling or drilling hardpan	If there is a compacted layer of soil 1 to 2 feet below the surface, subsoiling or deep plowing with a plow or backhoe when soil is dry may break up this layer. Also, holes can be drilled into the hardpan to provide drainage and root penetration.
Top Mulching	Organic content of soils can be increased by adding mulch on top of existing soil. However, the organic material takes many years to breakdown and combine effectively with the native soil.
Existing Sites	
Core aeration	Pore space in compacted soil may be increased by removing small soil cores to a depth of about 3 inches.
Vertical mulching	Holes 1 – 2 inches in diameter may be drilled in the compacted soil and filled with perlite, vermiculite or other amendment material.
Radial trenching	Trenches 6 – 8 inches wide and no deeper than the root system or depth of compaction could be dug with trenching equipment. The trenches are then backfilled with a mixture of soil and amendments.

E.6 Other Problems in Urban Soils

Other potential problems encountered in urban soils are a high or alkaline pH, low soil fertility (which reduces the ability to establish vegetation), and a high salt content. The high pH results from construction materials, such as mortar and concrete, being spilled or left on the ground. The addition of this calcium-based material, which is alkaline, raises the soil pH. A high pH may also cause chemical reactions in the soil that reduce its treatment capacity for stormwater pollutants. Road salt infiltration may result in increased salinity problems in the soil, which may affect plant growth in bioretention areas and may affect the pollutant removal capacity through soils.

In addition, when planning stormwater management practices, unusual subsurface geologic formations must be noted since those may affect infiltration flow and pollutant removal. In addition, excess infiltration in areas of fractured flow may accelerate subsurface soil erosion and cause sinkholes to develop. The location of perched clay lenses and other features of low permeability also need to be noted. A perched lens may cause an artificially high water table to exist in some areas, with the result that the area with a high water table may be unsuitable for infiltration.

APPENDIX F

IMPACTS OF URBAN RUNOFF AND DEVELOPMENT ON RECEIVING WATERS

F.1 General Effects of Urbanization on Watersheds and Receiving Waterbodies

Urban and suburban developments cause profound changes to natural watershed conditions by altering the terrain, modifying the vegetation and soil characteristics, and introducing pavement, buildings, drainage, and flood control infrastructure.

The increase in impervious area associated with urbanization has significant impacts on the hydrology and geomorphology of watersheds. These include:

1. Increased frequency of flooding and peak flow volumes,
2. Typically decreased base flow,
3. Increased sediment loadings,
4. Changes in stream morphology and habitat modification,
5. Increased stream temperature, and/or
6. Changes in pollutant concentrations in runoff.

Assessing the current watershed condition, as well as predicting the changes that may be incurred as a result of the planned development, is an integral part of determining the appropriateness of the various stormwater management techniques for a site. It is anticipated that most sites will require a combination of management and treatment technologies. Understanding whether the technique will provide a benefit to controlling the runoff from the site therefore is critical. It may require using a variety of assessment metrics or “tools.” Many of the tools required to assess watershed condition have been summarized by Burton and Pitt (2002) in their book *Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers*. This book has several extensive literature reviews designed for stormwater managers who require the additional background information to support the tools described in the book. In addition, Reuss (2005) provides historical perspectives on river management and the impacts of urbanization. The following discussion is designed to reference and supplement that information - not repeat it. It is included to provide the background material/literature references needed for stormwater managers to plan the appropriate set of assessments.

F.1.1 Frequency of Flooding and Peak Flow Volumes

It has been well documented that urbanization increases peak flow rates and peak flow volumes. Anecdotal evidence has shown that urbanization often results in increased flooding in areas where flooding was not frequent prior to development. For this reason, the Army Corps of Engineers has been tapped for flood analysis in many urban areas. As a result of these projects, much engineering design and work has been performed in the area of flood mitigation – usually

by the construction of engineered channels to move water quickly away from the affected areas. The books traditionally used for stormwater management education and the older hydrology texts (Viessman et al. 2008; McGhee, all editions; Metcalf and Eddy, *Collection Systems Design*; McCuen, all editions; Viessman and Lewis 2003; Bedient et al. 2008) all focused on how to calculate the peak flow rates and total and peak volumes generated from what have traditionally been labeled as flooding storms, e.g., infrequent storms. This has also been the focus of traffic engineering's interest in hydrology. In fact, the traffic engineering texts have usually recreated tables developed/published by the Federal Highway Administration that provide suggestions as to the size of the design storms that should be used to keep flooding on roadways to an acceptable level. Table F-1 shows both the design return period and the exceedence probability for each road type. The greater the traffic load and the greater the necessity of keeping the road open for emergency purposes, the smaller the exceedence probability (the smaller the chance that a storm of a specific size and duration having or exceeding that probability will occur).

Table F-1. Design Storm Selection Guidelines.

(Data summarized from AASHTO Model Drainage Design Manual and VDOT Drainage Manual)

Roadway Classification	Exceedence Probability	Return Period
Rural principal arterial system	2%	50 year
Rural collector system, major	4%	25 year
Rural collector system, minor	10%	10 year
Urban principal arterial system	2 – 4%	25 – 50 year
Urban minor arterial street system	4%	25 year
Urban collector street system	10%	10 year

NOTE: Federal law requires interstate highways to be provided with protection from the 2% flood event, and facilities such as underpasses, depressed roadways, etc. where no overflow relief is available should be designed for the 2% event.

F.1.2 Base Flow and Sediment Loading Changes

Most urban runoff studies have documented a reduction in base flows due to the reduction in infiltration which, in the long term, may drop the groundwater level and reduce the water available to enter the stream either through springs or through groundwater seepage through the channel bottom or through the sides. There are limited cases where an increase in base flow in streams has been documented after urbanization. Possible reasons for this include flow from on-site treatment systems, the use of detention/infiltration basins near the stream (which recharge water near the stream), and in Florida, several detention facilities are using side bank filtration to treat the runoff prior to entry in the stream. Assuming no point source (such as an industrial or municipal wastewater outfall) is nearby, base flow may be increased for two reasons: 1) more water is detained and then released over time, and 2) infiltration increases water in the soil near the basin and forces soil water away from the basin in all three directions. If a stream is nearby, it likely will see an increase in base flow.

Sediment loadings to streams are usually increased due to urban runoff. During quiescent times, the streams have stabilized as much as possible given the typical base flow conditions. During runoff events, the entering stormwater runoff carries sediment. In addition, the higher peak flows tend to scour at the banks, causing bank erosion and increasing the sediment load in the stream. The sources of the solids in urban runoff are discussed in more detail in the section on Pollutants of Concern: Sediment.

F.1.3 Changes in Stream Morphology and Habitat Modification

Dams, dredging, channelization, ditching, housing developments, highway construction and maintenance, and county operations cause habitat alterations or modifications along water bodies. Many of the modifications involve stripping streams of their natural wooded buffers, causing increased runoff and increased stream turbidity due to eroded soils and stream banks. However, it also has been documented that changes to stream morphology and habitat have occurred when the development is occurring inland from the stream. The increased water, energy and pollutant loads from the new developments reach the stream through the drainage system (which is designed to transport the water away from the development rapidly, and is not designed to attenuate it and its effects on the stream). There is a connection between current development practices, habitat and aquatic life because of the changes in sediment transport, flow, light, temperature, bottom substrate, and other stream health factors associated with these modifications.

There is no direct way to quantify the impact of urban stormwater on aquatic habitats. Rather, an assessment of the stream community (typically invertebrates or fish) should be required. Comparison of the community structure and function to information regarding other sites within the watershed or in comparable watersheds as well as the use of indicator organisms allows for an assessment of the stream community. This assessment should be coupled with a complete description of the stream morphology and surrounding land use. Based upon this information, an expert opinion of the overall health and stability of the aquatic ecosystem/community can be developed. However, as will be shown later in this section, long-term studies addressing the impact of development and the impact of BMPs designed to reduce the impact of development have not occurred.

F.1.4 Increased Water Temperature

Water temperature can increase as a result of the removal of riparian vegetation associated with urban development. In addition, summer runoff from rooftops and paved surfaces in urban areas adds heat to the receiving water. Finally, the control of stormwater in shallow detention facilities has led to increased temperatures in the slowly released waters.

Many aquatic organisms are sensitive to high water temperatures. This is a particular concern in areas with cold-water game fish such as trout, salmon, and steelhead. Furthermore, the solubility of oxygen in water is lower in warm water than it is in cold water. In some instances, disease-causing organisms (pathogens) and parasites grow better or have increased virulence in warm water. Not only can they attack aquatic organisms, the bacterium *Legionella*, which causes Legionnaires Disease is much more virulent at warmer temperatures. Significant changes in temperature can cause an alteration in the community structure in a stream that, chemically, would be expected to have more pollution-sensitive species.

In many cold-water streams in the U.S., temperature is seen as a significant pollutant. Regulations controlling discharge temperature exist in much of the Northwestern United States. Studies performed throughout the U.S. and other areas of the world have investigated the impacts of pollutants, including temperature, on urban aquatic organisms. The general conclusion regarding temperature has been that urban runoff often is warmer at its outlet to the stream than water already in the stream, likely due to the water flowing over surface covers that heat the runoff. Examples of surfaces that have been linked to thermal increases include blacktop and other dark, asphaltic surfaces. Even concrete surfaces absorb sunlight and can increase the

temperature of the runoff, although typically not to the extent of darker surface covers. Temperature fluctuations and resulting stresses on downstream aquatic organisms also have been demonstrated just below the outlets to urban stormwater detention ponds. Therefore, temperature is often considered a secondary pollutant in runoff. In areas with sensitive fisheries, the guidance/regulation suggests that the heated urban runoff not be allowed to enter the receiving water directly (such as through stormwater outlet pipes). Options to remove the runoff from the traditional drainage system, therefore, must be considered as part of an overall stormwater management plan in areas with temperature-sensitive fisheries.

Kieser et al. (2006) presents the results of a WERF-funded study on the thermal enrichment in urban watersheds as a result of stormwater discharges. The report presents the state-of-the-knowledge at the time on the effects of stormwater controls on runoff temperature, plus it presents a model thermal budget that can be used to simulate urban stormwater thermal enrichment.

F.2 Natural Streams versus Urbanized Streams: Impacts of Development

F.2.1 Introduction to the Impacts of Urbanized Streams

Urbanization has many different impacts on streams. This section reviews the biological impacts urbanization causes to stream biota. Biologists determine the extent of the impacts by focusing on the changes in both macroinvertebrate and fish communities. Macroinvertebrates and fish serve as good indicators stream integrity because they live in the environment year round, react strongly and predictably to environmental perturbations, they are long lived, and are easily collected and identified (Rosenberg and Resh, 1993). They also reflect the combined influences of changes to the stream environment: hydrology, channel morphology and water quality (Wang, 2003). The presence of indicator species is a reflection of the environment and that their physical, chemical and nutritional requirements are being met (Johnson et al., 1993). Further macroinvertebrates are important players in stream ecosystem functioning: nutrient cycling, decomposition, and translocation of material. They also serve as a link in trophic interactions between primary producers (algae) and predators (fish) (Cummins, 1992).

To understand the impacts of urbanization on streams, it is necessary to examine a natural stream, free of human impact. The Pedra Branca River is a 6 km, third order shaded clear water stream located in the Atlantic rainforest, São Paulo State, Brazil (Eichbaum Esteves, 2001). Rainforest are known for their high percentage of endemic species, including fish species. For this reason it is of particular importance that these areas be studied to determine what human impacts would be the most detrimental in order to effectively protect these areas. In the study of the Pedra Branca River, 17 fish species in nine families were collected. Ecological segregation was observed to exist among fish species based upon habitat utilization and food consumption. For example *H. multifasciatus* was observed to occupy areas close to the riverbank and *A. leptos* was usually found under submerged branches. Most of the fish were insectivores (37.5%), however within insect species there was specialization among fish species. Among the other trophic guilds, 21.4% were detritivores, 14.2% were benthivores, 14.2% were omnivores, 7.1% were herbivores and 7.1% were piscivores. Most studies of fishes in tropical streams have found that there is a heavy reliance on allochthonous food inputs. In the Pedra Branca, only a few species rely on allochthonous food, but they make up 87.2% of the total fish abundance, clearly indicating the importance of this food source (Eichbaum Esteves et al., 2001).

It has been suggested that alterations to the forest structure could have serious impacts to stream biodiversity because of a loss of shading, flow variability, siltation and allochthonous food inputs. Because of the small size of species populations, the high number of endemic species and the dependence on allochthonous food sources, it is clear to the researchers that Atlantic rainforest streams are very sensitive to anthropogenic impacts. Impacts like deforestation would cause a loss of food, shading and habitat resources, and increased turbidity and sunlight, which would cause small-scale but catastrophic extinctions (Eichbaum Esteves et al., 2001).

The alterations to stream habitat that the fish of the Pedra Branca River are sensitive to are all important changes found in urban streams resulting from anthropogenic impacts. Typical changes found in urban streams include increased runoff and altered flow regime, increased pollutants and nutrients, changes to the thermal regime, channel erosion, obstruction to fish movement, changes in bed composition, siltation and sedimentation, temperature increases compared to reference reaches, and loss of riparian zones (Wang et al., 1997; Moses and Morris, 1998; López-Rojas, 2000; Kieser et al. 2006).

There are three significant anthropogenic changes that influence the impacts on urban streams: imperviousness, physical habitat modification and water quality. These changes are constant themes that appear in both scientific and other literature. This section also will discuss the results of several restoration projects that have been undertaken to restore urban streams. These studies highlighted several areas of concern for future projects and identified solutions so that re-restoration is not required.

F.2.2 Links to Imperviousness

Imperviousness is defined as “the sum of roads, parking lots, sidewalks, rooftops and other impermeable surfaces in the urban landscape” (Schueler, 1994). Generally most researchers and scientists characterize the extent of urbanization by the amount of impervious surface cover (ISC) found in a given area. Although ISC is not a pollutant per se, it is a major contributor to the environmental degradation of urbanization. As ISC increases, fundamental components to the water cycle are altered: runoff increases, soil percolation decreases because of less pervious areas, evaporation decreases because there is less time for this to occur, and transpiration decreases because of removal of vegetation (Table F-2) (U.S. EPA, 2002).

Table F-2. Impacts of Urbanization on the Hydrologic Cycle.

Area Description	Evapotranspiration (%)	Runoff (%)	Shallow Infiltration (%)	Deep Infiltration (%)
Natural ground cover	40	10	25	25
10 – 20% impervious surface	38	20	21	21
35 – 50% impervious surface	35	30	20	15
50 – 75% impervious surface	30	55	10	5

The runoff from a one-acre parking lot is 16 times the runoff from an undeveloped meadow (Schueler, 1994). Impervious surface cover as little as 10% can destabilize stream channels, increase water temperature, reduce water quality and biodiversity (U.S. EPA, 2002).

Impervious surface cover causes major changes to the hydrology (the way water is transported and stored) of a watershed (Arnold and Gibbons, 1996). These changes include:

increase storm runoff volume, increased peak flow and duration, increased stream temperature, decreased base flow and changes in sediment transport. In turn these impacts cause flooding, erosion, habitat loss, channel widening and streambed alterations (U.S. EPA, 2002; Roesner and Poff 2003; Kieser et al. 2006). Klein (1979) found a definite relationship between imperviousness and baseflow: as imperviousness increased, baseflow decreased. Urban streams remain stable until about 10% imperviousness (Schueler, 1994). Continued development of impervious surface beyond the 10% threshold leads to unstable channels, erosion, undercutting of stream banks, channel widening and sedimentation, resulting in habitat degradation (Schueler, 1994; U.S. EPA, 2002). Beyond 15% ISC, urban stream habitats are consistently labeled as poor (Schueler, 1994). ISC also causes changes to physical habitat through erosion, channel widening and streambed alterations. Water quality is also degraded because of ISC due to the rapid transport of pollutants to aquatic systems (Schueler, 1994). Both physical habitat modification and water quality will be discussed in further detail later.

Characteristics of degraded and impaired urban streams focus on riparian habitat, macroinvertebrate communities and fish communities. Riparian habitat is greatly reduced, with bare, exposed banks, and widened stream channels. Fish and macroinvertebrate communities consist of pollutant tolerant species, with decreased diversity and reduced feeding requirements. Exotic and introduced species will also be found in fish communities. Wang et al. found that low quality values for macroinvertebrate measures were inevitable above 10% imperviousness (Wang and Kanehl, 2003). In a study measuring the impact of urbanization on fish communities, Wang et al. found that levels between 8% and 12% connected imperviousness are the threshold zone, where minor increases in urbanization can cause dramatic declines in fish community quality and base flow (Wang et al., 2001). In a study of the effects of urbanization on streams in Melbourne, Victoria, Australia, found that degradation was best explained by imperviousness and drainage intensity. As imperviousness increased, taxon richness and EPT richness decreased (Walsh and Breen, 2001). In another study examining the relationship of watershed land use to the biotic integrity of streams, researchers found that “urbanization impacts on biotic integrity were particularly severe and occurred at a relatively low level of land use” (Wang et al., 1997). Klein (1979) found in 3 of the 4 urban streams the dominant species was the Blacknose Dace (*Rhinichthys atralatus*), a fish that can tolerate a wide array of conditions and the ability to live where no other fish can. Schueler (1994) highlights one study where two sensitive species, trout and sculpin were lost at 10% imperviousness and when imperviousness increased to 25%, four more sensitive species were lost. At 55% imperviousness, only two fish species remained (Schueler, 1994).

Under the impervious cover model, the U.S. EPA classifies stream integrity based upon percentage of impervious cover. This model is intended to guide local officials and managers in devise goals and objectives for present and future land use, given the level of ISC in their watershed (U.S. EPA, 2002). Sensitive subwatersheds have less than 10% ISC. Streams in these watersheds have experienced few impacts and are close or at predevelopment levels. Officials and managers would want to focus on maintaining these conditions, discouraging new development unless it is designed to have no impact (U.S. EPA, 2002). Prevention of increasing ISC is key to maintaining this subwatershed classification. Degrading subwatersheds have between 11 and 25% ISC (U.S. EPA, 2002). The threshold noted above (10%) has been crossed and stream integrity has been degraded: some sensitive species have disappeared, riparian zones have decreased, stream channels and composition have been slightly altered. It is suggested that the focus should be on maintaining, and if possible restoring stream conditions (U.S. EPA,

2002). Nonsupporting subwatersheds, the final classification, have more than 26% ISC. Streams in these watersheds are severely impaired and may never recover. Reducing peak flows and removal and prevention of urban pollutants are the suggested objectives for these degraded conditions (U.S. EPA, 2002).

Schueler (1994) describes impervious cover as a “common currency that can be measured and managed by planners, engineers and landscape architects alike.” Imperviousness is a variable that can be quantified, managed and controlled during the development process (Schueler, 1994). For example, medium density single-family zoning can have impervious surface ranging anywhere from 25% to 60%. This significant variation presents developers with opportunities to reduce impervious are from 60% to 25% when land is being developed (Scheuler, 1994). Scheuler (1994) also suggests including the reduction of impervious surface as part of a development site’s Best Management Practice.

F.2.3 Physical Habitat Modification

The physical habitat plays an extremely important role in maintaining stream biological and physical integrity. Aspects of physical habitat include riparian zones, streambed composition, sinuosity and channel morphology and in stream habitat. Riparian zones act as buffers; protecting channels from erosion, reducing rapid runoff, sedimentation and pollution, fluctuations in stream temperature and supply habitat (shading and woody debris) and food for aquatic life (Wang and Kanehl, 2003; Davis, 2003). Streambed composition is important for diverse aquatic life. A mixture of gravel, cobbles and boulders provide a stable substrate for spawning and refuge habitat. Sinuosity refers to the meanders a stream takes. Channel morphology refers to the shape and form a stream. Sinuosity provides more complex habitat conditions (riffles and pools) and reduces velocity of flow, turbulence and erosion. Should sinuosity be lost, channel morphology can be affected by channel widening and streambed alterations. In-stream habitat includes overhanging vegetation, undercut banks and vegetation inputs such as large woody debris (Davis, 2003). These areas provide habitat for shading, refuge and spawning, important to a diverse aquatic community.

Physical habitats are generally modified in two ways, either directly or indirectly. They are often modified indirectly through increased impervious surface usually related to the resulting increased flooding and runoff. The more frequent and severe flooding causes channel instability, which results in widening stream banks, downcutting the streambeds, and increased erosion (Roesner and Poff 2003). This in turn has detrimental effects to in-stream habitat: pool and riffle sequences are destroyed, overhead cover and large woody debris is removed resulting in reduced aquatic diversity (Schueler, 1994). Studies continuously demonstrate, that sites with the highest number of species also have the highest degree of habitat diversity and sites that are more uniform structurally have the lowest number of species (Jansen et al., 2000). Once impervious surface cover reaches 10% or more, stream channels were found to be consistently unstable. Beyond 10-15% ISC, in-stream habitat is regularly classified as poor (Schueler, 1994).

Physical habitats are modified directly through human engineering: channelization, canals, and reservoirs. In the United States over 200,000 miles of waterways had been channelized by 1972 (Morley, 2002). In Vancouver, most streams have been culverted, destroying fish habitat (Finkenbine, 2000). Detrimental impacts to physical habitat due to channelization include increased in-channel incision, bank erosion, sedimentation, reduced substrate, channel diversity, aquatic habitat and riparian vegetation. The result of modified urban

streams is a stream habitat of riffles and pools being replaced with a homogeneous habitat, which diminishes aquatic species diversity and abundance (Jansen et al., 2000; Fitzgerald et al., 1997). A study of streams in Ontario was conducted to evaluate the effect of impoundment and channelization on stream integrity. Construction of impoundments were found to be a major factor in the reduction of fish species. Reservoirs were found to modify flow rates, thermal regimes and sedimentation processes, which is detrimental to specialized fish species. Channelization destroyed riffles and pools that provide habitat for macroinvertebrates and fish. A decrease in macroinvertebrates affects the food resources of fish of specialized feeding guilds. Two of the creeks in the study were characterized by impoundments and channelization. In both creeks, species requiring clean spawning substrates, high oxygen levels, cool water temperatures, and variable flows were replaced by species tolerant to siltation, regulated flows and homogeneous habitats (Fitzgerald et al., 1997).

The River Seine (Paris, France) was heavily modified to meet the navigational and flow regulation needs of the city. The physical modifications to the Seine were extremely detrimental, causing the original fish fauna to disappear. Canal links have caused non-native fish species to colonize the Seine and the weirs and locks have closed the passage to the upstream spawning grounds of the native migratory fish, resulting in the extirpation of seven migratory fish species. The channelization- widening, deepening and straightening- of the river have caused a loss of habitat diversity and a homogenization of the flow; consequently specialized species decreased and were replaced by more tolerant fish species. Flow regulation severely modifies the natural flow characteristics of a river, reducing the periods and duration of floods. Pike fish (*Esox lucius*) need flooded-natural grasslands for spawning. In a comparison between different types of discharges (natural flow, flow regulated by one dam, and flow regulated by two dams), there was a significant decrease in useful spawning grounds. In flows regulated by two dams, only one year in five produced suitable pike spawning conditions instead of one year out of two under natural flow conditions. Clearly physical habitat modifications have had a strong effect on fish communities: migratory species are extinct, rheophilous species are threatened, fish diversity has been lost and pollutant-tolerant species are now successful (Boët, 1999).

Most suggestions to address habitat modification focus on minimizing it and if possible avoiding it. It is critically important to protect streams and rivers that are still healthy as it is easier to protect habitats than to restore them. Riparian zones are important in minimizing the impacts of ISC because even when small riparian areas are converted to urban land use there appears to be significant impacts on stream conditions. In areas where there is low to moderate development, riparian buffer zones have the potential to maintain or even improve biological integrity (Morley, 2002). For areas already affected, efforts should focus on recreating natural conditions. Researchers from the Seine River study stress the importance of re-establishing variable flow conditions (Boët, 1999).

F.2.4 Water Quality

Water quality is degraded through two methods: point source discharges and non-point source discharge. Typical pollutants found in urban runoff include: Total suspended solids (TSS), phosphorous, nitrogen, fecal coliform, petroleum hydrocarbons, heavy metals, insecticides and herbicides (U.S. EPA, 2002).

Point source discharge includes discharges coming from sewage treatment plants and industrial plants. In the United States, Western Europe, and other developed countries, the

effluent is treated before being released back into the stream, however in less developed countries and countries that were slow to improve sewage treatment, or when there is a leak or damage to the treatment process the effluent can have extremely detrimental effects. Paris, France, does not have a good history of wastewater disposal. By the late 1960's conditions downstream of Paris at the Achères STP were totally anoxic and devoid of life. Although there has been an improvement in wastewater treatment to reduce oxygen demand, there is still a significant decrease in fish species below the Achères STP (Boët, 1999). In the Río Lerma Basin in México has experienced severe declines in water quality due to rapid population growth and major untreated industrial and municipal waste discharges and high levels of groundwater extraction (Soto-Galera et al., 1999). Seventeen of forty-two native species have either disappeared or declined dramatically. Some areas have no longer have water or have such poor water quality nothing can live there (Soto-Galera et al., 1999). Nedeau et al. (2003) conducted a study of the effect of industrial effluent on the water quality, habitat quality and aquatic life of Portage Creek, a tributary of Kalamazoo River in Michigan. They found that the effluent from the industrial plant always had a rusty colored appearance and had 20 times more Fe and total particulate Fe than upstream. While effluent water temperature in the winter was 13 to 18 °C warmer, concluded that iron deposition was the chief cause for the impaired macroinvertebrate community downstream of the discharge as surfaces downstream were covered in a fine layer of ferric hydroxide. This deposition inhibits the growth of diatoms and algae. With the loss of this food source and increased temperatures, it would be difficult for sensitive species to live in these conditions. The effluent increased the total discharge of the stream by 50-150%. Researchers noted that this increase in discharge from the effluent, caused sediments to remain suspended, impairing water quality through increased turbidity (Nedeau et al., 2003). Clearly effluent from point discharges, when untreated or not meeting standards, can have a continuous deleterious impact on aquatic life.

Nonpoint source discharges cover everything else: agricultural runoff, stormwater runoff, and urban runoff. Urban runoff has been associated with increased sediment, pollutant and nutrient loads, increased water temperatures, and increased fecal coliforms, among other water quality parameters. While urban runoff may indeed be associated with these problems, there is little evidence that conclusively links urban runoff with impaired stream integrity (Jones, 1987), possibly due to the flashy nature of urban runoff. It only occurs during storm events, and thus is episodic in nature rather than a constant, like a point discharge from a wastewater treatment plant. Water quality parameters that are often found to be higher are TSS and total dissolved solids while conductivity and dissolved oxygen are found to be lower. Heavy metals are sometimes found in the water but in concentrations so low that they are unlikely to be toxic (Gray, 2004). In a study of Provo River in Provo, Utah, Gray (2004) found that closely following the storm flow surge, TSS and metal concentrations increased and conductivity and dissolved oxygen decreased. The parameters returned to pre-storm values within 12 hours or so (Gray, 2004). In the Provo river water quality from storm events did not have a significant event on benthic communities, and during normal flows water quality was similar (Gray, 2004). Heavy metals appear to be found more often found in the sediments. Ostrander et al. (1995) studied both the water quality and sediments of the Arkansas River in the Tulsa area for chemical contaminants. They also examined the channel catfish (*Ictalurus punctatus*) to determine what effects contaminants may be having on the fish. Only three chemicals were found in the water samples, but a total of 14 chemicals, including anthracene, pyrene and benzo(a)pyrene, were found in the sediments. The catfish at impacted sites displayed significant differences in weight,

length and gross abnormalities than those at the reference site. The average age (3.7 yrs) of the fish had also decreased at the impacted sites from the fish at the reference site (4.3 yrs) (Ostrander et al., 1995). In preparation for a restoration project, Davis et al. (2003) assessed the water quality, habitat and biological integrity of Gypsum Creek in Wichita, Kansas. It is necessary to determine whether water quality is sufficient to sustain aquatic life before starting a restoration project. Water quality samples showed high dissolved oxygen levels and in 44% of all samples, fecal coliform bacteria exceeded water quality standards. Two pesticides were found in elevated concentrations: triazine herbicides and organophosphate insecticides. These two pesticides have been found to have toxic synergistic effects on aquatic macroinvertebrates. This toxicity on aquatic organisms was evident during the spring fish collections. "All individuals collected from the three sites were either dead or showing signs of severe stress". Researchers concluded that the data indicated that urbanization has impacted water quality as well as the physical habitat and biotic integrity of the stream (Davis et al., 2003).

Clearly water quality is an important factor in the integrity of urban rivers. In the River Tame in the West Midlands of England, water quality is so poor that physical habitat modification is irrelevant. Researchers believe water quality is the primary limiting factor of invertebrates along the River Tame (Beavan, 2001). Rehabilitation in these situations would be fruitless until water quality has been improved. What is unclear about water quality in urban streams is its exact impact. When does it become more than an episodic event, leaving a permanent mark on stream integrity? Does ISC really worsen urban runoff and thus ruin the water quality in an urban stream. Is water quality ever bad without ISC and physical habitat modification? And when, in implementing these changes does it become a problem? Finally, what role does water quality play in stream restoration?

F.2.4 Restoration

In recognition of important stream ecosystem functions (groundwater recharge, increased water quality, reduced floodwater velocity and flooding), stream restoration projects have become more common (Moerke and Lamberti, 2004; Purcell et al., 2002). Many projects focus on habitat restoration: riparian areas, riffles and pools and stream sinuosity. However, there is a considerable lack of data on the success and failures of the restoration projects. "Each restoration that is not evaluated is potentially a loss of critical information that could benefit future restoration projects" (Moerke and Lamberti, 2004). Lack of monitoring of their success can often be attributed to poor planning or lack of funding. Restoration projects that include monitoring results include the Baxter Creek project (Purcell et al., 2002), Mersey Basin project (Nolan, 1998), Pipers Creek maintenance restoration project (Gustav et al., 1994) and a review of ten restoration projects in Indiana (Moerke and Lamberti, 2004). All of these projects included planting riparian vegetation, added pool and riffle sequences and meanders. All restorations were rated as fairly successful to very successful. The fish population of Pipers creeks in Seattle, Washington experienced an eight-fold increase in the section that was restored (Gustav et al., 1994). The restored section of Baxter Creek, in El Cerrito, California, was compared to an unrestored section of the creek. Researchers found that both habitat quality and biological quality had improved. However when the newly restored site was compared to a creek that had been restored 12 years previously, the habitat of the newly restored site was of lower quality (Purcell et al., 2002). A year after restoration, the Mersey Basin creeks also experienced improved conditions. At both sites vegetation cover has been very good and species diversity has increased, as well as the attraction of additional wildlife (Nolan and Guthrie, 1998). Clearly

many restoration projects have felt that restoring physical habitat is the key to successful restoration, Moerke et al. (2004) suggest focusing on restoring stream function (nutrient cycling, detritus processing and sediment transport) instead. It is also suggested that larger scale restorations that repair riparian-aquatic linkages would be more effective in reducing watershed influences (Moerke et al., 2004). There is still a serious lack of evidence regarding stream restoration and questions to be answer:

- ◆ Does restoration work?
- ◆ On what kind of time scale do we see improvements?
- ◆ Are some methods more successful than other?
- ◆ Do different streams (cold water versus warm water) need different restoration practices to achieve success?

Based the available information, it would appear that physical habitat restoration is key to successful restoration, and with that in mind it would be prudent to maintain stream habitats, in-stream and riparian. Two recent investigations that address the challenges of stream restoration in an urban area are Hughes et al. (2005) and Bernhardt and Palmer (2007). They highlight the unusual conditions related to working in an urbanized watershed.

APPENDIX G

URBAN RUNOFF POLLUTION SOURCES

G.1 Introduction

Urban surfaces are subject to the deposition of contaminants, which are then subject to wash-off by rainfall or snowmelt. Typical contributors to pollutants in runoff include vehicular traffic, industry, power production, lawn care, pets, eroded sediments, and vegetation litter (literature summarized annually in *Water Environment Research*, or see Clark et al., 2008). Several different flow phases are considered to be part of “urban runoff” or “wet-weather flow”: dry-weather base flows, stormwater runoff, and snowmelt. Other sources of wastewater that enter the storm drainage system include non-stormwater flows (such as irrigation water from lawns) and inappropriate entries such as combined sewer overflows and sanitary wastewater. The importance of each of the above flow phases depends upon many factors, with the two most important being season and land use. Season (cold versus warm weather, or dry versus wet weather) often is not as critical as land use in determining the pollutant load in the stormwater runoff, explaining why land use has been considered an important design variable in urban runoff treatment selection. It has been shown that commercial and industrial facilities can contribute a larger pollutant loading to stormwater runoff for runoff volumes and pollutant concentrations of the same land area.

G.2 Meta Analysis of Stormwater Data

Where available or readily collectible, site data is preferred. If site data is not available, then local or regional data should be obtained. In the United States, this information may be available from the regional authority that controls the area’s stormwater discharge permits. Where local or regional data is not available, national databases may be good sources of data for estimating pollutant concentrations from a source area.

For stormwater runoff quality, two potential sources of U.S. stormwater data are the Nationwide Urban Runoff Program (NURP) and the National Stormwater Quality Database (NSQD). The NURP study, funded by the U.S. EPA, was performed in the late 1970s and early 1980s with the results published in 1983. The NSQD, also funded by the U.S. EPA, was performed as an update of the NURP data and contains the NURP data as well as data from other small- and large-scale studies. These studies analyzed stormwater runoff data from many municipalities for relationships between water quality and readily-available parameters such as land use, pollutant source, season, rainfall region, percent impervious area, etc.

G.1.1 Nationwide Urban Runoff Program (U.S. EPA, 1983)

The Nationwide Urban Runoff Program was designed to supplement stormwater quality data collection activities in several locations around the U.S. in the late 1970s and early 1980s. The data from these locations was analyzed primarily for relationships to season and land use. The linkage between land use and quality was found for several parameters and led to many other researchers attempting to establish similar relationships in other geographic regions of the world and in cities not involved in the NURP study. Two parameters, TSS and total phosphorus,

where land-use linkages were seen are shown in Figure G-1. The NURP results also highlighted the tremendous variability in the data set, indicating that specific pollutant concentrations cannot be estimated simply by knowing the land use.

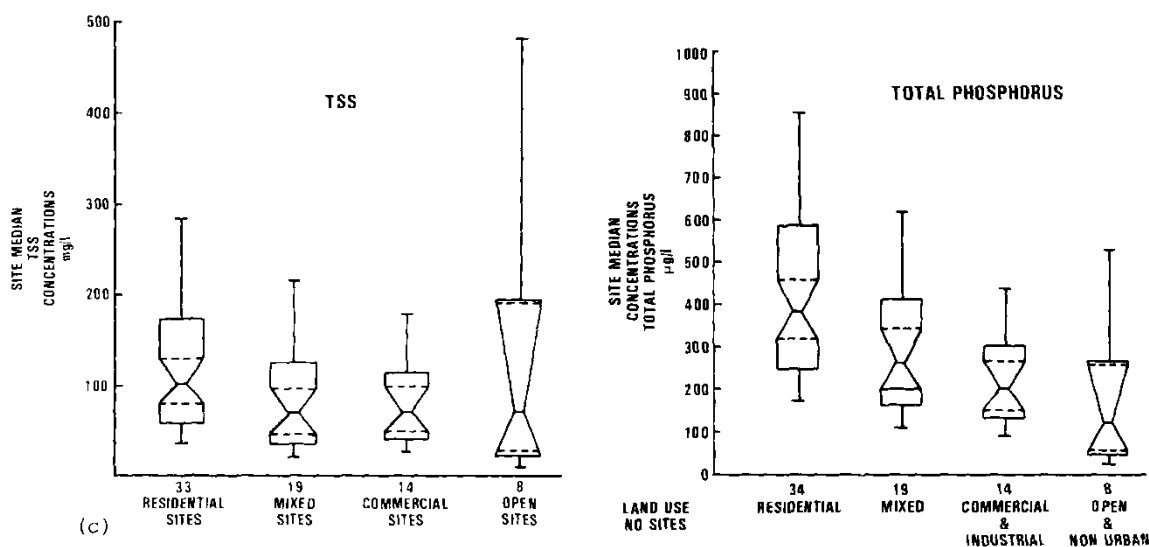


Figure G-1. Comparison of Pollutant Concentrations by Land Use (U.S.EPA 1983).

G.1.2 National Stormwater Quality Database (Pitt et al., 2008)

The latest version of the National Stormwater Quality Database (NSQD), version 3 (<http://rpitt.eng.ua.edu/Research/ms4/mainms4.shtml>), compiles data collected from various stormwater sampling efforts including the NURP program (U.S. EPA, 1983), the International BMP Database (ASCE, 2002), the U.S. Geological Survey Urban-Stormwater Database (Driver, et al., 1985; Smullen et al., 1999; Smullen and Cave, 2002), and from Phase 1 NPDES (National Pollutant Elimination System) MS4 (municipal separate storm sewer system) stormwater permit holders. Most of the data are from MS4 communities and monitored during the current cycle. The earlier NURP data was used to supplement the MS4 data from the upper Midwest and northeastern areas of the country. The other databases also helped in obtaining information for under-represented situations. The NSQD contains data from more than 8,500 events. The data has been sorted and analyzed for relationships between the pollutant concentrations and the factors that are presumed to affect the concentration, including land use, season, geographical location, drainage system type, and antecedent dry days. Figure G-2 illustrates the lack of seasonal trend in fecal coliform concentrations.

Temporal trends also were analyzed, with the primary trend being the reduction in lead concentration between the NURP and MS4 data sets, due to the phase-out of leaded gasoline (Figure G-3).

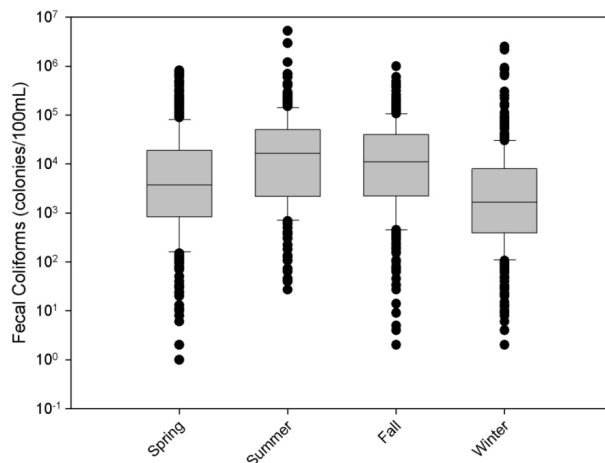


Figure G-2. Fecal Coliform Concentrations as a Function of Season.

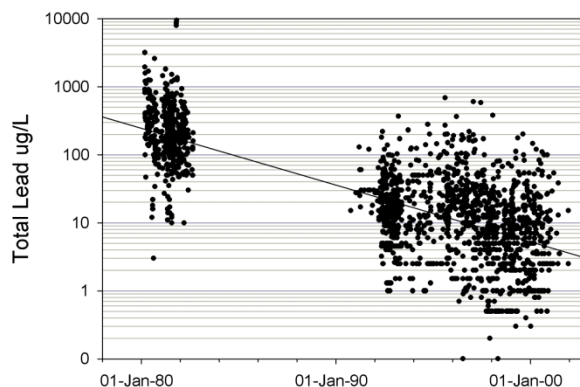


Figure G-3. Trend of Lead Concentrations with Time in EPA Rain Zone 2.

The general conclusions from this data evaluation included the following:

- ◆ Substantial fractions of the pollutants at the outfall were particulate-associated.
- ◆ Comparing NURP and NSQD, most pollutant concentrations were similar, with the exception primarily of lead.
- ◆ The NSQD confirmed the effects of land use and source areas (parking areas, vehicle service stations, rooftops, streets, landscaped areas, etc.) on stormwater runoff quality.
- ◆ Critical source areas of urban runoff pollution, and where treatment should be installed prior to the runoff mixing with water from cleaner areas, include large paved areas, heavy vehicular traffic or areas with many vehicular starts, and the outdoor use and/or storage of problem pollutants. These critical source areas likely needing special stormwater treatment are industrial manufacturing facilities, vehicle service stations, vehicle maintenance facilities, scrap yards, highways and some other commercial developments.

The NURP and MS4 databases can provide a first estimation of anticipated end-of-pipe concentrations of urban runoff pollutants, which then could be used as input data in performance modeling of the management devices.

G.3 Sources of Pollutants

Impervious structures like rooftops, driveways, sidewalks, and roads affect urban runoff quantity and quality by not only reducing rainfall infiltration but also by degrading runoff quality. Links between the quantity of urban runoff and the percentage of directly-connected impervious areas (DCIA) have been demonstrated over the years (see Appendix F). In the typical urban setting, DCIA includes paved streets, driveways, parking areas draining to curb-and-gutter drainage systems, and roofs draining directly to a storm or combined sewer (U.S. EPA, 1983). It has been well-documented that highways and other paved surfaces such as vehicle servicing and maintenance stations had the greatest abundance of observed organics, compared to residential/landscaped areas. However, these landscaped areas had many of the observed organics, just in lesser concentrations (Galvin and Moore, 1982; U.S. EPA, 1983; Pitt and McLean, 1986).

The term often applied to sites requiring stormwater control is ‘critical source areas.’ Critical source areas of non-point pollution appear to be large paved areas, heavy vehicular traffic or areas with many vehicular starts, and the outdoor use and/or storage of problem pollutants. It has been demonstrated that treating runoff from these areas is beneficial and economically feasible for treatment of urban runoff. These general guidelines indicate that the problem critical source areas likely needing special stormwater treatment are industrial manufacturing facilities, vehicle service stations, vehicle maintenance facilities, scrap yards, and some other commercial developments.

G.3.1 Highways

Road-vehicle-related activities produce a substantial number of potentially toxic substances (oil and tar products, oxygenated compounds, polycyclic aromatic hydrocarbons [PAHs], metals, deicing salts, and asbestos). Table G-1 demonstrates the effect that large urban roadways have on runoff quality.

Table G-1. Highway Site Median Concentrations.
(Data Summarized from Federal Highway Administration 1990)

Pollutant (mg/L)	Average daily traffic < 30,000	Average daily traffic > 30,000
Total suspended solids (TSS)	41	142
Chemical Oxygen Demand (COD)	49	114
Total Kjeldahl Nitrogen (TKN)	0.87	1.83
Nitrite + Nitrate (NO ₂ + NO ₃)	0.46	0.76
Total phosphorus	0.16	0.40
Copper	0.022	0.054
Lead	0.080	0.4
Zinc	0.080	0.329

Various hydrocarbons are present in lubricating oils and fuels, whereas metals are present in fuel (e.g., lead), brake linings (e.g., copper), vehicle tires (e.g., zinc and cadmium), and road deicing salts (e.g., copper and chromium). A review of the Nationwide Urban Runoff Program (NURP) data, 1979 to 1982, showed detectable concentrations of organic compounds (pesticides, halogenated aliphatics, phenols and cresols, phthalate esters and poly-aromatic hydrocarbons) that ranged from 0.003 to 115 µg/L with the highest concentration seen for phenols and bis(2-

ethylhexyl)phthalate (U.S. EPA, 1983). Kayhanian et al. (2003) reported the results of a study to evaluate correlations between average annual daily traffic (AADT) and storm water runoff pollutant concentrations generated from California Department of Transportation (CALTRANS) highway sites for four years (1997-2001) and found that pollutant concentrations from urban highways were higher than those found from non-urban highways.

Other transportation-related critical sources areas are streets and parking lots. Streets are critical sources areas in general. Parking lots are critical in commercial and industrial land use areas (Bannerman et al., 1993) because not only of their pollutant loading, but also because of their large size. The sources of these potential urban runoff pollutants are shown in Table G-2. Existence of these sources in the watershed or site likely indicate a need to include these pollutants in the chemical assessment.

Table G-2. Sources of Common Highway Pollutants.
(Data summarized from Federal Highway Administration 1984)

Pollutant	Source
Particulates	Pavement wear, vehicles, atmosphere, maintenance
Nitrogen, Phosphorus	Atmosphere, roadside fertilizer application
Lead	Leaded gasoline, tire wear, lubricating oil and grease, bearing wear
Zinc	Tire wear, motor oil, grease
Iron	Auto body rust, steel highway structures, moving engine parts
Copper	Plating, bearing/bushing/brake wear, engine parts, insecticides
Cadmium	Tire wear, insecticide application
Chromium	Metal plating, moving engine parts, brake lining wear
Nickel	Fuels, oils, metal plating, bushing wear, brake lining wear, asphalt
Manganese	Moving engine parts
Bromide	Exhaust
Cyanide	Anti-cake compound used to keep deicing salt granular
Sodium, Calcium	Deicing salts, grease
Chloride	Deicing salts
Petroleum	Spills, lubricants, antifreeze and hydraulic fluids, asphalt
Polychlorinated biphenyls	Pesticides, atmospheric deposition, catalyst in synthetic tires
Pathogenic bacteria	Soil litter, bird droppings, livestock and stockyard wastes
Rubber	Tire wear
Asbestos	Clutch and brake lining wear

G.3.2 Industrial Areas

Industrial area runoff typically is considered highly contaminated compared to residential runoff. However, residential and open-space runoff often is a major contributor of several conventional stormwater pollutants including solids/sediment, nutrients like nitrogen and phosphorus, and bacteria. Choe et al. (2002) characterized the surface runoff in urban (residential and industrial) areas. The event mean concentrations (EMCs) of COD, suspended solids (SS), TKN and total phosphorus (TP) in the residential zone were 313 mg/L, 279 mg/L, 8.45 mg/L, 1.98 mg/L; those concentrations in the industrial zone were 80 mg/L, 106 mg/L, 5.07 mg/L, and 1.93 mg/L, respectively. Many of the other pollutants correlated well with suspended solids, indicating that control of suspended solids should provide reductions in these pollutants in runoff. If infiltration is selected as the preferred control technique, pretreatment of solids to prevent clogging may provide the additional benefit of pollutant reductions. This decreases the

likelihood that the chemical capacity of the vadose zone soils will be exceeded during the design life of the infiltration device.

G.3.3 Roofing

One source of concern for all land uses should be the contribution of roofing materials to stormwater loadings. This, in particular, should be of concern as stormwater agencies are encouraging direct infiltration of roof runoff. Clark et al. (2008 a,b) addressed pollutant concerns of roof runoff. Earlier modified-TCLP tests on roofing material test coupons indicated potential for release of nutrients and metals. Clark et al. (2008b) compared pilot-scale testing of uncut roofing panels and green roofs for runoff quality (Figures G-4 for pH and nitrate; G-5 for copper and zinc). Roofing materials with metallic protection were shown to be releasing metals three years after installation.

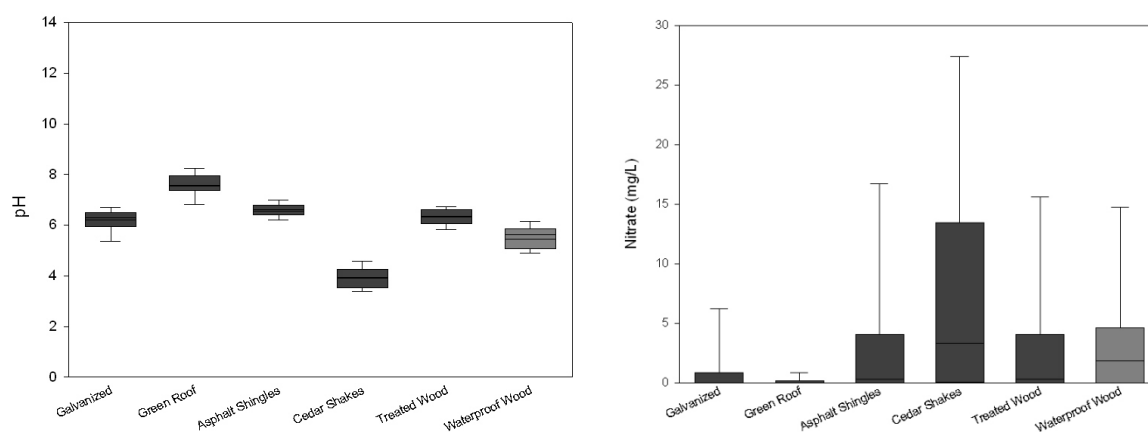


Figure G-4. Runoff pH and Nitrate from Roofing Materials.

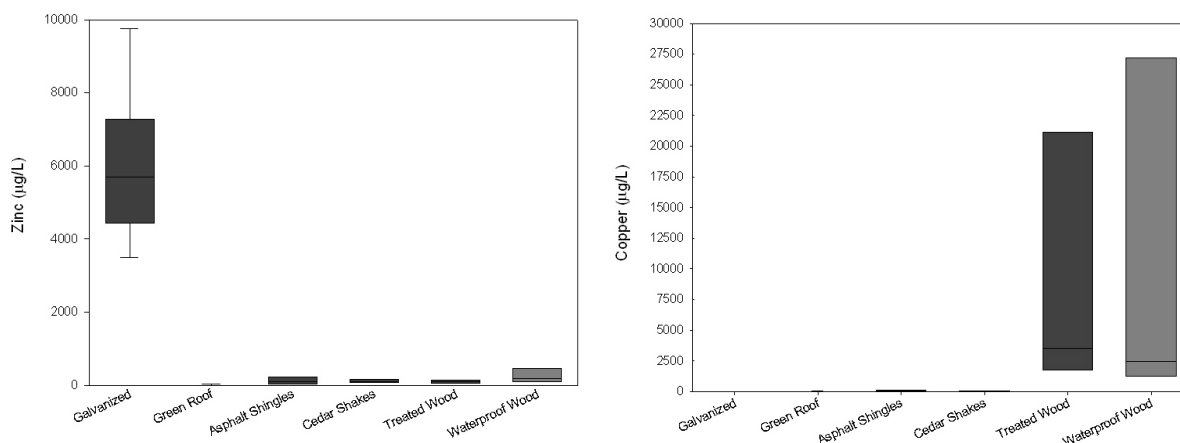


Figure G-5. Runoff Zinc and Copper (Total Fraction) from Roofing Materials.

G.4 Pollutants of Concern in Urban Runoff

Much of the early stormwater management activities focused on removal of water from an area. Addressing water quality concerns have only come into the foreground of in-the-field

planning within the last decade or so. Part of addressing water quality concerns is understanding the nature of the pollutants likely to be found in stormwater runoff. This section addresses those categories of pollutants individually. However, it is safe to assume realized that these pollutants are not in runoff as isolated chemicals, but in fact often act synergistically to exacerbate the degradation of urban streams.

Research has shown that the BOD₅ and nutrient concentrations in stormwater (non-snowmelt season) are approximately equal to concentrations in treated sanitary wastewaters. However, urban stormwater often has relatively high concentrations of bacteria, as well as high concentrations of many metallic and some organic toxicants, when compared with treated sanitary wastewater. The U.S. EPA has reported that only 57% of the rivers and streams in the United States fully support their beneficial uses and that many of these impairments are caused by urban runoff. Concentrations of many urban runoff toxicants exceeded substantially the U.S. EPA water quality criteria for human health protection. Maltby et al. (1995a) conducted toxicity tests by using highway runoff and found that runoff was not acutely toxic to a test organism, *G. pulex*. However, exposure to the stream sediments immediately below the outfall did result in a small but statistically significant reduction in survival. Toxicity testing using juvenile minnows showed that exposure to runoff affected the minnows' growth and survival (Marsh, 1993).

The major categories of pollutants associated with urban stormwater runoff, and hence the major parameters that should be assessed in the initial characterization of the watershed are as follows:

- ◆ Sediment
- ◆ Nutrients
- ◆ Oxygen-demanding substances
- ◆ Toxic chemicals
- ◆ Chloride
- ◆ Microorganisms

G.4.1 Sediment

Sediment is made up of soil particles that are washed or blown into lakes and streams. It may be transported to surface waters via overland flow. Sediment may also be eroded from stream banks during high flows or resuspended from the substrate by changes of speed or direction of the water current. Sediments that enter the surface water are either deposited on the stream/lake bed (bed load) or stay suspended within the water column (suspended load). The stream current may transport particles in either the bedload or the suspended load. The volume of sediment transported at any time depends on the particle size and the flow velocity. Hence streams receiving urban runoff, which typically contains higher flow rates than the pre-development flow rates which stabilized the stream, transport a greater number of larger particles than a similar stream without the effects of urbanization. This discussion of urban sediment loads in runoff does not include those particles that result from streambank erosion.

The solids in urban runoff have been characterized by many researchers, usually as part of their treatment evaluation. Pitt et al. (2005) reviewed much of the literature regarding sources

of solids in urban runoff and focused on two major sources of many pollutants, including solids: transportation activities and atmospheric ‘dustfall.’

Automotive Activities. In an early study, Shaheen (1975) found that most of the street surface dust and dirt materials (by weight) were local soil erosion products, although some materials were contributed by motor vehicle emissions and wear. Minor contributions were made by erosion of street surfaces in good condition. According to Pitt (1979), approximately half of the airborne particulates generated by tire wear settle on the street, and most of the rest settle usually within about six meters of the roadway, enhancing the ability of these particles to enter the urban stormwater system. Exhaust particulates, fluid losses, drips, spills and mechanical wear products can all contribute lead and other pollutants to street dirt. Deposition in areas adjacent to roads also occurred through wind transport of particles resuspended from the road surface due to traffic-induced turbulence.

Solomon and Natusch (1977) studied automobile exhaust particulates in the Champaign-Urbana, IL area, and showed that the exhaust particulates had two distinct morphological forms. The smallest particulates were almost perfectly spherical, having diameters in the range of 0.1 – 0.5 μm , consisted almost entirely of PbBrCl (lead, bromine, chlorine) at the time of emission, and likely would remain airborne for substantial distances due to their small size. The second major form of automobile exhaust particulates were roughly 10-20 μm in diameter. These particles typically had irregular shapes and somewhat smooth surfaces. The elemental compositions of these particles were inconsistent, and included iron and calcium with the lead, chlorine and bromine. Individual particles also contained aluminum, zinc, sulfur, phosphorus and some carbon, chromium, potassium, sodium, nickel and thallium. The aerodynamic properties of these particles would suggest that they would be deposited within a few meters of the emission point onto the roadway. They also examined urban particulates near roadways and homes in urban areas. Lead concentrations in soils were higher near roads and houses, indicating contamination likely due to road dust and peeling house paint. The lead content of the soils ranged from 130 to about 1,200 mg/kg. Drainage systems installed along the sides of roads are likely to receive higher loadings of these pollutants. If infiltration is used as the management method, the soil profile would be expected to remove these pollutants prior to water reaching the groundwater.

Atmospheric Deposition. Atmospheric deposition may be characterized in two ways: dryfall and total deposition. Dryfall, or dry deposition, includes those particles that settle out of the air stream during dry conditions. Total deposition, which measures both dryfall and wetfall, quantifies the total particles that are removed from the atmosphere during rain or snow conditions. Some of these particles would have been removed as dryfall; others would remain entrained in the atmosphere until scrubbed by the rain. In some areas, the contaminant contribution due to dry deposition is small, compared to the contribution from precipitation (Malmquist, 1978). However, in heavily urbanized areas, dustfall can contribute a much higher percentage of the annual load than the wet precipitation, especially when dustfall includes resuspended materials.

Dustfall and precipitation affect all of the major runoff source areas in an urban area. Dustfall, however, is typically not a major pollutant source but fugitive dust is a mechanism for pollutant transport. Most urban dustfall is resuspended particulate matter from street surfaces or wind erosion products from vacant areas (Pitt, 1979). Point source pollutant emissions can also

significantly contribute to dustfall pollution, especially in industrial areas. Transported dust from regional agricultural activities can also affect urban stormwater.

Non-urban area rain can be substantially better than urban rain. Many important heavy metals have not been detected in rain in many areas of the country. The most prevalent heavy metals found in rain have been lead and zinc, both being present in rain in concentrations from about 20 µg/L up to several hundred µg/L, qualified by the fact that much of this data precedes the complete phase-out of leaded gasoline in automobiles. Iron is also present in relatively high concentrations in rain (about 30-40 µg/L).

In dustfall, iron, zinc and lead were present in high concentrations (up to several thousand mg of pollutant per kg of dry weight). Spring et al. (1978) monitored dry dustfall near a major freeway in Los Angeles, CA, and found that lead concentrations were high on or near the freeway, but dropped quickly up to 150 m away. However, chromium concentrations did not vary substantially between on/near sampling locations and away locations.

Pitt (1979) found, while monitoring airborne particulate concentrations near typical urban roads, that the number of downwind roadside particulates were about 10% greater than upwind conditions. About 80% of this increase was due to particles in the 0.5-1.0 µm size range. However, about 90% of the increases by weight were associated with particles greater than 10 µm. PEDCo (1977) found that the re-entrained portion of the traffic-related particulate emissions (by weight) was an order of magnitude greater than the direct emissions due to vehicle exhaust and tire wear. They also found that particulate resuspensions from the street were directly proportional to the traffic volume and that the suspended particulate concentrations near the streets are associated with relatively large particle sizes. The medium particle size found, by weight, was approximately 15 µm, with about 22% of the particulates occurring at sizes greater than 30 µm. These pollutant loadings have to be accounted for in stormwater treatment design.

Several early stormwater studies collected dry soil samples from various urban surfaces, typically by dry vacuuming the surface, for gravimetric, particle size, and quality analyses. Street dirt shows the variations in chemical quality between particles from different land uses and source areas, and can be used to identify potential critical source areas with care (limited by differential effects of washoff and erosion from the various source areas). Researchers such as Dr. Rushton have quantified gross solids associated with urban runoff.

(Excess) sediments in streams are associated with numerous effects. The major effects include the following:

- ◆ Turbidity: Turbidity is the term used to describe the cloudiness associated with the presence of extremely small (colloidal) particles in water. Increased turbidity can interfere with recreation use of a waterbody by interfering with esthetics or by obscuring submerged hazards. Increased turbidity can also interfere with the feeding of aquatic organisms by reducing an organism's vision and hence its ability to detect food.
- ◆ Benthic aquatic communities: A large volume of suspended sediment will reduce the light penetration in water and hence initially will reduce photosynthesis. This results in the production of less food (algal biomass) for benthic invertebrates. As a result, macroinvertebrates numbers may decline reducing the amount of food available to support fish populations. While the organisms in most aquatic ecosystems are capable of

coping with moderate sediment loads, excess sediment disrupts aquatic communities. In addition, excessive sediment can smother the eggs of fish and kill newly hatched fry.

- ◆ Transport of adsorbed contaminants. The pollutants of concern and their potential associations with the solid matter will be described later in this section.
- ◆ Direct effects on aquatic organisms. Suspended sediment can interfere with the filter mechanisms essential to the feeding of many benthic invertebrates. The gills of fish may suffer abrasive damage. This decreases the organism's resistance to disease and suppresses or completely stops feeding activity.
- ◆ Partial clogging of drainage systems. Many gravity drainage systems tend to have sediment deposition at junctions and manholes when the velocity in the pipes is not great enough to continuously suspend the particles. Recommendations for velocities in stormwater pipes are from 0.6-4 m/sec at design flow. A velocity of 0.6 m/sec (2 ft/sec) should be sufficient to keep solid matter entrained in the water flow, while velocities no greater than 4 m/sec should prevent the pipe itself from eroding (assuming a typical reinforced concrete storm drain pipe. These recommendations will vary at the higher velocities depending on the pipe material). It is assumed that a velocity of 0.6 m/sec is sufficient to scour out pre-settled materials, although limited research is showing that may not be true. Sediment, depending on its chemical characteristics, may "glue" its particles to each other, thus creating a larger particle that is difficult to move, or by "gluing" the larger particle to the pipe itself. Litter, especially leaves, is often the cause of clogged storm drain inlets.

Particle sizing at urban outfalls was summarized and confirmed in Clark (1996). That research found median particle sizes in Birmingham, Alabama, of between 5 to 50 μm . Higher median particle sizes have been reported for specific land uses, such as highway runoff (Glenn and Sansalone 2002, plus other reports by Dr. Sansalone). In addition to particulate matter, dissolved solids in urban runoff are typically associated with salt used to deice roads during the winter and with fertilizers and pesticides used on residential lawns, parks, golf courses, and roadsides in warmer weather (Merkel et al., 1988).

G.4.2 Nutrients

Inorganic nutrients, primarily the various forms of nitrogen and phosphorous, are essential for the growth of aquatic plants (algae and rooted aquatic plants). Only dissolved forms of these inorganic nutrients are directly available for plant growth: for nitrogen and phosphorus these include ammonia, nitrate, nitrite, and orthophosphate in pristine watersheds, low concentrations inorganic nutrients usually limit the growth of these organisms.

Nitrates and phosphorus compounds are found in urban runoff due primarily to highway runoff. The nitrates result from both the vehicular exhaust onto the road itself and adjacent soils and from fertilization of landscaped roadsides. Whenever these very soluble nitrates come into contact with the soil, the potential for leaching to the groundwater is high (Hampson, 1986; Schiffer, 1989; German, 1989). Nitrates tend to stay in the percolation water until it joins the groundwater. The amount of nitrogen available for leaching has been directly related to the impervious cover in the watershed (Spalding and Kitchen, 1988). The NURP data show that the highest concentrations of nitrogen-containing compounds, measured both as Total Kjeldahl Nitrogen (TKN) and nitrite plus nitrate ($\text{NO}_2 + \text{NO}_3$), found in urban runoff was from residential

areas, likely as a result of fertilization and watering of residential lawns. In a study in Wisconsin, total phosphorus concentrations in runoff from lawns were about 2 to 18 times larger than the concentrations in runoff from other residential source areas (Bannerman et al., 1993). Phosphorus tends to accumulate in sediments in association with colloids and organic matter in the bottom of the lake. It is not washed out as water flows out of the lake, but remains as a reservoir available to organisms over a long time.

The addition of inorganic nutrients to aquatic ecosystems stimulates the growth of algae. While initially, the increased algal growth provides more food for invertebrate and fish communities, continued increases lead to a process known as eutrophication. Eutrophic aquatic ecosystems are characterized by:

- ◆ High turbidity due to high algal biomass
- ◆ Oxygen depletion
- ◆ Reduced number of invertebrate and fish species
- ◆ Noxious algal blooms
- ◆ Production of algal toxins
- ◆ Algae physically clog waterways and plug water intakes

In addition to its involvement in eutrophication, nitrogen in the form of ammonia ($\text{NH}_3/\text{NH}_4^+$) is a highly toxic compound. At higher pH (typically above pH 7.5-8.0), the uncharged or “free” form of ammonia (NH_3) predominates. This form is readily taken up through membranes and has a direct toxic effect. Fish are particularly sensitive to the ammonia toxicity. The toxicity of ammonia increases as the temperature of the water increases.

G.4.3 Oxygen-Demanding Compounds

Oxygen is only sparingly soluble in water and so the levels of dissolved oxygen found in aquatic systems are generally low. The decomposition of organic matter consumes oxygen. Photosynthesis and diffusion add oxygen to water; however, if the amount of organic matter to be degraded is excessive, depletion of the oxygen in the water will result.

Oxygen-demanding substances can have many sources in the urban environment. Degradation of leaf litter in the stream environment will consume oxygen. Discharge of untreated or partially treated sewage consumes dissolved oxygen. In particular for the concern of stormwater runoff are the discharges of organic matter. Many invisible pollutants consume oxygen. These and other toxic substances are discussed in the next section.

Oxygen depletion resulting from the presence of high concentrations of oxygen-demanding compounds has a profound impact on aquatic ecosystems since few organisms are tolerant of low oxygen levels. The effects characteristic of excessive concentrations of oxygen-demanding compounds and the resulting oxygen depletion are:

- ◆ Elimination of most fish and invertebrates
- ◆ Development of septic conditions

G.4.4 Toxicants

The section on toxic chemicals is divided into three parts: heavy metals, organics (non-pesticides), and pesticides. Each of these categories has chemicals/compounds within them that can cause toxicity to aquatic organisms in receiving waters.

Heavy metals. Heavy metals in urban runoff originate both at industrial sites and in areas such as vehicles service stations and industrial facilities and are also seen in areas where large amounts of metal pollutants are left as part of the exhaust and other residue originating from vehicular use (Lloyd et al., 1988). However, these pollutants seem to be more prevalent in stormwater runoff from industrial areas and are also commonly found in runoff from residential and commercial areas but at lower concentrations. The work conducted by Pitt and McLean (1986) demonstrated that high concentrations of many of the heavy metals in industrial area runoff were found during both dry- and wet-weather conditions. Table G-3 (Pitt et al., 1995; Clark, 2000) lists the maximum median and the maximum concentration of several heavy metals in urban runoff, as well as the source areas associated with the highest metal concentrations in the runoff. Table G-4 (Clark, 2000) highlights the metals concentrations from automobile scrap yards by particle size. Data in Tables G-3 and G-4 show the ranges of metal concentrations that have been found in urban runoff from various source areas. The data in Table G-4 shows the large fraction of metals that are either dissolved in the runoff or associated with very fine particulate matter (indicating the potential difficulty in treating this runoff by using traditional techniques). It is seen that scrap recyclers had slightly but significantly higher concentrations of copper, lead, zinc, nickel, and cadmium when compared with end-of-pipe runoff from industrial sites and that wood preservers had significantly greater concentrations of arsenic and chromium (Line et al., 1996).

Table G-3. Heavy Metal Source Area Concentrations.

Toxicants	Concentration (µg/L)	Source area
Cadmium		
Maximum	8	Vehicle service area runoff
Maximum median	220	Street runoff
Chromium		
Maximum	100	Landscaped area runoff
Maximum median	510	Roof runoff
Copper		
Maximum	160	Urban receiving water
Maximum median	1250	Street runoff
Lead		
Maximum	75	Combined sewer overflow
Maximum median	330	Storage area runoff
Nickel		
Maximum	40	Parking area runoff
Maximum median	130	Landscaped area runoff
Zinc		
Maximum	100	Roof runoff
Maximum median	1580	Roof runoff

Leaching from rooftop material has also been shown to be significant contributor of nickel and zinc to roof runoff. Total recoverable zinc was significantly greater in runoff from

industrial roofs (1,500 µg/L or 2 to 20 times larger than runoff from other source areas). The relatively large concentrations of zinc in roof runoff indicate that galvanized roofing materials likely were the source of zinc (Pitt et al., 1995). Roofing materials also have been shown to be a source of copper and lead in the runoff, with the concentrations of dissolved copper and total recoverable copper and lead slightly larger in the residential roof runoff than in runoff from driveways and lawns (Bannerman et al., 1993).

Highways and other surfaces that are used by vehicles contribute a wide variety of metal pollutants to runoff. Automobile exhaust may contain a wide variety of metals, including lead. For arsenic, cadmium, chromium, mercury, antimony, vanadium, and lead, atmospheric fallout could explain a large amount of the metal content in the storm water. Runoff from asphalted traffic areas and leaching/corrosion from refuse dumps and sludge deposits also cause higher concentrations in the stormwater (Horkeby and Malmquist, 1977). Metals also can be derived from a number of other vehicular sources, including brake linings, fuel additives, tires, and corrosion products (Maltby et al., 1995b).

Table G-4. Concentrations of Metals in Scrap Yard Runoff.
(Summarized from Clark, 2000)

	Iron (mg/L)	Aluminum (mg/L)	Zinc (mg/L)
Total	20 – 810	15 – 70	1.6 – 8
< 63 µm diameter	22 – 767	15 – 58	1.5 – 7.6
< 38 µm diameter	21 – 705	15 – 58	1.4 – 7.4
< 20 µm diameter	15 – 534	12 – 50	1.1 – 7.2
< 0.45 µm diameter (filterable fraction)	0.1 – 38	0.1 – 5	0.1 – 6.7
	Copper (mg/L)	Lead (mg/L)	Chromium (mg/L)
Total	1.1 – 3.8	0.6 – 1.7	0.1 – 1.9
< 63 µm diameter	1.1 – 3.6	0.1 – 1.6	0.1 – 1.6
< 38 µm diameter	1.1 – 3.3	0.1 – 1.6	0.1 – 1.4
< 20 µm diameter	1.0 – 2.8	0.1 – 1.6	0.1 – 1.2
< 0.45 µm diameter (filterable fraction)	0.1 – 0.3	0.1 – 0.3	0.1 – 0.3
	Nickel (mg/L)	Calcium (mg/L)	Sodium (Na)
Total	0.1 – 3.3	31 – 230	22 – 1200
< 63 µm diameter	0.1 – 3.1	31 – 220	3 – 1175
< 38 µm diameter	0.1 – 2.9	31 – 210	3 – 1155
< 20 µm diameter	0.1 – 2.2	31 – 210	3 – 1155
< 0.45 µm diameter (filterable fraction)	0.1 – 0.2	8 – 210	3 – 1051
	Potassium (mg/L)	Magnesium (mg/L)	Manganese (mg/L)
Total	8.4 – 54	4.5 – 50	0.4 – 7.7
< 63 µm diameter	7.9 – 50	4.5 – 48	0.3 – 7.3
< 38 µm diameter	7.9 – 49	4.5 – 42	0.3 – 6.7
< 20 µm diameter	7.7 – 47	4.2 – 31	0.3 – 5.0
< 0.45 µm diameter (filterable fraction)	5.9 – 41	1.8 – 12	0.1 – 1.2

Sorme and Lagerkvist (2002) investigated the sources of heavy metals in urban wastewater in Stockholm, Sweden. Results showed that it was possible to track the sources of heavy metals for some metals such as copper and zinc (110 and 100% found, respectively) as well as nickel and mercury (70% found). Other metals sources were poorly understood or

underestimated (cadmium 60%, lead 50%, chromium 20% known). The largest sources of copper were tap water and roofs. Runoff from streets seemed to contain the largest mean concentration for all the contaminants, except for total recoverable zinc (runoff from industrial roofs) and phosphorus (runoff from residential lawns) (Pitt et al., 1995). Heavy metals and organic compounds are also been added to urban stormwater from the air through wet and dry deposition.

Organic toxicants. Land use has been found to be a significant factor in organic toxicant concentrations and yields. Runoff from industrial areas, when compared with residential and commercial areas, has higher concentrations of certain organics such as pentachlorophenol and bis(2-ethylhexyl) phthalate and some of the polycyclic aromatic hydrocarbons or (PAHs) (chrysene, fluoranthene, phenanthrene, and pyrene) (Pitt and McLean, 1986). Hydrocarbons in road runoff often result from lubricating oils and greases, fuel, exhaust emissions, and road wear. Crankcase oil leakage was found to contribute up to 88 % of the total hydrocarbon loading in highway runoff in England, and the abundance of PAHs increases with increased oil use. PAHs are fuel components that either dissolve into the oil or are produced by incomplete fuel combustion. Fuel combustion also leads to the production of carbonyl compounds such as aldehydes and ketones (Maltby et al., 1995b). Hydrocarbons in runoff in Madrid, Spain were derived from both anthropogenic and natural sources, with fuel oils being a major source of aliphatic hydrocarbons.

Waxes of vascular plants from the landscaped and residential areas also contributed a significant load of natural hydrocarbons to runoff (Bomboi and Hernandez 1991). It was estimated that in Rhode Island, 44 metric tons of petroleum hydrocarbons were poured on the road or into sewers annually, accounting for approximately 19% of the total hydrocarbon loading in the city's combined storm and sanitary sewage treatment system (Hoffman et al. 1980). The concentrations of many of these toxic pollutants substantially exceeded the U.S. EPA water quality criteria for human health protection. Typical standards for PAHs in surface waters used as sources of drinking water are 0.0028 µg/L (U.S. EPA, 1986). Table G-5 highlights some of the most common PAHs found in any urban runoff (Pitt et al., 1995). The low BOD₅ to COD ratios also suggest that the organic solids could be resistant to biochemical degradation. The concentrations of polychlorinated dibenzo-p-dioxins and dibenzofurans in the sediments from the River Po (Italy) were studied by Fattore et al. (2002). Principal component analysis suggested that widespread sources such as urban runoff and domestic wastewaters were probably the main cause of these levels of polychlorinated dibenzo-p-dioxins and dibenzofurans.

Pesticides. Pesticides are commonly used in urban areas for weed and insect control along the roadsides, in parks, on golf courses, and on private lawns. A wide variety of pesticides (e.g., α -benzene-hexachloride (BHC), γ -BHC, chlordane, and α -endosulfan) are found in runoff. Pitt and McLean (1986) mostly found these pesticides in dry-weather flows from residential areas. In some locations, pesticides have been related to the amount of impervious cover and to the distance the runoff must travel before infiltration (Lager, 1977; Pruitt et al., 1985; Butler, 1987; German, 1989; Wilson et al., 1990; Domagalski and Dubrovsky, 1992). Unused commercial sites, when compared with residential and industrial sites, have been found to contain the highest and most frequent concentrations of pesticides. However, it has been suggested that the presence of pesticides is ubiquitous and not strictly a function of land use because high concentrations and endrin were found at all the sites and because land use was dissimilar among the concentrations of chloride, methoxychlor sampling locations. Pesticides

can leach into the groundwater when their residence time in the soil is less than the time required to filter them or to biochemically convert them to an innocuous form. (Jury et al., 1983).

G.4.5 Microorganisms

Bacterial contamination, resulting from the introduction of fecal material into surface water, is among the leading causes of TMDL violations. In the vast majority of cases, this contamination cannot be traced to a single point discharge. Rather, the pollution is a result of diffuse, non-point discharge. In urban and suburban areas, nonpoint sources of pathogens include urban litter, contaminated refuse, domestic pet and wildlife excrement, and failing sewer lines. Population growth results in conversion of open land into non-permeable surfaces, which increase runoff and can impact water quality through addition of sediment, toxic chemicals, microbial pathogens, and nutrients. (Jagals, 1997; Angela et al., 2004). Urban stormwater, is increasingly recognized as a major source of fecal and other microbial pollution (Anderson et al., 1993; Bannerman et al., 1993; Arnold and Gibbons, 1996; Comstock, 1997; U.S. EPA, 1998; Krikelis et al., 1985; 1985a). Storm waters can be contaminated from leaking sewers, illegal hookups, animal waste, septic systems, and many other sources. There are correlations between microbial loads of stream water and runoff associated parameters (Atherhold et al., 1998; Ferguson et al., 1996; Geldreich et al., 1968; Payment et al., 2000; Thurman et al., 1998; Kistemann et al., 2002). In urban streams, fecal bacteria densities are directly related to the density of housing, population, development, percent impervious area, and domestic animal density (Young and Thackston, 1999).

Table G-5. Toxic Organic Source Area Concentrations.

Toxicant	Maximum (µg/L)	Detection Frequency (%)	Significant Sources
Benzo(a) anthracene	60	12	Gasoline, wood preservative
Benzo(b) fluoranthene	226	17	Gasoline, motor oils
Benzo(k) fluoranthene	221	17	Gasoline, bitumen, oils
Benzo(a) pyrene	300	17	Asphalt, gasoline, oils
Butyl benzyl phthalate	128	12	Plasticizer
Bis (2-chloroethyl) ether	204	14	Fumigant, solvents, insecticides, paints, lacquers, varnishes
Bis (2-chloroisopropyl) ether	217	14	Pesticides
Chlordane	2.2	13	Insecticide
1,3-Dichloro-benzene	120	23	Pesticides
Fluoranthene	128	23	Oils, gasoline, wood preservative
Phenanthrene	69	10	Oils, gasoline, coal tar
Pyrene	102	19	Oils, gasoline, bitumen, coal tar, wood preservative
Naphthalene	296	13	Coal tar, gasoline, insecticides

Surface waterbodies are presumed to be more vulnerable to fecal contamination than groundwater reservoirs due to the absence of natural soil protection and filtration and the possibly short distances between the source of contamination and water extraction. In the case of heavy rainfall the microbial loads of running waters may suddenly increase substantially and reach reservoir bodies very quickly (Kistemann, 1998, 2001, 2002). Significant concerns persist about microbiological safety of recreational waters, especially for high contact users, such as

surfers and swimmers, and those with weak immune systems, such as small children and the chronically ill.

Although sewage is usually treated before it is released into the environment, storm water runoff usually passes directly to surface water and beaches (Noble and Fuhrman, 2001). Urban area stormwater runoff that contains human fecal waste is a threat to swimmers and to individuals who consume inadequately cooked shellfish and inadequately treated domestic water supplies. For example, an epidemiological study (Haile et al., 1999) showed a significant increase in risk of illness is associated with swimming near flowing storm drains. Infection with organisms from these sources is usually, but not always, associated with gastrointestinal (GI) diseases.

Recently, researchers and regulators have recognized that there are a number of non-gastrointestinal diseases associated with recreational use of water (Cabelli et al., 1979). These diseases are not normally considered in the analysis and treatment of drinking water. The U.S. EPA has proposed the designation Recreational Water Infections (RWIs) for these diseases. RWIs include the traditionally recognized infections acquired via ingestion of water during recreational activities as well as a variety of respiratory, skin, ear, eye, and wound infections. One study that developed a risk assessment protocol for stormwater-borne microorganisms was Olivieri et al. (2008).

A stormwater management plan must balance two competing priorities. It must maintain accessible aquatic recreational resources by minimizing beach closings and swimming advisories while simultaneously minimizing the public health risk from RWIs. This review presents an overview of the ecology and effects of microorganisms associated with RWIs and an evaluation of the tools available to monitor and control these organisms in the development of stormwater BMPs.

Pathogens. Many of the pathogens of concern in stormwater runoff are well known organisms of concern in potable water. These include a large number of microorganisms associated with gastrointestinal diseases (i.e. nausea, vomiting, diarrhea) as well as other pathogens specific to recreational contact. The impacts of stormwater runoff into surface water is not limited to possible contamination of potable water sources or the accidental ingestion of contaminated water. Individuals may be exposed via a variety of contact and non-contact recreational activities including swimming, boating, surfing and fishing. In addition to the pathogenic organisms that are transmitted by ingestion, urban runoff may contain organisms causing respiratory, skin, ear and eye infections. These organisms are not normally monitored in recreational water and little is known about their occurrence and survival in aquatic environments.

Exposure to a minimum number of organisms, usually greater than 1, is required for a pathogen to successfully infect a susceptible host. This number is called the minimum infectious dose. In general, enteric viruses and protozoa have low infectious doses, typically between 1 and 100. Bacterial pathogens tend to require larger doses to cause infection. The infectious dose for bacterial pathogens ranges from 100 to 1,000,000.

There are four major groups of pathogens found in water: viruses, bacteria, protozoa and helminth worms.

Pathogens: Viruses. Viruses are infectious particles of nucleic acid (DNA or RNA) enclosed in a protective protein coat. They are essentially inert outside of the host organism and

are not capable of independent growth, metabolism, or reproduction. Once a virus infects a host organism, however, it rapidly takes control of the infected cell and manufactures huge numbers of new viruses. Viruses are usually very host specific. Each type of virus only infects one or a limited number of types of host organisms. Thus most human viruses only infect humans (and perhaps a small number of related primates).

There are over 100 different types of human viruses known to be transmitted by fecally contaminated water (Berg, 1983). While some viruses cause life-threatening diseases, a large number of viruses cause relatively mild symptoms. In fact, the nausea, vomiting, diarrhea that many people refer to as “the flu” is likely to be an infection with an enteric viruses via either contaminated food or water. Because of the relatively mild symptoms associated with many viral infections, it is likely that the actual number of infections in the United States and other areas is underestimated.

Pathogens: Bacteria. Bacteria are the smallest living organisms capable of independent existence. The vast majority of bacteria are essential components of natural ecosystems; however some bacteria are human pathogens. The bulk of pathogenic microorganisms responsible for contaminating surface water enter the water with fecal material from either animals or humans.

Within recent decades, a number of new waterborne microorganisms have been identified. Many of these organisms are opportunistic pathogens and tend to infect at risk groups such as children, the elderly, immunosuppressed individuals, and individuals with underlying chronic diseases. For many of these organisms, a waterborne route of infection has not been definitely established and additional research is needed.

Pathogens: Protozoa. The two major protozoan infections associated with contaminated water are *Giardia* and *Cryptosporidium*. Infection with either of these organisms is associated with a self-limiting gastrointestinal disease in otherwise healthy individuals; however in individuals with compromised immune systems infection can result in a chronic, life-threatening disease. While protozoan infections can be transmitted via the contamination of water with human sewage, these two organisms each are associated with specific animal reservoirs. *Cryptosporidium* is a common infection in cattle and therefore, improper management of agricultural wastes is a major factor in its introduction into surface water. In *Cryptosporidium* infections, species from one infected host can infect other hosts; therefore, *C. parvum* from cattle manure can infect human beings. Other animals that are carriers of *Cryptosporidium* are pigs, cats, deer, guinea pigs, mice, rats, and sheep. Not all of these hosts are farm animals. Some, (cats) are pets and some are vermin (rats). Fecal matter from these and similar organisms, containing infectious *Cryptosporidium* oocysts can easily contaminate urban runoff.

Giardia is more frequently associated with wild animals than it is with domestic animals although it has been determined that a variety of pet wastes (dog, cat, bird etc.) can be contaminated with *Giardia* cysts. Improper disposal of pet fecal matter can introduce the organism into urban wastewater and storm water runoff.

Pathogens: Parasitic Worms. The eggs of parasitic worms are excreted in the feces of infected domestic and wild animals. *Ascaris lumbricoides* and *Toxiplasma gondii* eggs have both been detected in domestic wastewater and biosolids and can enter surface water through either the discharge of combined sewer overflows or transport from land applied biosolids. Ingestion of eggs by individuals can lead to infection. *Toxiplasma* is a particular concern for pregnant women since this organism can be transmitted to the fetus.

Recreational Water Infections (RWIs). Recreational waters normally contain a variety of naturally occurring aquatic microorganisms. In addition, microorganisms from the surrounding watershed are frequently introduced into recreational water through runoff and other transport mechanisms. The vast majority of these microorganisms are non-pathogenic; in fact, they are vital components of the aquatic ecosystem. A small number of free-living microorganisms found in aquatic environments are capable of causing infections. In addition to these microorganisms, large numbers of enteric bacteria are often introduced into recreational water through contamination with fecal material.

Since human contact with recreational water is qualitatively different from contact with drinking water, infections caused by contaminated recreational water are not limited solely to organisms transmitted by ingestion of water. Disease-causing microorganisms can be transmitted to swimmers, boaters and other recreational users by inhalation and cutaneous (skin/wounds) routes as well (Fewtrell et al., 1992; Fleisher et al., 1996). Infections transmitted through contact with recreational water are now recognized as a separate, though interrelated and overlapping, group of infections compared to drinking-water-borne infections. Not surprisingly, these infections are referred to under the general category of recreational water infections (RWIs).

Between 1985 and 1998 a total of 64 RWI outbreaks involving over 5,000 individuals were reported (Kramer et al., 1996; Craun et al., 1997; Levy et al., 1998). In 2001-2002, there were 65 RWI outbreaks involving a total of 2,536 individuals in the United States (Yoder et al., 2004). Increased recognition and reporting of RWIs may account for some of the difference between these two reporting periods; however, it is unlikely to account for the entire increased incidence reported. Thus, the limited data indicates a substantial change in RWIs within the recent past. In all likelihood, the reported number of outbreaks significantly underestimates the incidence of RWIs since many of these are self-limiting, resolving without medical attention. In addition, it is difficult to identify the source of many RWIs and hence, they frequently go unreported (Pruss, 1998).

Gastroenteritis resulting from the accidental ingestion of fecally contaminated water is the most common RWI. As is the case with drinking-water-related diseases, gastroenteritis can result from infection with a variety of enteric organisms. There also are wide ranges of non-enteric diseases that are associated with recreational water. The following sections present a brief summary of the more important of the pathogens associated with RWIs. For additional information on clinical and public health aspects of these organisms, the U.S. Centers for Disease Control or State Public Health Laboratories should be consulted

RWIs: Enteric Pathogens. The term enteric pathogen refers to the type of infection caused by a pathogen, not the specific microorganism responsible for the infection. Enteric diseases are diseases associated with the gastrointestinal tract. The intestines of all animals are colonized by a large number of microbes. Most of these are harmless, or even beneficial. Others are harmless in normal individuals, but can produce disease in the very young, those with weakened immune systems, or in a new host that has no prior experience with the microbe. Some microorganisms are much more pathogenic and can produce disease in normal individuals on a regular basis.

The enteric organisms most often associated with disease in humans are Enteric viruses, *Salmonella*, *Campylobacter*, Enteropathogenic *E. coli*, *Shigella*, *Cryptosporidium* and *Giardia*.

The human enteric virus group, which includes Norwalk virus, rotavirus, hepatitis A

virus, adenovirus, and enterovirus, is one of the leading causes of human illness. Human enteric viruses are a diverse group of organisms. Relatively little is known about many of the viruses in this group because many enteric viruses are difficult to culture or are not culturable and produce diseases that are not readily identifiable (i.e. have symptoms that are common with other pathogens). Infection with these organisms typically results in a self-limiting gastroenteritis. The main symptoms of viral gastroenteritis are watery diarrhea and vomiting. The affected person may also have headache, fever, and abdominal cramps ("stomach ache"). In general, the symptoms begin 1 to 2 days following infection with a virus and may last for 1 to 10 days, depending on which virus is involved. Adenoviruses 40 and 41 have been recognized as important etiological agents of gastroenteritis in children (Cruz et al., 1990, Uhnou et al., 1986.). Respiratory adenoviruses are capable of causing large, persistent epidemics (McNeil et al., 1999), and it is suspected that they may be more important than enteric viruses as a contagion during recreational water activities because of their potential transmission in aerosols. In some instances, water-associated viruses can cause life-threatening diseases such as myocarditis and aseptic meningitis.

Three viruses associated with water, hepatitis A, hepatitis E and polio virus, are of particular concern. Hepatitis, inflammation of the liver, has many possible causes, including a group of viruses termed hepatitis viruses. This group is a mixture of different viruses all having in common a similar set of clinical symptoms. Hepatitis A and hepatitis E are the members of this group transmitted via water (Gammie and Wyn-Jones, 1993). Both of these viruses cause a relatively mild self-limiting illness, except in pregnant women where infection with hepatitis E can be life threatening. As a result of routine vaccination of children, infection with polio virus is almost unheard of in the United States although outbreaks are still reported in developing countries. The virus, which in a very small minority of cases (probably about 0.1%) can result in paralysis, can be transmitted by both waterborne and respiratory routes.

The genus *Salmonella* includes a very large number of species and serotypes. Many *Salmonella* are infectious for man. Reptiles, birds, and wild rodents can carry *Salmonella* and therefore the presence of these organisms in water does not necessarily reflect contamination with human wastes. *Salmonella* has a high infectious dose with ingestion of about one million (10^6) organisms required to cause illness. Despite this high infectious dose, salmonellosis is one of the most common causes of diarrhea in man. Infection with *Salmonella* is characterized by watery diarrhea often with abdominal cramping, nausea, vomiting, fever and chills. Salmonellosis accounts for about 30% of the cases of diarrhea in the United States and is responsible for about 1,000 deaths per year.

In addition to enteric infections two other diseases caused by *Salmonella* are typhoid and paratyphoid fever. Typhoid fever, caused by *Salmonella typhi*, is a bacterial infection of the intestinal tract and bloodstream. Symptoms can be mild or severe and include sustained fever as high as 39-40°C, malaise, anorexia, headache, constipation or diarrhea, rose-colored spots on the chest area and enlarged spleen and liver. Most people show symptoms one to three weeks after exposure. Paratyphoid fever has similar symptoms to typhoid fever but is generally a milder disease.

Campylobacter is generally regarded as one of the most common bacterial causes of gastroenteritis worldwide. It is estimated to account for about 45% of the cases of diarrhea in the United States. (It infects about 1 out of every 100,000 individuals per year approximately 2×10^6 cases and 500 deaths per year). The infectious dose of *Campylobacter* is significantly lower

than that of *Salmonella* with <500 cells necessary to cause infection. It can be carried by most mammals and by birds: it is especially likely to be found in cattle, sheep, dogs and poultry. Symptoms of the infection include diarrhea (often including the presence of mucus and blood), abdominal pain, malaise, fever, nausea and vomiting. The illness usually lasts two to five days but may be prolonged by relapses, especially in adults. Many of those infected show no symptoms. In some individuals a reactive arthritis (painful inflammation of the joints) can occur. Rare complications include seizures due to high fever or neurological disorders such as Guillain-Barre syndrome or meningitis. Death from campylobacteriosis is rare and is more likely in the very young, the very old, or those already suffering from a serious disease such as AIDS. It is also a frequent cause of traveler's diarrhea.

Escherichia coli is one of the most common intestinal bacteria and is a normal part of every mammal's intestinal flora. While most strains of *E. coli* are harmless, there are a few specific types of *E. coli* that can produce disease. Disease caused by pathogenic strains of *E. coli* is most likely to be seen in cattle, swine, and humans. Infection with *E. coli* O157:H7 results in hemorrhagic colitis a severe, systemic condition that occurs principally in children under 10 years of age. In approximately 10% of the cases, hemorrhagic colitis leads to hemolytic uremic syndrome (HUS). While HUS has a 90% survival rate with treatment, approximately 30% of the cases result in permanent kidney damage ultimately leading to kidney failure. The outbreak of HUS in Walkerton, Ontario in the last decade is the best-known occurrence of waterborne HUS. This outbreak was traced to contamination of wells with manure from nearby cattle farms.

Shigella is a tropical bacteria species that is often seen in primates, but rarely in other animals. Infection with *Shigella* can cause diarrhea, cramping, and fever. Most cases are minor, but these infections can be quite severe, especially in the young, the pregnant, or those with compromised immune systems.

Infection with *Cryptosporidium*, termed cryptosporidiosis, is the result of ingestion of oocysts of *Cryptosporidium parvum* (now also called *Cryptosporidium hominis*). Cryptosporidiosis was recognized as a disease only relatively recently. The first report of human infection with *Cryptosporidium* occurred in 1976. It is now estimated that cryptosporidiosis accounts for approximately 5% of infectious intestinal disease in which a causative agent is identified, making it one of the most significant cause of waterborne diseases today (Kramer et al., 1998). Infectious *Cryptosporidium* oocysts are able to persist in the environment for long periods of time; under certain conditions, they may remain infectious for months (Carrington and Miller, 1993). Cryptosporidiosis is characterized by severe watery diarrhea lasting several days to a week. In immunosuppressed individuals it can develop into a chronic and life-threatening infection.

Ingestion of cysts of *Giardia lamblia* (also referred to as *Giardia duodenalis* and *Giardia intestinalis*) causes giardiasis. As with cryptosporidiosis, the infectious dose is small, with as few as 10 cysts can result in infection. In most individuals, the disease is self-limiting; however, in immunosuppressed individuals, it can develop into a chronic and debilitating infection.

While gastroenteritis is the most frequent disease associated with water-related infections, there are a wide range of non-enteric diseases that are also transmitted via water. Waterborne protozoa can cause liver damage, brain infections, skin infections (cercarial infection, e.g., swimmer's itch), and severe eye infections. People wearing contact lenses are particularly at risk for protozoan eye infections. Non-enteric water-related bacterial diseases include pneumonia

(*Legionella pneumophila*), kidney infections, as well as skin and wound infections (*Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Vibrio vulnificus*). Finally, research has linked water-related viruses a host of non-enteric diseases.

Swimmer's itch (cercarial infections) is a skin condition resulting from an allergic reaction to infection with the larvae of parasites normally found in birds and non-human mammals. The parasite enters the water via eggs discharged in the feces of infected wild animals and Swimmer's itch is not associated with contamination of water with human sewage. After the eggs hatch, the developing larvae can burrow into human skin. Typically this only occurs if they cannot find a suitable host. Humans are not a suitable host for the parasite. Larvae that infect humans are unable to complete their development and die. The symptoms of Swimmer's itch are caused by an allergic reaction to the presence of the larvae and do not represent a true infection.

The symptoms of swimmer's itch are those found in a typical allergic reaction. They can range from tingling, burning, and itching of the skin to the formation of small blisters depending on the intensity/severity of the allergic reaction. It is a self-limiting disease and gradually goes away over a week or two.

Swimmer's itch has been reported in recreational areas from every state within the United States as well as large regions of Canada. It is particularly associated with marshy shoreline areas and areas where large bird and snail (the organism's normal hosts) populations are found.

Legionella pneumophila was discovered in 1976 during investigations into an outbreak of pneumonia occurring at an American Legion convention in Philadelphia. Since then, the organism has been found in many aquatic samples. Transmission of *Legionella* is via inhalation of aerosols containing the organisms. The organism grows best in warm water environments such as hot tubs and parts of large plumbing and air conditioning systems. Hence, infection is often associated with HVAC systems and showers within buildings. Transmission via recreational water is unlikely; however, it is possible.

Two RWIs are associated with the bacterium *Pseudomonas aeruginosa* – Swimmer's ear and "Hot Tub Rash". Swimmer's ear (*Otitis Externa*) is characterized by itching and inflammation of the outer ear. While several microorganisms can cause this type of infection, *Pseudomonas aeruginosa* is the most commonly identified cause of the disease. Infection is the result of having contaminated water in the ear. It is most commonly seen in children and young adults although all ages can be infected. Swimmer's ear is not the same as the middle ear infections common in children.

"Hot Tub Rash," also called *Pseudomonas dermatitis/folliculitis*, is a skin infection resulting from direct contact with contaminated water. The symptoms include an itchy, red rash. Although uncomfortable, it is generally a self-limiting disease and usually does not require medical treatment. Although infection is most commonly associated with hot tubs and spas, the organisms may be present in contaminated pools and lakes, also.

Vibrio vulnificus is limited to saltwater environments such as marine and estuarine areas. The intestinal infection is associated with the consumption of undercooked seafood, particularly shellfish such as oysters, which concentrate bacteria from contaminated water. The symptoms of this infection are diarrhea, vomiting, and abdominal pain.

In addition to gastrointestinal illness, *V. vulnificus* also can cause a serious infection when the organism comes in contact with open wounds. Infection is rare and is more likely in

individuals with underlying liver disease than in healthy individuals. The symptoms include fever, chills, decreased blood pressure (shock), and blistering skin lesions. About 50% of the individuals infected with *V. vulnificus* wound infections die from the infection. *V. vulnificus* infections are rare in the U.S. (fewer than 100 cases per year) and most of the cases occur in the Gulf states (Louisiana, Alabama, Florida, Mississippi, and Texas)

Indicator Organisms. Stormwater managers are, or may be, concerned with a spectrum of different possible impacts and potential uses of surface water receiving urban runoff. Thus, an understanding of the use and limitations of a variety of indicator organisms is essential.

Monitoring for the presence of specific pathogens is not practical for routine control purposes. Reliance is therefore placed on relatively simple and more rapid bacteriological tests for the detection of intestinal indicator bacteria. The ideal indicator organism, which probably does not exist, would meet the following criteria (WHO, 1993; Grabow, 1996)

- ♦ The organism would not be present in the absence of contamination (no false positives)
- ♦ The organism would always be present when pathogens are present (no false negatives)
- ♦ The organism would always be present in higher numbers than pathogens
- ♦ The organism would have similar survival in water to pathogens
- ♦ The organism would be unable to multiply in the environment
- ♦ The organism would be easy to isolate and characterize
- ♦ The organism would be found in all types of water
- ♦ The organism would be non-pathogenic

Drinking Water Indicators. Assessment of the microbiological quality of drinking water has depended, traditionally, on the use of organisms whose presence is associated with fecal contamination. Traditionally, this has focused on the coliform group of organisms. Operationally, the coliform group of bacteria has been divided into three interrelated and overlapping groups—total coliforms, fecal coliforms, and *E. coli*. Each of these categories includes a different set of organisms. Moreover, each category is used for different regulatory purposes and is assayed using different detection methods.

Indicators: Total Coliforms. The total coliform grouping is the broadest and most inclusive of the bacteriological indicators of water quality. The term total coliform does not apply to a single species or genus of bacteria. Instead, organisms are identified as members of the total coliform group on the basis of certain morphological and physiological characteristics. They fit certain characteristics in the way they look and in what they do. Specifically, total coliform organisms are aerobic and facultative anaerobic, gram-negative, non-spore-forming, rod-shaped bacteria that ferment lactose with the formation of acid and gas within 48 hours at 35°C (APHA, 1989).

The total coliform group includes members of the family Enterobacteriaceae including organisms belonging to the genera *Citrobacter*, *Enterobacter*, *Escherichia*, and *Klebsiella* (Bitton, 1994). These organisms are all commonly found in the intestinal tract of humans and other warm-blooded animals; however, members of the total coliform group are not limited to these habitats. They can be isolated from intestinal tract of such organisms as turtles (Harwood et

al., 1999) as well as such non-living sources as paper mill (pulp mill) effluent (Gauthier and Archibald, 2001).

Total coliforms were first proposed for use as indicator organisms in 1914 when the U.S. Public Health Service began using the total coliform group to assay the sanitary quality of food and water. The choice of this group of organisms was more an acknowledgement of the lack of suitable methods for the enumeration of *E. coli* than an endorsement of total coliforms as the best indicators of fecal contamination.

Indicators: Fecal coliforms. Eijkman first defined the group known as fecal coliforms and proposed their use as indicators of water quality. Fecal coliforms represent a subset of the coliform group. Specifically, fecal coliforms are limited to those coliforms capable of fermenting lactose at an elevated temperature (44.5°C). Thus, fecal coliforms, also referred to as thermotolerant coliforms, are selected using a temperature that reflects the intestinal tract of warm-blooded vertebrates. Bacteria such as *Escherichia coli* and *Klebsiella pneumoniae* dominate this group. Many environmental coliforms as well as those associated with cold-blooded vertebrates are excluded from this group by the higher growth temperature. Thus, fecal coliforms generally are more specific for sewage pollution and the likely presence of human pathogens than the total coliform group.

The widespread occurrence of fecal coliforms among warm-blooded vertebrates precludes the use of these organisms to distinguish between animal and human sources of fecal contamination. Furthermore, although their occurrence is restricted, fecal coliforms have been isolated from several cold-blooded vertebrates (Harwood et al., 1999).

Indicators: E. coli. *Escherichia coli* (*E. coli*), originally named *Bacterium coli* commune by Theodor Escherich who isolated it in 1885 is the most specific subset of the coliforms. Interestingly, Sharding first proposed the use of *E. coli* as an indicator of fecal contamination in 1892. Sharding's suggestion was made on the basis of the observation that *E. coli* is easily detected in human and animal feces but is not usually found in other habitats. Unfortunately, Sharding's observation was ahead of the development of practical techniques for the enumeration of *E. coli* and hence broader microbial groupings (i.e. coliforms) became the standard microbiological indicators. During the later decades of the 20th century the development of new techniques for the isolation and identification of bacteria has made the direct enumeration of *E. coli* as an indicator organism possible.

Like all coliforms, *E. coli* is able to ferment lactose. Two additional characteristics, cytochrome oxidase and β -galactosidase, are specifically used to identify *E. coli*. Several commercially available media incorporate the necessary components for the determination of these characteristics and so allow for the direct simultaneous enumeration of both total coliforms and *E. coli* in the same assay. With the development and validation of these techniques, the use of *E. coli* is rapidly replacing reliance on total or fecal coliforms for the monitoring of fecal contamination in drinking water and source water.

Recreational Water Indicators. Some recreational water illnesses (RWIs) result from exposure to or ingestion of pathogens originating from human or animal feces. Many of these pathogens cannot be directly measured, and bodies of water often contain several different pathogens making enumeration of each impractical (U.S. EPA, 2000). To protect public health from contaminated water, beach water quality criteria are based on indicator organisms, such as *Enterococcus* spp., that if present in high densities, have been shown to be associated with an

elevated risk of swimming-related illness (Cabelli et al., 1982, 1983; Dufour, 1984).

Traditional indicators of drinking water quality - total coliforms, fecal coliforms, and *E. coli* – have all been used to monitor the quality of recreational water. Several additional indicator organisms have been proposed for use with recreational water. Of these, the most widely used are *enterococci*.

Enterococci is the term applied to all members of the genus *Enterococcus* that meet a specific set of physiological and cultural conditions. The dominant organisms in the genus *Enterococcus* associated with polluted aquatic environments are *Enterococcus faecalis*, *E. faecium*, and *E. durans* (Volterra et al., 1986; Sinton et al., 1994; Audicans et al., 1995). Older monitoring studies and reports may refer to fecal streptococci instead of enterococci. While these two groups of organisms are not identical, fecal streptococci can be used as a rough approximation of enterococci when no other data is available.

U.S. EPA recommends the use of *E. coli* or Enterococci for monitoring freshwater recreational water while the use of Enterococci alone is preferred for marine environments.

Water Quality Guidelines. Based upon information derived from epidemiological and other health studies, both the World Health Organization (WHO) and the United States Environmental Protection Agency (U.S. EPA) have developed guidelines for recreational water quality. These regulations classify recreational water in terms of the risk to swimmers of contracting disease on exposure to water containing a specified number of microorganisms (IAWPRC, 1991; Jin et al., 2004).

Microbiological infections are not the result of exposure to an average (mean) number of organisms. Rather, infection typically results when an individual is exposed, in a single dose, to a number of microorganisms equal to or higher than a specific minimum infectious dose. Thus, rather than basing a standard on a single value of the number of microorganisms in a sample, regulatory standards are based on either percentage compliance standards or the geometric mean value of a specified number of replicate samples.

Calculation of either the geometric mean or 95th percentage compliance of microbiological results is not as straightforward as the calculation of an average used to evaluate chemical measurements. This is particularly true for the calculation of 95th percentage compliance where there are three different methods that can be used for the calculation. Each of these methods – Weibull, Hazen and Excel – gives a slightly different result when applied to the same set of data. Thus, in comparing monitoring results, it is essential that the same method be used to calculate the results. Details concerning the application of the geometric mean and 95th percentage compliance can be found in several reviews and journal articles outlining the mathematical basis of these techniques (Bartram and Rees, 2000; Bertram et al., 2001) will not be covered here.

U.S. EPA Ambient Water Quality Criteria (1986) for Recreational Water, establish guidelines for both freshwater and marine systems. These criteria provide a baseline used by individual states to establish specific water quality criteria. Stormwater managers should consult with the appropriate state agency for information on criteria for specific receiving water.

In addition to determining which indicator organism(s) is (are) appropriate for use in monitoring the impact of urban runoff on recreational water, it is essential that the stormwater manager have a clear understanding of the technical difficulties and limitations of any type of

microbiological monitoring. Unlike chemical contaminant, microorganisms do not dissolve in water forming a uniform solution. Instead, microorganisms are distributed within a waterbody in a clumped, uneven distribution. Because of this, there is a low degree of precision commonly found in microbiological data and data generated using different methods, or even by different laboratories using the same method are difficult to compare.

U.S. EPA Criteria for Bathing (Full Body Contact) for Recreational Waters (U.S. EPA, 2003). In freshwater, based on a statistically sufficient number of samples (generally not less than 5 samples equally spaced over a 30-day period), the geometric mean of the indicated bacterial densities should not exceed one or the other (only one indicator should be used) of the following:

<i>E. coli</i>	126 per 100 mL or
Enterococci	33 per 100 mL

No sample should exceed a one-sided confidence limit (CL) calculated using the following guidance:

Designated bathing beach	75% C.L.
Moderate use for bathing	82% C.L.
Light use for bathing	90% C.L.
Infrequent use for bathing	95% C.L.

Based on a site-specific log standard deviation, or if site data are insufficient to establish a log standard deviation, then using 0.4 as the log standard deviation for both indicators.

In marine water, based on a statistically sufficient number of samples (generally not less than 5 samples equally spaced over a 30-day period), the geometric mean of the enterococci densities should not exceed 35 per 100 mL.

No sample should exceed a one-sided confidence limit using the following as guidance:

Designated bathing beach	75% C.L.
Moderate use for bathing	82% C.L.
Light use for bathing	90% C.L.
Infrequent use for bathing	95% C.L.

Based on a site-specific log standard deviation, or if site data are insufficient to establish a log standard deviation, then using 0.7 as the log standard deviation.

Limitations of Indicator Organisms. The coliforms, total coliforms, fecal coliforms, and *E. coli*, have become the mainstay of water quality monitoring and surveillance. Despite this, there are significant limitations associated with coliforms as indicator organisms. Surprisingly, coliforms have been criticized as too conservative, indicating the presence of pathogens when none are present (false positive) and as not conservative enough, failing to detect pathogens when they are present (false negative).

A false positive result occurs when the presence of an indicator organism is detected in the absence of pathogens. Thus, false positives lead to the classification of water as non-potable when microbiologically it is safe to drink. From a public health perspective false positives reflect an overly conservative approach in which there is no increase in the likelihood of disease transmission. Thus, the “cost” of false positive results is not an increase in morbidity or mortality, but, rather, reflects the social and economic costs of unnecessarily restricting or prohibiting the use of safe water. False positives have been caused by the presence of environmental isolates of indicator organisms in water samples. Non-fecal strains of *Klebsiella*, *Enterobacter* and *Citrobacter* can be isolated from numerous habitats and limits the usefulness of both total and fecal coliforms by yielding false positive results.

While the overwhelming majority of *E. coli* detected in water samples reflects recent fecal pollution, there is mounting evidence that this organism may persist for the extended time periods in some aquatic habitats. Elevated concentrations of *E. coli* are found routinely when samples obtained from sediment and the water column in the same location are compared (Davies et al., 1995; Fish and Pettibone, 1995; Sherer et al., 1992; Anderson et al., 2005). Thus, sediments may serve as a reservoir in which *E. coli* is able to persist for a longer time than pathogenic enteric bacteria (Lisle et al., 2004; Sherer et al., 1992). Under these circumstances, resuspension of the sediments may lead to the detection of *E. coli* in water column in the absence of pathogens. In addition, *E. coli* has been consistently found in pristine tropical rain forest aquatic and plant samples and seems to be a natural inhabitant of these environments (Hazen and Toranzos, 1990; Rivera et al., 1988, Byappanahalli and Fujioka, 1998; Fujioka et al., 1999; Solo-Gabriele et al., 2000). Finally, members of the coliform group have been associated with regrowth in water pipes in the absence of pathogens (LeChevallier, 1990).

Reliance on members of the coliform group as indicators of water quality also can result in false negative results. False negative results, where the indicator organism is absent even though the pathogen is present, has much more serious public health implications than false positive results. There is an increased possibility of disease transmission when false negatives occur.

Instances in which pathogenic microorganisms were present in water samples in which traditional indicator organisms were not detected indicate that the absence of traditional indicators is not necessarily protective of human health (Hsu et al., 2001; Harwood et al., 2005). Treated water supplies that meet standards can have enteric viruses and protozoan cysts (Enriquez et al., 1995; Grabow, 2001).

Numerous living (biotic) and non-living (abiotic) factors are known to influence the persistence of coliform organisms in the environment. These include temperature, osmotic stress, nutrient limitation, solar irradiance, pH and a large number of other factors (Barcina et al., 1986, 1990; Davies and Evison, 1991; Davies-Colley et al., 1994; Fujioka et al., 1981; Sinton et al., 2002; Beaudeau et al., 2001; Nobel et al., 2004).

Alternative Indicators. Given the limitations of the coliform group and enterococci to consistently reflect the presence (or absence) of pathogens, particularly viral and protozoan pathogens, a considerable amount of research has focused on identifying and evaluating alternative indicators of the microbiological quality of water. Several different bacteria and viruses have been proposed for use in place of or in conjunction with traditional indicator organisms. These include sorbitol-fermenting *Bifidobacteria*, *Clostridium perfringens* spores

(Lisle et al., 2004; Shibata et al., 2004; Harwood et al., 2005; Long et al., 2005; Skanavis and Yanko, 2001; Byamukama et al., 2005; Mendez et al., 2004; Payment and Franco, 1993). While research is still preliminary, available data indicates that the use of *Cl. perfringens* spores and somatic and F⁺ coliphage as indicators of pathogenic protozoa and viruses is worth more intensive investigation (Calci et al., 1998; Davies et al., 2003). Finally, the application of both quantitative microbial risk assessment and hazard assessment and critical control point (HACCP) approaches has the potential to focus microbiological water quality monitoring on key sites and parameters to increase public health protection (Ashbolt and Bruno, 2003).

Unfortunately, the ideal indicator does not exist. Some indicators come close to these characteristics (e.g. fecal coliforms), but even so, they are only useful for one group of pathogens. Thus, while fecal coliforms are an extremely good indicator; they are limited to the indication of the presence of bacterial pathogens. They are not reliable for other types of microorganisms.

Determining the Source of Fecal Pollution (Bacterial Source Tracking). Most fecal indicators are indirect and only warn of the possibility of the presence of fecal pathogens, which are not necessarily from humans. Current monitoring and analytical methods for coliforms and enterococci do not distinguish between indicator bacteria of human and nonhuman origin (Turner et al., 1997). Therefore, the environmental and public health implications of monitoring data are difficult to interpret in cases where contamination comes from multiple sources. This would not be a problem if there were a way to identify bacterial strains that are specific to a particular host. Extensive research over the past several years has focused, therefore, on the development and evaluation of fecal source tracking methods (Scott et al., 2002; Simpson et al., 2002). The new methods developed can be divided into three broad categories – culture – dependent methods, chemical methods and culture –independent methods. Culture dependent methods include the development of alternative indicator organisms (e.g. F⁺ phage and *Bacteroides*) (Alderisio et al., 1996; Noble et al., 2001), as well as molecular and phenotypic characterization of individual indicator isolates such as antibiotic resistance profiles or ribotyping (Whitlock et al., 2002; Cho and Kim, 2000; Choi et al., 2003). Chemical approaches to fecal source tracking, on the other hand, have emphasized the identification of chemical markers unique to different pollution sources. For example both caffeine and optical brighteners (found in laundry detergents) have been proposed as indicators of human fecal pollution. Culture-independent methods are designed to circumvent the problem of viable but non-culturable (VBNC) organisms. It has long been recognized that the vast majority of microorganisms in the environment cannot be grown in the laboratory. Culture-independent methods depend on the direct extraction of DNA from the microbial community followed by either DNA fingerprinting (LaMontagne et al., 2003; Liu et al., 1997; Osborn et al., 2000) or PCR amplification and restriction or sequencing of specific DNA sequences (e.g. 16s rDNA) (Bernhardt and Field, 2000a, 2000b; Khatib et al., 2002; Satokari et al., 2001).

Despite the extraordinary growth in fecal source tracking methods, there is no consensus regarding which method is the best. Rather there are advantages and disadvantages recognized for each approach and method. Culture based methods rely on the prior development of libraries of characterized organisms from known sources which can be laborious and time consuming. Furthermore, these methods are highly susceptible to sample size bias. Finally, by relying on the characterization of individual isolates, culture-dependent organisms fail to examine all of the information available to characterize the fecal source. In spite of these limitations, culture-based

methods have been used with success. For example, the antibiotic resistance patterns of fecal streptococcus isolates were used to identify the source of bacteria at three highly contaminated sites. In the stream samples fecal streptococci classified as being predominantly from cattle. Using this information to guide stream restoration, corrective actions were instituted to restrict the access of cattle to the streams resulting in the reduction of fecal coliforms by an average of 94%.

Molecular methods may offer the most precise identification of specific bacterial sources. All molecular techniques, however, require highly trained personnel and there are many places in the procedures where mistakes can happen that could produce different band patterns. Molecular methods rely on the small, but unique differences in the DNA between different strains of bacteria associated with different hosts. These subtle differences are most likely the result of differences in the intestinal environments between host organisms. These differences exert a selective pressure on the fecal microorganisms leading to genetic changes in the organisms. It is important to note that the majority of the DNA in the fecal microorganisms does not change and therefore, molecular methods are targeted to detecting small differences against a larger similar background. In molecular approaches, the DNA of either a particular isolate or of the entire community, depending on the approach being used, must first be carefully extracted, purified, and quantified. Among the most frequently used techniques in molecular fecal source tracking are ribotyping, pulse field gel electrophoresis (PFGE), terminal restriction fragment length polymorphism (TRFLP), denaturing gradient gel electrophoresis (DGGE) and randomly amplified polymorphic DNA (RAPD). All of these techniques depend on the ability to either amplify (PCR) small specific segments of DNA or to precisely and consistently cut intact DNA into smaller segments. Several reviews (Hadrys et al., 1992; Yang et al., 2000; Muyzer et al., 1993; Massol-Deya et al., 1995; Sudarshana, 1999; Field et al., 2003; Griffith et al., 2003) have described these methods and they will not be covered in detail here.

Microorganisms in the Environment: Distribution and Fate. Determining what happens to microorganism once they reach a waterbody is often a challenging as identifying and tracking their sources. As living organisms, microbes require certain conditions to survive, grow, and reproduce. Many factors influence the die-off rate of viruses, bacteria, and protozoa in the environment. These factors include sunlight and variation of spectral quality of sunlight (Pommepuy et al., 1992), temperature (Berry et al., 1991; Terzieva and McFeters, 1991), pH, chemical damage (Pathak and Bhattacharjee, 1994), and predation (Davies-Colley et al., 1994; Brettar and Höffle, 1992), salinity and osmotic stress associated with moving from fresh to marine water (Kator and Rhodes, 1994; Tassoula, 1997), nutrient deficiencies and starvation (Korhonen and Martikainen, 1991), turbidity and association with particles and oxygen concentration. Some of these factors have a direct influence on mortality of microorganisms, whereas other indirectly affects organisms (Brettar and Höffle, 1992).

Urban stormwater runoff is recognized as a major contributor to non-point source contamination of surface water with microorganisms. These organisms enter the stormwater conveyance system from a variety of sources. Historically, one of the major sources of microbial contaminants was combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs) associated with heavy rainfall (Christen, 2002, 2004). Additional sources include runoff from gardening and landscaping, pet and animal wastes, illegal discharge and cross-connections and other sources.

There is a significant relationship between land use characteristics (extent of urbanization) and the quality of surface water (Crowther et al., 2003; Shehane et al., 2005; Lee and Stenstrom, 2005; Marsalek and Rochford, 2004). Generally, increased urbanization, with the concomitant increase in impervious cover, is associated with increased discharge of microorganisms to surface water (Lee and Stenstrom, 2005; Arnold et al., 2004; Kelsey et al., 2004; Eyles et al., 2003; Interlandi and Crockett, 2003; Tufford and Marshall, 2002; Line, 2002; Mallin et al., 1999).

In addition to the direct discharge in the water, stormwater runoff and conveyance systems can be indirect sources of microorganisms to receiving waters. The sediments that accumulate at (in) the bottom of stormwater discharge pipes can provide a suitable, moist environment for the growth of microorganisms deposited there. During wet weather, much of this microbially enriched sediment is discharged along with the stormwater. Furthermore, the velocity of the discharged stormwater during wet weather flows can resuspend sediments that had settled within them. These sediments often function as a reservoir in which microorganisms can persist (Jensen, 2002; Mermillod-Blondin et al., 2005; Arnold et al., 2004; Reeves et al., 2004).

Parallel to studies focusing on microbiological methods for fecal source tracking, hydrologists and stream ecologists have evaluated the relationships between geology, land cover, hydrology and fecal contamination (Kashefipour et al., 2002). Generally, these studies are either observational or anecdotal, or they rely on statistical correlations between the presence of indicator organisms and demographic and land use factors. (Gordon, 2001). An association between the proportion of improved pasture and the variance of high-flow concentrations of indicator organisms was found in a large rural catchment (Crowther et al., 2001). Reeves et al. (2004) noted that the dominant source of fecal coliforms to coastal streams in California depended highly on stream-flow discharge. In a similar study, Schiff and Kinney (2003) found significant differences between both the concentration and source of indicator bacteria to creeks in the Mission Bay area depending on the time of sampling (wet season vs. dry season).

Tong and Chen (2002) adopted a watershed-based water quality assessment tool, the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) model, in their investigation of indicator organisms. The GIS component of the model was used to identify watersheds that have high levels of contaminants and percentages of agricultural and urban lands. Im et al. (2004) simulated the fate and transport of fecal coliform bacteria in a watershed using the Hydrological Simulation Program-FORTRAN (HSPF). Steets and Holden (2003) developed a mass balance-based mechanistic model of fecal coliform concentration throughout a coastal lagoon. Their model accounts for advective flow and dispersion, decay, and sedimentation and resuspension of sediments during high flow erosional conditions. Field measurements of indicator organisms were within an order of magnitude of the concentrations predicted by the model.

Until recently, very little research has focused on combinations of methods from different perspectives (Sharon and Plummer, 2004). Hyer and Moyer (2004) combined FST with watershed models to guide the development of TMDLs for three streams. While initial comparison of simulated bacterial sources with the observed data indicated that the fecal coliform sources were represented inaccurately, revised model simulations appeared to provide a better representation of the sources of fecal coliform bacteria. The authors recommend a coupled approach incorporating source tracking data into fecal coliform transport models. Kelsey et al.

(2003) used a combination of FST via antibiotic resistance patterns and regression modeling techniques in a study on a small high-salinity creek. The antibiotic resistance patterns of *E. coli* isolates indicated that the majority of the fecal pollution detected was from non-human sources despite the close proximity of high densities of septic tanks. Haack et al. (2003) combined HSPF and ribotyping of bacterial isolates to evaluate the sources and fate of indicator organisms in a study of the Great Lakes. During the period of their study, the percent errors in total runoff volumes between observed and simulated values ranged from 0.4 to 4.2% for the calibration period, and 0.4 to 6.7% for the validation period. In addition, they reported the HSPF moderately underpredicted the geometric mean concentration of fecal coliforms in one sub-watershed studied and slightly over-predicted for another.

Health Effects – Epidemiological Studies. Epidemiological studies are essential to understanding the potential public health impact of urban stormwater runoff. While there are a limited number of epidemiological studies focusing on recreational water quality and health, research specifically targeting urban stormwater runoff is more difficult to find (Craig et al., 2003; Gaffield et al., 1997; Godfree et al., 1990; Kay et al., 1994; Kay et al., 1999). Prüss (1998) summarized epidemiological studies related to health effects from exposure to recreational water. She confirmed that most of the studies reviewed indicated an increased risk was associated with high-levels of indicator microorganisms, particularly enterococci (marine and freshwater) and *E. coli* (freshwater). Unfortunately, there is no appreciable data concerning hydrological conditions or land-use patterns associated with these studies.

In a follow-up analysis, Wade et al. (2003) conducted an extensive review of the available studies to determine the relationship between recreational water quality, exposure and health effects. Of the 976 published studies relating to the microbiological quality of recreational water, they were able to identify only 27 studies that provided data on the variables they were examining. Their analysis concluded that enterococci (marine and freshwater) and *E. coli* (freshwater) were the best predictors of health outcomes (gastrointestinal illness). As with the Prüss review, the authors were unable to evaluate the source of the microorganisms and so, no conclusions regarding the importance of urban stormwater runoff compared to other diffuse and point sources cannot be determined.

Health Effects: The Santa Monica Bay Project. The Santa Monica Bay Project is the only large-scale research which has focused directly on the linkage between stormwater runoff and human health effects (SMBRP, 1996; Jiang et al., 2001). This project combined extensive sampling and analysis of areas with known stormwater runoff inputs with a survey of over 10,000 individuals involved in water-contact recreation on the same day the water quality samples were obtained. Thus, the researchers were able to assess the association between adverse health effects and the presence of indicator organisms in stormwater discharge with which the bathers had been in contact.

There was a statistically significant but moderate increase in the risk of several adverse health outcomes (symptoms) associated with exposure to urban stormwater runoff. The symptoms with increased risk were fever, chills, ear discharge, vomiting, coughing with phlegm, gastrointestinal illness and significant respiratory disease (SMBRP, 1996; Pitt, 2003).

While the results from the Santa Monica Bay Project presents compelling evidence of an association between exposure to stormwater runoff and adverse health outcomes, significant more research is needed. Specifically, studies similar to the Santa Monica Bay Project must be

conducted in a range of geographic and climatic conditions in both freshwater and marine environments before the findings from Santa Monica Bay can be confirmed.

G.4.6 Dissolved Salts

Salts, typically chlorides, are usually applied during the early phase of snowfall to prevent the bonding of snow with the pavement. Typical salt quantities used in the U.S. ranges from 180 to 550 kg per two-lane street per mile (Hoffman et al., 1980). Salt has to be applied before every snowstorm, resulting in repeated applications at these rates over the entire winter season. High amounts of chlorides wash off to the receiving waters either directly through runoff or indirectly through percolation to the groundwater (Huling and Hollocher, 1972). Hoffman et al. (1980) statistically tested chloride data for various lake groupings in North Carolina. The average chloride in the contaminated snow was 30 times higher than in plain snow. It was found that the streams crossing highways had higher chloride concentrations downstream of the crossing when compared with upstream (Tsihrintzis and Hamid, 1997).

G.5 Urban Snowmelt Water Quality

Snow and ice removed from the streets may contain 10,000 mg/L of sodium chloride and 100 mg/L of oil (from automotive exhaust). This contamination occurs because salt is applied on the pavements every year to prevent the bonding of ice with the pavement. In addition to the chlorides in the deicing chemicals, many of the road salts contain special additives that have been used as corrosion inhibitors. Common examples include ferric and sodium ferrocyanide that have been used to minimize caking of the salt piles. Chromate and phosphate additives may have been added to the salts as corrosion inhibitors (Field et al., 1993). The few studies that are available on snowmelt runoff have shown that the median concentrations of pollutants in snowmelt are not strikingly different from the Nation Urban Runoff Program average concentrations, except for chloride, some solids, and bacteria concentrations. Roadways generally contributed the most pollutants (yields and concentrations) to snowmelt runoff. Pitt and McLean (1986) analyzed snow samples along a snowpack transect perpendicular to a road. These data showed that the pollutant levels dropped dramatically at greater distances from the roadway. At distances greater than about 3 to 5 m from the edge of the roadway, the snowpack pollutant concentrations were relatively constant and lower than the concentrations seen next to the sand.

Glenn et al. (2002) reviewed the accumulation and partitioning of heavy metals associated with snow exposed to urban traffic and winter highway maintenance activities. Results from partitioning analysis indicate that lead, copper, cadmium, zinc, aluminum, magnesium, and iron were all highly particulate bound, and that sodium and calcium were mainly dissolved for all highway sites. Partition coefficients for most heavy metals in snowmelt ranged from 10^3 to 10^6 L/kg. High chloride concentrations could proportionally decrease these partition coefficients, causing more metals to be in their dissolved and likely more toxic form. A study of Lincoln Creek in Milwaukee, Wisconsin, examined both winter and non-winter runoff at the same urban outfall. Results demonstrated that snowmelt runoff contains higher heavy metal concentrations, compared to non-winter runoff, likely due to the high chloride concentrations (Novotny et al., 1999). The results of this study are summarized in Table G-6.

Bacterial data are not shown in Table G-6, but bacteria have been determined to be significantly lower in snowmelt when compared with warm-weather-rainfall runoff. Pitt and McLean (1986) found that fecal coliforms, fecal streptococci, and *Pseudomonas aeruginosa* populations were significantly lower (by about tenfold) in cold-weather runoff than in warm weather runoff. The city of Anchorage, Alaska was also found to have winter coliform measurements that were almost exclusively lower than in warm-weather runoff (Jokela, 1990). If snow removal occurs in a jurisdiction, then the impacts of snowmelt runoff need to be considered by stormwater managers. As discussed in Chapter 7.0, the contents of snowmelt runoff, particularly the salts, will affect the ability of treatment devices to provide effective treatment both during the snow season and potentially, for an undetermined amount of time afterward.

Table G-6. Summary of Lincoln Creek Winter (Snowmelt) and Non-Winter (Stormwater) Pollutant Levels.
(Data summarized from Novotny et al., 1999)

Parameter	Sampling Period	
	Winter	Non-winter
Suspended Solids, mg/L	46	129
Total Phosphorous, mg/L	0.43	0.24
Tot. Kjeldahl Nitrogen, mg/L	1.10	0.65
COD, mg/L	57	37
Chlorides, mg/L	1,612	40.5
Copper total, µg/L	33	16.6
Copper soluble, µg/L	16	4.7
Lead total, µg/L	42	24.4
Lead soluble, µg/L	15	<1
Zinc total, µg/L	104	99.5
Zinc soluble, µg/L	49	<10
pH	7.8	7.78

APPENDIX H

STORMWATER MONITORING PROGRAMS

H.1 Selecting the Sampling Locations

Specific sampling locations are determined based on the objectives of the study and site specific conditions, but also with a consideration to safety. The process of selecting a sampling site is often given minimal thought when designing an assessment study. Site selections are driven by two basic criteria: accessibility/safety and upstream-downstream locations of pollutant discharges. Channel, flow, and stratification characteristics, however, are particularly important when locating sample sites in streams, rivers, lakes and reservoirs and must be considered. Sampling near shore is seldom satisfactory except in small, upper reach streams. Whether using a random or systematic approach, one should carefully note the channel, flow, or stratification (lakes and reservoirs) conditions. Depositional zones, such as river bends and mouths, pools, and impoundment structures, should be sampled for sediment contamination and toxicity.

Paired analyses are the most efficient sampling strategy. This can be simply sampling the influent and effluent of a control structure, outfalls of test and control watersheds, comparable stream habitats in test and control streams, or even the same stream sampling location, but at different seasons. Paired sampling can eliminate much variability, as many influencing factors are assumed to remain constant, enabling effects to be more easily seen. Obviously, if the expected differences are expected to be large between the two elements in the pair, and the background random variability is small, many fewer sampling pairs are needed to identify a statistically significant difference in the observations. Great care must be taken to select correct pairs, as the random variability can easily be greater than expected.

The actual sampling location is dependent somewhat on the type of sampler to be used. However, in all cases, the sample taken must be representative of the flow being characterized. Several researchers have addressed the concerns of sampling, including types of samplers, locations in flow streams and sample processing in the field and laboratory (Winterstein and Stefan, 1983; Horowitz et al., 1990; Edwards and Glysson, 1999; Bent et al., 2000; Breault and Granato, 2000; Graczyk et al., 2000; Cristina et al., 2002; Kayhanian et al., 2005; Guo, 2007; Roesner et al., 2007; Selbig and Bannerman, 2007; Chan et al., 2008; Clark and Pitt, 2008; Clark and Siu, 2008; Siu et al., 2008; Clark et al., 2009).

H.2 Receiving Water and Discharge Sampling

Water samples can be collected by manual grab or automatic samplers, the latter being more directly expensive, but often superior when conditions fluctuate rapidly or sporadically, or when available personnel are lacking. Automatic samplers are essential for the NPDES program when effluents are monitored for permit requirements. Many types of automatic samplers exist and none are ideally suited for all situations (Table H-1 compares automatic versus manual sampling). The following variables must be considered when selecting a sampler (U.S. EPA 1982):

- ◆ Water or effluent variation (flow and constituents)

- ◆ Suspended solids concentration, dissolved gases, and specific gravity of effluent
- ◆ Vertical lift required
- ◆ Maintenance

Table H-1. The Advantages and Disadvantages of Manual and Automatic Sampling (U.S. EPA, 1982).

TYPE	ADVANTAGES	DISADVANTAGES
Manual	Low capital cost	Probability of increased variability due to sample handling
	Not a composite	
	Point-in-time characterization	
	Compensate for various situations	
	Note unusual conditions	
Automatic	No maintenance	Inconsistency in collection
	Can collect extra samples in short time when necessary	High cost of labor*
	Consistent samples	Repetitious and monotonous task for personnel
	Probability of decreased variability caused by sample handling	Considerable maintenance for batteries and cleaning; susceptible to plugging by solids
	Minimal labor requirement for sampling	Restricted in size to the general specifications
	Has capability to collect multiple bottle samples for visual estimate of variability and analysis of individual bottles	Inflexibility
		Sample contamination potential
		Subject to damage by vandals

* High cost of labor assumes that several samples are taken daily, large distances between sampling sites, and labor is used solely for sampling.

Bed load may be important when characterizing stormwater sediment discharges. In northern areas where sands are used for ice control, relatively large amounts of sand material can be transported along the drainage system as bed load. At the Monroe St. detention pond site in Madison, the bed load accounted for about 10% of the total annual sediment loading. This fraction was much greater during the spring when most of the sand was flushed from the drainage area. Conventional water samplers may not adequately collect bed load material. A slot sampler placed in a drilled hole in the bottom on a discharge pipe can effectively collect this material. However, the slot dimensions and placement exposure times usually need to be determined by trial and error. In addition, several bed load samplers should be used in close proximity because of the varied nature of bed load transport. Bed load samplers that are full upon retrieval may not represent actual conditions. If full, then the slot widths should be reduced and/or the exposure time should be shortened. The slot length should be as long as possible for the container lid, as bouncing bed load particles may jump over openings that are too short. In addition, the slot widths should be at least ¼ inch wide, as narrower slots will filter out large materials. Basket samplers are probably most applicable in streams, where the opening width is a small fraction of the stream width. Again, several samplers need to be used in close proximity and the best exposure period needs to be determined by trial. For grab samples, both hand-held

and cable suspended Helley Smith (Geological Survey) bed-load samplers are available from Halltech Environmental, Inc. (at 519-766-4568).

H.3 Experimental Design

All sampling plans attempt to obtain certain information (usually average values, totals, ranges, etc.) of a large population by sampling and analyzing a much smaller sample. The first step in this process is to select the sampling plan and then to determine the appropriate number of samples needed. When evaluation previously collected data, it is often desirable and effective to organize the data according to a specific sampling plan (shown later).

Many sampling plans have been well described in the environmental literature. Box, et al. (1978) and Gilbert (1987) contain much information concerning sampling strategies. An important aspect of any research is the assurance that the samples collected represent the conditions to be tested and that the number of samples to be collected are sufficient to provide statistically relevant conclusions. Unfortunately, sample numbers are most often not based on a statistically-based process and follow traditional “best professional judgment,” or are resource driven. Gilbert (1987), Berthouex and Brown (2001), and Burton and Pitt (2002) describe several methods for calculating the appropriate number of samples.

APPENDIX I

SOILS AND INFILTRATION

I.1 Introduction

One of the primary concerns with the use of infiltration devices is the protection of groundwater resources. This appendix contains the literature to support the evaluation of infiltration BMPs as pollutant removal devices. This appendix discusses the water movement in the subsurface and relates it to the design of infiltration devices. Primarily, it reviews the theory of infiltration and groundwater flow.

I.1.1 Water Movement in the Subsurface

I.1.1.1 Introduction

There are two basic regions in the subsurface, the unsaturated zone and the saturated zone. The unsaturated zone, also known as the vadose zone, is just below the ground surface, consists of various types of soil, and contains some moisture but is not usually saturated. Further into the subsurface, below the unsaturated zone, is where the saturated zone can be found. This region consists of porous rock and soil layers that are saturated with water. The top of the saturated zone is called the water table (Fetter, 1994). Both of these zones can vary in depth below the ground surface.

The water stored in the saturated zone, groundwater, may be the drinking water source for a group of people. Some groundwater is very old, while shallow groundwater recently, comparatively, may have been rainfall and runoff. Because a certain amount of surface water will end up as groundwater, it is important that the infiltrating water be as unpolluted as possible to preserve the quality of the groundwater. Pitt et al. (1996) completed a comprehensive review of literature discussing the problem of groundwater contamination from stormwater infiltration. A later section will address the issues of stormwater pollutants in the subsurface.

I.1.1.2 Water Movement Through the Vadose Zone

Introduction to the Vadose Zone and Soil The vadose zone is the region of the subsurface that lies between the ground surface and the saturated zone. It is characterized by unsaturated weathered rocks, mineral fragments, decayed organic matter, microorganisms, and air. This region can contain some moisture or can be very dry depending on the geographical location. The vadose zone contains nutrients that are vital for plant growth (Selker et al., 1999). When combined, all of these components are known as soil. Soil is a product of the weathered parent material (rocks). Thus, a major component of soil is mineral fragments. They can exist in their original form or can be transformed into new mineral material as a result of infiltrating water, microbial activity, plant enzymes, or pollutants. Soils may seem stable, but in reality they are in constant transition. Organic matter is another component of soil that constantly in a state of change because of constant inputs of decaying organic matter. The organic content of soil ranges from less than 0.05% to greater than 80%, but is most often between 2 and 5%. In addition,

countless numbers of microorganisms exist in the soils of the vadose zone. They fix nitrogen and degrade organic matter and various pollutants. Depending on the composition, soil can have significant pore volume between the grains. These pore spaces may be filled with water or air. Since the vadose zone is an unsaturated region, both water and air are usually present at the same time. Water is a major part of the dynamic nature of soil because of its capacity to dissolve minerals and transport substances. The soil atmosphere contains nitrogen, oxygen, and carbon dioxide. Free oxygen and nitrogen are naturally present in soil, with carbon dioxide being a result of microbial respiration or abiotic chemical reactions. Without water and air, the vadose zone would be very lifeless and unreactive. Because of the dynamic components of soil, the vadose zone is a region where many physical, chemical, and biological reactions take place (Winegardner, 1996).

In the vadose zone, soils are arranged in layers that are also called horizons by the U.S. Department of Agriculture (USDA). These horizons that are designated as O, A, E, B, C, and R. Table I-1 illustrates the orientation of the horizons and briefly describes their composition.

Table I-1. Orientation and Description of Soil Horizons.

O – Horizon	Surface litter consisting primarily of organic matter
A – Horizon	Topsoil consisting of humus and inorganic minerals
E – Horizon	Zone of leaching where percolating water dissolves soluble material Sometimes called the A ₂ -horizon
B – Horizon	Subsoil below the A-or-E horizons that contains minerals and humic compounds
C – Horizon	Zone consisting primarily of undecomposed mineral and rock fragments
R – Horizon	Layer of very low permeability that can also be called bedrock

Depths of the vadose zone range from a few feet to hundreds of feet. In the same manner, the soil horizons will also vary in depth. These layers may be very distinct or barely distinguishable due to depositional processes and the heterogeneous nature of soil. In any event, individual soil horizons are usually recognizable because of differences in color and texture (Selker et al., 1999).

Soil Characterization Soils have been classified based on their physical features and formative processes. Several classification systems exist. However, the Unified Soil Classification System (USCS) and the U.S. Comprehensive Classification System, developed by the USDA, are the two most popular systems (Selker et al., 1999).

Soil is classified by particle (grain) size distribution, consistency, particle shape, structure, color, and texture. All the major systems classify soils based on particle size. Table I-2 shows particle size distributions in the different soils as determined by two primary classification systems. Each soil will exhibit a certain consistency depending on its water content. Fine grained soils can exist in four states of consistency: solid, semisolid, plastic, and liquid. In addition, the shape of individual particles can be unique. For example, bulky (equidimensional) grains may be rounded or angular, flaky (plate-like) grains tend to be very flat, and elongated grains have a fibrous appearance. Grains of varying shapes interact to create a specific structure. Soil structure describes the geometric orientation of the soil grains with respect to each other. Another physical characteristic of soil is color. Soils can be brown, reddish, yellowish, greenish, grayish, or black. Finally, soils will exhibit specific textures based on the grain size, shape, and consistency. The soil textural triangle (Figure I-1), shows the way that soils are classified by texture. There are

different versions of the textural triangle, but the USDA triangle is the most common (Winegardner, 1996).

Table I-2. Grain Size Limits by Various Classification Systems.

Sediment Type	Size	Unified Soil Classification System
Cobble	Grain Size (mm)	> 80
	Sieve Size	> 3 inches
Coarse Cobble	Grain Size (mm)	80 – 20
	Sieve Size	3" – ¾"
Fine Gravel	Grain Size (mm)	20 – 5.0
	Sieve Size	¾" – 4"
Coarse Gravel	Grain Size (mm)	5.0 – 2.0
	Sieve Size	4 – 10
Medium Sand	Grain Size (mm)	2.0 – 0.3
	Sieve Size	10 – 40
Fine Sand	Grain Size (mm)	0.3 – 0.07
	Sieve Size	40 – 200
Fines Silt or Clay	Grain Size (mm)	0.07 – 0.001
	Sieve Size	< 200

Sediment Type	Size	American Association Of State Highway and Transportation Officials	U.S. Department of Agriculture	Massachusetts Institute of Technology
Cobble	Grain Size (mm)	> 80	> 80	> 80
	Sieve Size	> 3 inches	> 3 inches	> 3 inches
Gravel	Grain Size (mm)	80 – 2.0	80 – 2.0	80 – 2.0
	Sieve Size	3" – 10"	3" – 10"	3" – 10"
Sand	Grain Size (mm)	2.0 – 0.08	2.0 – 0.05	2.0 – 0.06
	Sieve Size	10 – 200	10 – 270	10 – 240
Silt	Grain Size (mm)	0.08 – 0.002	0.05 – 0.002	0.06 – 0.002
	Sieve Size	< 200	< 270	< 240
Clay	Grain Size (mm)	< 0.002	< 0.002	< 0.002
	Sieve Size	< 270	< 270	< 270

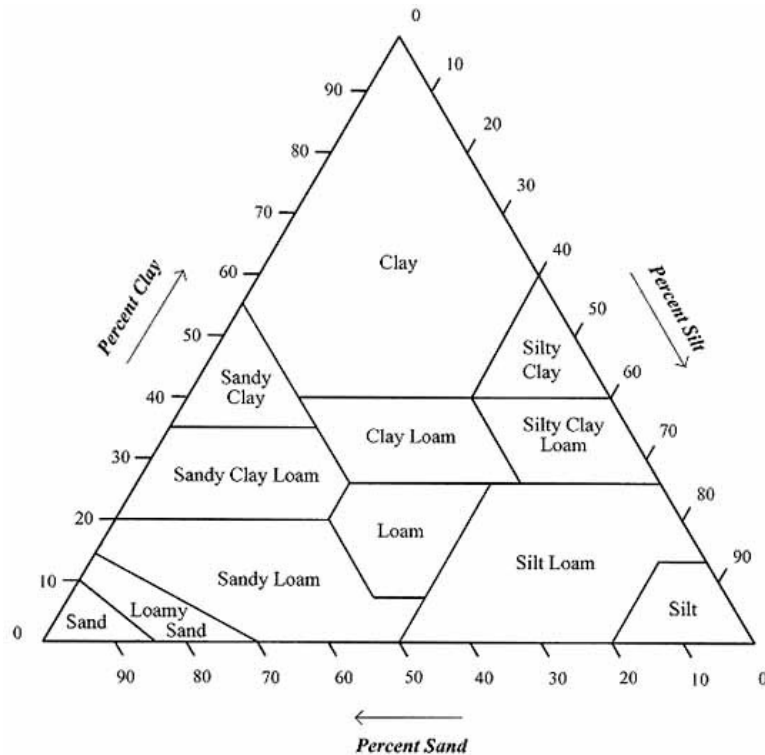


Figure I-1. Soil Textural Triangle. (USDA)

Despite the differing interpretations of grain size for sand, silt and clay, each soil classification system has agreed that those three are the basic soil types. Physical weathering has combined these three soil types in different proportions to create unique soils such as sandy clays, silty clays, loams, clay loams, or sandy loams, for example. Thousands of soil types have been identified. The U.S. Soil Conservation Service (SCS), currently known as the National Resource Conservation Service (NRCS), created county soil surveys for most areas of the United States. The SCS classified 14,000 soils series in these soil surveys. Soil surveys are excellent general resources because they contain information about the soils in a specific county, including maps of areal coverage, the name of the soil, description, land use, hydrologic cover, tendency to erode, hydrologic conductivity, and hydrologic soil group classification. They were intended for agricultural purposes, but their use has broadened (McCuen, 2004). Since soil surveys show general locations of soils types, they can be useful in selecting an area to be used for infiltration.

One piece of information that is very useful in designing stormwater infiltration facilities is the hydrologic soil group classification. The USDA created hydrologic groups A, B, C, and D as a way of describing how well water will move through a specific type of soil. Table I-3 shows detailed descriptions of the soil groups found in McCuen (2004).

Table I-3. Hydrologic Soil Group Descriptions.

Group A	Deep sand; deep loess, aggregated silts; rapidly draining
Group B	Shallow loess; sandy loam; well drained
Group C	Clay loams; shallow sandy loam; low organic content; high clay content; slow draining
Group D	Soils that swell significantly when wet; heavy plastic clays; certain saline soils; very poorly drained

Soil Mechanics and Structure Soil is a porous medium. It contains voids called pore spaces between the mineral grains. Water and air can be present in these pore spaces. Pore spaces allow for the storage and passage of water through the soil profile. The *porosity* (n) of soil can be found by

$$n = 100 \frac{V_w}{V_t} \quad \text{Equation I.1}$$

in which V_w is the volume of water that is required to saturate the pore space and V_t is the total volume of soil in the specified area. Therefore, porosity is expressed as a percentage (Selker et al., 1999). Table I-4 shows the porosities of the common soil types.

Table I-4. Soil Porosities.

Soil Type	$n(\%)$
Sand	25-50
Silt	35-50
Clay	40-70

The porosity of soil depends on its bulk density. Bulk density is impacted by soil particle size and the “tightness” of their packing. Soil particles of uniform size will pack together loosely resulting in higher porosities. On the other hand, particles of varying sizes have the tendency to pack together more tightly causing soil to have a lower porosity. Therefore, soils with high bulk densities usually have lower porosities and soils with low bulk densities have higher porosities. The density of soil is often expressed as dry bulk density. An amount of soil is weighed, dried, and then weighed again to determine the density without the presence of water (Sumner, 2000). According to Sumner (2000), the dry bulk density can be calculated by Equation G.2.

$$\rho_b = \frac{\text{Mass of Solids}}{\text{Volume of Solids and Voids}} \quad \text{Equation I.2}$$

Because soil is a porous media, it is also permeable. One of the main properties of soil is *intrinsic permeability*, which refers to the ease at which water will flow through the soil’s pore spaces. For example, sand is much more permeable than clay and water will flow through sand easier than clay (Fetter, 1994). Table I-5 shows the permeability of different soil types. Intrinsic permeability affects infiltration ability of a soil. When soil is disturbed, its intrinsic permeability changes. If soil is compacted, its permeability decreases. If soil is loosened, its permeability may increase despite the decrease in porosity. The original permeability of a soil cannot be restored to its original state because the connectedness of the pore spaces is changed during disturbance (Selker et al., 1999).

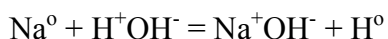
Table I-5. Ranges of Intrinsic Permeabilities for Soils and Sediments.

Material	Intrinsic Permeability (cm ²)
Clay	$10^{-15} - 10^{-12}$
Silt, sandy silts, clayey sands, till	$10^{-12} - 10^{-10}$
Silty sands, fine sands	$10^{-11} - 10^{-9}$
Well-sorted sands, glacial outwash	$10^{-9} - 10^{-7}$
Well-sorted gravel	$10^{-8} - 10^{-6}$

Soil structure is not only due to the arrangement of mineral grains, but it is mainly the result of the activity of living organisms. Soil is a living medium because of bacteria, fungi, earthworms, ants, and other insects that inhabit it. These living organisms help soil to maintain its porosity and permeability (Winegardner, 1996). One of the most common causes of compaction is the repeated movement of earth moving equipment and vehicles across the soil at a construction site. Once the soil is compacted, it cannot regain its original structure. Activities such as tilling can only recover some of the surface infiltration rate.

Interactions between Water and Soil Because of its properties, water is one of the most versatile fluids on the earth. Compared to other liquids, water has a high melting point, boiling point, heat of fusion, heat of vaporization, specific heat, dielectric constant, viscosity, and surface tension. The hydrogen and oxygen molecules in water are bonded together by Van Der Waals and covalent bonds. They tend to be attracted to neighboring water molecules because of hydrogen bonding. The density of water is normally 1.0 g/cm^3 at 5°C (40°F), but when water freezes it expands about 9% in volume and its density decreases to 0.9 g/cm^3 . However when water freezes in soil, it causes the soil to expand and the surface elevation to rise. At the opposite end of the spectrum, hydrogen bonds make it difficult for water molecules to escape into the vapor phase. It takes approximately 550 calories/gram of heat to cause vaporization at 1 atm of pressure. Less heat is required at lower pressures because there is less resistance for water molecules to overcome (Winegardner, 1996).

Water is often called the “universal solvent” for its ability to dissolve at least a small concentration of almost any chemical. The water molecule has no net charge, but the distribution of charges causes it to be dipolar. Water can dissociate into H^+ (H_3O^+) and OH^- . Many ionic substances, such as salts, are very soluble in water because they can dissociate into separate charges in a chemical reaction. The pH of pure water is 7.0 (neutral). Water has a high dielectric constant, which means that water molecules tend to surround other polar molecules and prevent some chemical reactions. Water undergoes hydrolysis with certain atoms, usually metals.



In this reaction, the metal (Na) becomes a hydroxide and the hydrogen is released as a gas. The resulting solution becomes alkaline because of the increase in OH^- concentration. While inorganic molecules are generally soluble in water, most organic compounds are only slightly soluble (Winegardner, 1996).

Because of hydrogen bonding, water molecules have the ability to resist deformation (shearing forces), measured as viscosity. High viscosity fluids flow slowly, while low viscosity fluids flow freely. Water is less viscous than oil, but it is still able to resist flow in soil. The viscosity of water is expressed as absolute viscosity and has an effect on infiltration rates. For example during a hot summer day, the rate of water infiltration will be almost twice that of a cold winter day (Winegardner, 1996; Emerson and Traver, 2008).

When water comes in contact with soil, especially clay and fine silt, it tends to rise due to capillarity. The increased molecular attraction to the soil is what allows water to exhibit surface tension. Small amounts of salts or ionic substances (electrolytes) dissolved in water increase the surface tension. In groundwater, dissolved minerals act as electrolytes, thus increasing the

surface tension of water. Conversely, small amounts of organic substances, soap, or acids will decrease the surface tension (Winegardner, 1996).

The second factor that leads to capillarity is the adhesion of water to solid surfaces. Water molecules adhere well to mineral surfaces because the minerals all contain elements or functional groups that can attract hydrogen or oxygen atoms. Because water molecules tend to adhere to mineral grains, capillary rise occurs in the vadose zone. The capillary fringe is saturated because groundwater is pulled upward into the vadose zone. The height of the capillary fringe depends on the type of soil. Finer grained soils with smaller pore spaces will have higher capillary fringes (Winegardner, 1996).

I.3 Predicting Infiltration Rates

The infiltration capacity of a soil is the maximum rate at which infiltration can occur under specific conditions of soil moisture. Therefore, infiltration capacity does not depend on soil type, but on the water content of the soil. If a soil is initially dry, the infiltration capacity will be high. In contrast, the capacity to infiltrate water will be low if the initial water content is high (Fetter, 1994). The capacity can be expressed as the depth of water that can be infiltrated per unit time. If the rainfall rate is greater than the infiltration rate, the excess rainfall that has not infiltrated will pond on the surface, drain as surface runoff, or evaporate. As water infiltrates into the soil, the infiltration capacity steadily decreases.

The models described in Table I-6 rely on the following fundamental infiltration equations. Three of the equations (Horton, Green-Ampt, and the Phi Index) are described further below since they are commonly cited in hydrology textbooks.

The infiltration capacity can be estimated by several questions, including Horton's equation. In this method, the infiltration rate f is represented by the function

$$f = f_c + (f_0 - f_c)e^{-Kt} \quad \text{Equation I.4}$$

where f_c is the infiltration capacity after a long period of continuous wetting, f_0 is the initial capacity, t is the duration of rainfall, and K is a constant that describes the decay of the capacity with time and represents the top layer of soil. This equation results in the infiltration capacity curve, which can be subtracted from the rainfall hyetograph to estimate the amount of rain that becomes runoff. Infiltration capacity is relatively high for sandy soil, compared to a much lower capacity for clayey soils (McCuen, 2004).

A second common method of calculating infiltration is the Green-Ampt Model (McCuen, 2004). In the Green-Ampt model, the total depth of infiltration, the volume of infiltration that occurs when the soil surface is saturated, and the infiltration capacity can be calculated using the Green-Ampt Model. This method derives an equation for the total depth of infiltration F which is

$$F = \frac{K_s S_w (\theta_s - \theta_i)}{i - K_s} \quad \text{Equation I.5}$$

where θ_s and θ_i = the saturated and initial volumetric water contents, respectively; S_w = the soil water suction (negative pressure) at the wetting front; i = the rainfall intensity (in/hr); and K_s = the saturated hydraulic conductivity.

The method assumes that the well defined wetting front advances at a constant rate, the volumetric water contents is constant above and below the wetting front, and the soil water

suction below the wetting front remains constant. The volume of infiltration that occurs when the soil surface is saturated F_s can be calculated by the equation:

$$F_s = \frac{S_w(\theta_s - \theta_i)}{\left(1 - \frac{i}{K_s}\right)} \quad \text{Equation I.6}$$

In addition, the infiltration capacity f can be calculated using the equation:

$$f = K_s + \frac{K_s S_w(\theta_s - \theta_i)}{F} \quad \text{Equation I.7}$$

Table I-6. Common Infiltration Modeling Equations.

Infiltration Estimation Approach	Generic Equation	Comments
Green-Ampt	$f = K_s + \frac{K_s S_w(\theta_s - \theta_i)}{F}$	Theoretically-based; uses concept of wetting front moving through soil to describe infiltration
Horton	$f = f_c + (f_0 - f_c)e^{-kt}$	Empirically based; assumes infiltration rate can be described by an exponential decay as soil become saturated
Phi-Index	$\phi = \frac{(P - Q)}{D}$	Calculates infiltration as difference between observed precipitation and runoff; constant infiltration rate over time
Philip's Equations	$f = (0.5)st^{-0.5} + A$ $F = st^{0.5} + At$	Uses a "sorptivity" concept to estimate water flow
Richards' Equation	$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K(h) \frac{\partial h}{\partial z} + 1 \right)$	Theoretically based
SCS Curve Number	$Q = \frac{(P - I_a)^2}{[(P - I_a) + S]}$	Indirect estimation of losses (including infiltration)

Notes: K_s = saturated hydraulic conductivity
 θ = soil water content (initial and saturation)
 S_w = suction pressure at the wetting front
 F = cumulative volume infiltrated
 f = infiltration rate at time t
 f_c = final infiltration rate
 f_0 = initial infiltration rate
 k = infiltration rate constant for Horton's equation
 t = time
 P = volume of precipitation
 Q = volume of runoff
 D = duration of runoff hydrograph
 s = "sorptivity" of the soil
 A = coefficient related to K_s
 $K(h)$ = hydraulic conductivity associated with initial matric potential
 I_a = initial abstraction
 S = storage constant for a watershed that describes how much precipitation does not become runoff)

The movement of water through the vadose zone is referred to as unsaturated flow. Infiltration, which is due to gravity, is the beginning of water flow in the vadose zone. Just like infiltration, unsaturated flow depends on the amount of soil moisture that is initially present. Unsaturated flow can be expressed in terms of gravity potential Z and moisture potential ψ . *Gravity potential* is the vertical distance that water must travel to reach saturated soil. The *moisture potential* is the tension on water in the pore spaces due to its attraction to soil particles. When the soil is very dry, moisture potential is high. Depending on soil-moisture content, either the gravity potential or moisture potential may predominate. The potential for water to flow in the vadose zone can be calculated as total potential ϕ by the equation:

$$\phi = \psi(\theta_v) + Z \quad \text{Equation I.8}$$

where θ_v is the volumetric water content of the soil (Fetter, 1994).

It has also been found that Darcy's law is valid for unsaturated flow. Darcy's law, which will be discussed later in more detail, was developed initially to describe water flow in saturated soil. For saturated flow, Darcy's law includes the saturated hydraulic conductivity K , which is a constant. *Hydraulic conductivity* refers to the rate at which water can move through a porous medium. The unsaturated hydraulic conductivity is affected by amount of soil moisture. Because the amount of water in the soil fluctuates, the unsaturated hydraulic conductivity $K\theta_v$ is not a constant when applied to Darcy's law for unsaturated soil. The volumetric water content of the soil θ_v allows the fluctuation in soil water to be accounted for in the Darcy's law equation:

$$Q = -(K\theta_v)A \left(\frac{dh}{dL} \right) \quad \text{Equation I.9}$$

Where Q = the discharge rate of groundwater flow (m^3/sec); $K\theta_v$ = the unsaturated hydraulic conductivity (m/sec or cm/sec); A = the cross sectional area of flow (m^2); dh/dL = the hydraulic gradient ($(h_2 - h_1)/L$) where L is the distance between h_1 and h_2 .

Despite the validity of Darcy's law in the vadose zone, it may not apply to all unsaturated flow conditions. Because water flow in soil is actually very complex it is still not fully understood as to when non-Darcy flow exists. Therefore predictions of water flow in the vadose zone using Darcy's law may be quite poor in areas where the hydraulic conductivity does not vary with the volumetric water content. Caution should be exercised when applying Darcy's law to soils with low permeability, such as clays (Tindall and Kunkel, 1999). Even though much is known about water flow through soil, the vadose zone continues to be the subject of ongoing research so that the all of its processes can be better understood.

I.4 Groundwater Movement

The Saturated Zone As mentioned earlier, the saturated zone consists of rock and soil layers that allow for the storage and flow of groundwater. Therefore, an aquifer is defined as a geologic unit that can store and transmit water at various rates depending on the type geologic material. Unconsolidated sands and gravels, sandstone, limestone, dolomite, and fractured igneous and metamorphic rocks are examples of geologic units that have been known to be aquifers (Fetter, 1994). There are three main types of aquifers: unconfined, confined, and perched.

An *unconfined* aquifer is also known as a water table aquifer because the top layer forms the water table. Water that infiltrates through the vadose zone will be able to recharge an

unconfined aquifer at a fairly rapid rate (Fetter, 1994). This type of aquifer can vary in thickness and will have a confining layer as the lower boundary.

A confining layer is a geologic unit that has an extremely low permeability. Most common confining layers are clays, shales, and dense igneous rocks (Freeze and Cherry, 1979). A confining layer greatly reduces the vertical flow of water in an unconfined aquifer. Groundwater will move through most confining layers, but at a very slow rate (Fetter, 1994). Confining layers can form the upper and lower boundary of an aquifer. This type of aquifer is known as a *confined* aquifer. The water in a confined aquifer is under pressure. Recharge of confined aquifers is can be very slow because of the low permeability of the upper confining layer. Confined aquifers are deep water bearing units that eventually become exposed at the ground surface. These exposed areas allow infiltrating surface water to recharge confined aquifers (Fetter, 1994).

Sometimes there are low-permeability layers in the vadose zone. Infiltrating water will accumulate on top of this layer. A pocket of saturated soil will form above the water table creating a *perched* aquifer. Water will eventually seep around the low-permeability layer, downward towards the water table. If the perched aquifer is close enough to the ground surface, water may discharge at the surface as a spring. Perched aquifers are usually small and are common in glacial outwash and volcanic terrains. Clay or silt will form a confining layer within the permeable glacial or volcanic material in the vadose zone, slowing the infiltrating water, and allowing the accumulation of perched groundwater (Fetter, 1994).

Aquifer Properties Even though an aquifer is generally defined as unconfined, confined, or perched, they can be more uniquely characterized by specific properties. All aquifers are characterized by the same properties, but the values of these properties can be and usually are different for each individual aquifer. The way that water flows through an aquifer depends on the values of its properties. Porosity and bulk density are important aquifer properties. They are defined based on the porosity of the aquifer media.

Effective porosity is another term used to express porosity. This is the porosity available that will allow groundwater flow. In addition, porosity can be calculated as total porosity by the equation

$$n = 100 \left[1 - \left(\frac{\rho_b}{\rho_d} \right) \right] \quad \text{Equation I.11}$$

where n = the total porosity as a percentage; ρ_b = the bulk density of the aquifer material (M/L^3 ; g/cm^3 or kg/m^3); ρ_d = the particle density of the aquifer material (M/L^3 ; g/cm^3 or kg/m^3).

Clays and organic rich soils have higher porosities than sands and gravels. This is partly because organic materials do not pack very closely due to their irregular shapes. Sands and gravels tend to pack together more tightly, creating less pore space between the grains. Clay minerals have electrostatic charges that cause the clay particles to be repelled by each other. This allows for more pore space. Rocks on the other hand are more compacted and have lower porosities. However, fractures in rocks will raise their porosity (Fetter, 1994).

All porous media is permeable to water, but not all porous media has the same *permeability*. Grain size and shape affects permeability and the direction in which infiltrating

water will travel through the porous media. Sediments with larger grain sizes have higher permeabilities. The shape of the grains will also influence permeability.

The aquifer media *hydraulic conductivity* refers to the rate at which water can move through a porous medium. Just because the geologic material in an aquifer has a high porosity, it does not mean that groundwater will flow at a high rate. Pore spaces need to be connected in order for hydraulic conductivity to be high enough to allow groundwater flow. Clay has a high porosity, but a low hydraulic conductivity because the pore spaces are not well connected. The layered structure of clay particles causes the pore spaces to be poorly connected. In contrast, groundwater flows at a higher rate through sands and gravels because the pore spaces are well connected. Hydraulic conductivity can be represented by the coefficient (K), which has the units of length divided by time, which is calculated using Equation I.12.

$$K = -\frac{Q}{A} \left(\frac{dh}{dL} \right) \quad \text{Equation I.12}$$

Where Q = groundwater discharge rate from a saturated geologic unit; A = area of flow; and (dh/dL) is the hydraulic gradient. The *hydraulic gradient* refers to the likelihood that water will flow between two points in an aquifer. It can also be explained as the change in *hydraulic head* between two points.

Aquifers can be either homogeneous or heterogeneous in nature. A *homogeneous* aquifer will have the same major properties at all locations. Hydrogeologists consider porosity, hydraulic conductivity, transmissivity, storativity, specific storage, and thickness to be the major properties of an aquifer. These properties determine the behavior of water in a saturated geologic unit. If an aquifer has different properties, then it is considered to be *heterogeneous*. In some cases, the individual layers of an aquifer are homogeneous, but the entire aquifer is still heterogeneous (Fetter, 1994).

Principles of Groundwater Flow The density, viscosity, and compressibility of water are functions of temperature and pressure. However, they can be considered constants in groundwater flow calculations because the range of temperatures and pressures that occur in groundwater do not change very much. At 15.5°C, $\rho = 1.0 \text{ g/cm}^3$, $\mu = 1.124 \text{ cP}$, and $\beta = 4.4 \times 10^{-10} \text{ m}^2/\text{N}$ (Freeze and Cherry, 1979).

In 1856, a French hydraulic engineer named Henry Darcy published his report on the water supply under the city of Dijon, France. In that report, Darcy described a laboratory experiment he performed to study the flow of water through sand. The main component of the experiment was an apparatus built by Darcy. Figure I-2 shows the apparatus.

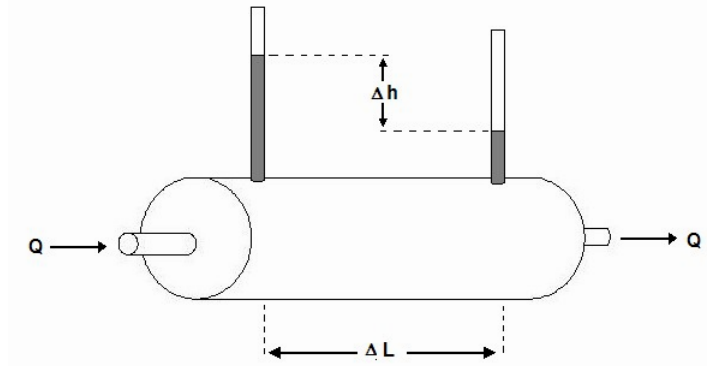


Figure I-2. Experimental Apparatus to Illustrate Darcy's Law.

The main body of the apparatus is filled with sand. Q is the flow rate of water. Two manometers to measure the hydraulic head protrude out the top of the cylinder. Darcy studied the flow of water through the sand in the cylinder to understand the way that groundwater flows through an aquifer. Results of the experiment were generalized into a mathematical form called Darcy's law (Freeze and Cherry, 1979). Darcy's law is expressed as:

$$Q = -KA \left(\frac{dh}{dL} \right) \quad \text{Equation I.13}$$

Where Q = the discharge rate of groundwater flow (m^3/sec); K = the hydraulic conductivity (m/sec or cm/sec); A = the cross sectional area of flow (m^2); dh/dL = the hydraulic gradient ($(h_2 - h_1)/L$) where L is the distance between h_1 and h_2 .

Darcy's law has an upper and lower limit. The validity of Darcy's law is still in question for flow through low-permeability sediments under very low hydraulic gradients. There is still no agreement on the lower limit of flow (Freeze and Cherry, 1979). Freeze and Cherry (1979) also cite the work of Todd (1959) and Bear (1972) that shows the breakdown of Darcy's law at very high flow rates. In addition, Fetter (1994) uses Linquist (1933) and Rose (1945a,b) to show that the validity of Darcy's law can be defined by the Reynolds number for flow through porous media. The Reynolds number is a dimensionless number that expresses the ratio of inertial to viscous forces during flow:

$$\text{Re} = \frac{\rho v d}{\mu} \quad \text{Equation I.14}$$

In this equation, ρ is the fluid density, v is the specific discharge, d is the length dimension for the porous medium, and μ is the fluid viscosity (Freeze and Cherry, 1979). The Reynolds number needs to be less than 1 to 10 for Darcy's law to be valid, a slow moving groundwater. Therefore, the upper limit is a much greater limiting factor than the lower limit. Under most natural conditions, the velocity is such that Darcy's law is valid (Fetter, 1994).

Groundwater Flow Systems In addition to flowing at different rates and directions, groundwater also has very unique flow lengths. For example, groundwater can flow short distances and then come to the surface as a spring, or it can flow very long distances before coming to the surface.

Three types of groundwater flow systems usually exist at any given time within a region. The first is a *local flow system*. In this type of flow system, infiltrating water will only flow a short distance before reaching a discharge area. At the same time, some of the infiltrating water will flow a little further before discharging. This type of flow system is called an *intermediate flow system*. In some cases, there may be a recharge area that allows water to infiltrate into an aquifer that extends for a long distance in the subsurface. These conditions are an indication that a *regional flow system* exists. Regional flow systems extend deep into the subsurface, while local flow systems tend to be shallow in nature. Because of their shallow nature, local flow systems involve unconfined, water table aquifers. In contrast, deep, confined aquifers are the basis for regional flow systems (Fetter, 1994). Figure I-3 illustrates the orientation of these three flow systems.

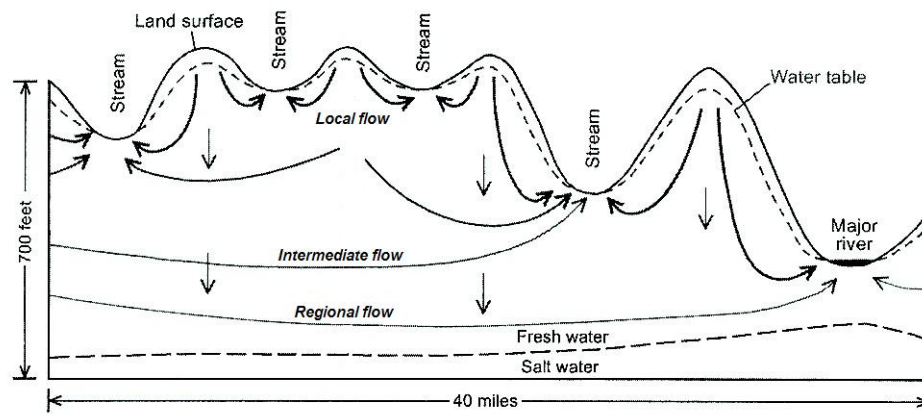


Figure I-3. Types of Flow Systems. (U.S. EPA)

Another factor that affects groundwater flow is topography. It is assumed that the water table closely follows the contour of the ground surface. Therefore, one could conceivably predict the type of flow system by looking at the topography of a region. For example, a region with hilly terrain will be dominated by a local flow system, whereas a region with a relatively flat ground surface will most likely be dominated by regional flow. This principle generally holds true for the United States. However, one should be cautious not to rely solely on the topography to predict groundwater flow. The subsurface is a complex environment that has been known to produce very abnormal flow patterns.

Groundwater Recharge As mentioned earlier, groundwater is recharged, replenished, by precipitation that infiltrates through the vadose zone. Therefore, recharging the groundwater in developed areas through the use of stormwater infiltration practices is a good way to maintain a good water balance in any given watershed. There are two ways that groundwater recharge can occur. It can happen naturally or it can be induced artificially. Up to this point, all the discussion involving infiltration has actually been about natural infiltration. Precipitation will naturally infiltrate in areas covered by grass, uncompacted soil, gravel, mulch, and other vegetative covers. According to Jocson et al. (2002), natural recharge depends on the type of subsurface materials and rainfall type. In addition, Jocson et al. (2002) observed that recharge rates were lower with very high and very light rainfall intensities. Very high rainfall intensities cause more runoff and less infiltration while light rainfall is usually lost to evapotranspiration. They concluded that

moderate rainfall intensities are the best for rapid groundwater recharge. Because stormwater often contains pollutants such as nutrients, pesticides, herbicides, metals, chlorides, and organic compounds, the potential for contamination of shallow groundwater always exists. Johnson et al. (2001) showed that the herbicides isoproturon and chlorotoluron could persist in the soil for three years. Because of this, the quality of the stormwater should be evaluated before it is infiltrated (Pitt et al., 1996).

Artificial groundwater recharge is not a new concept. For example, Detay and Haeffner (1997) report that France has been using artificial recharge techniques for more than 35 years. Increased groundwater usage and land development caused a decline in groundwater levels. To combat this problem, artificial infiltration basins were built around the cities of Flins-Aubergenville and Croissy-sur-Seine to promote rapid groundwater recharge. Seine River water was pumped, treated and discharged into the infiltration basins. Detay and Haeffner (1997) concluded that artificial recharge is an effective tool in groundwater management. Also, the treatment processes and innovative basin designs create very pure groundwater.

A similar situation arose in Nassau County, Long Island, New York. Infiltration basins were installed throughout the county to increase groundwater recharge. The results were positive for stormwater runoff control and groundwater management. The groundwater table rose as much as five feet in developed areas and declined about three feet in areas where stormwater was discharged into streams and tidewater (Ku et al., 1992).

In Nebraska, Ma and Spalding (1997) reported that the water table below infiltration basins rose rapidly. However, infiltration rates began to decline over time because of clogging. Sediment and microbial biofilms were responsible for the clogging of the basins. In order to fix this problem, a pulsed recharge method was used to create dry and wet conditions. This maintained low standing water levels in the basins which reduced microbial growth and therefore increased infiltration. In addition to clogging, the pesticide atrazine was also a problem for artificial recharge in Nebraska. This was addressed through diluting the runoff with Platte River water. It was documented that nitrate levels decreased down gradient from the infiltration basins.

One major disadvantage of artificial recharge is the formation of groundwater mounds beneath infiltration basins. Groundwater mounds form when infiltrating water collects on top of less permeable soil layers, and is similar to perched aquifer formation. If groundwater mounds continue to grow, the vadose zone will become waterlogged and basement flooding could occur (Bouwer et al., 1999). Also, soil stability and strength will be compromised. According to Gobel et al. (2004), high infiltration rates are to blame for groundwater mounding. Therefore, it is very important to properly investigate the subsurface beneath infiltration basins. Bouwer et al. state that sands and gravels are generally best for artificial recharge, but finer soils can be used as long as they are amended to promote better infiltration (Bouwer et al., 1999).

Besides groundwater mounding, the potential for groundwater contamination also exists during artificial recharge. This potential is highest in areas where the water table is shallow. In some cases the contamination potential was proven to be a reality. For example, Barraud et al. (1999) studied the impact of intentional stormwater infiltration on soil and groundwater. They analyzed contaminants found beneath a recently constructed infiltration basin and one that was 30 years old. They found low concentrations of heavy metals in the groundwater beneath both basins and that these metals had migrated further beneath the older basin. Fischer et al. (2003) also showed that groundwater contamination can occur through the use of infiltration basins.

They compared background samples, groundwater samples collected away from the basin, to samples from beneath the basin. Their results suggested that high infiltration rates tend to increase concentrations of contaminants commonly found in stormwater and dilute contaminant concentrations found in background groundwater. Even though it was difficult to determine actual contaminant levels in background groundwater, this study clearly showed the increased groundwater contamination beneath an infiltration basin.

In addition, the potential for groundwater contamination was substantiated even further by Datry et al. (2003). They did laboratory experiments and computer modeling to determine the likelihood that sediments retained by infiltration basins are a potential source of dissolved contaminants. Their research showed that heavy metals and hydrocarbons were retained in the bed sediments of the basin while dissolved organic compounds (DOC), phosphates, and ammonium were found in water directly beneath the basin. It was concluded that there was no evidence suggesting that groundwater contamination occurred, only that the potential for contamination did exist.

After reviewing some of the important stormwater infiltration research, it is clear that artificial recharge has its advantages and disadvantages. Even though disadvantages exist, they can be lessened by making wise decisions. Groundwater mounds can be avoided by doing thorough subsurface investigations before infiltration basins are constructed and the potential for groundwater contamination can be decreased by limiting the amount and monitoring the quality of stormwater that enters infiltration basins. Nevertheless, each situation involving the infiltration of stormwater should be properly evaluated to ensure that groundwater quality is preserved.

Challenges of Karst Terrain. As mentioned in Chapter 7.0, karst geology poses its own risks for infiltration. Table I-7 describes the regulatory environment for infiltration in karst.

Table I-7. Regulations Relating to Infiltration in Karst Geology.

Regulating Authority	Regulatory Guidelines
Alabama	Areas prone to sinkhole development should be avoided in locating impoundments. Where impoundments must be constructed in areas prone to karst on other hazardous geologic environments, extra engineering design must be used to mitigate potential releases or failures; http://www.adem.state.al.us/_vti_script/search.htm0.idq No fueling, servicing, maintenance, or repair of equipment or machinery should be done within 50 feet of a stream, or within 100 feet of a stream classified for public water supply (PWS) or Outstanding Alabama Water (OAW), or designated as an Outstanding National Resource Water (ONRW), or a sinkhole. http://www.adem.state.al.us/_vti_script/search.htm0.idq
Georgia	Karst terrain can limit the use of some structural controls as the infiltration of polluted waters directly into underground streams found in karst areas may be prohibited. In addition, ponding areas may not reliably hold water in karst areas. http://www.georgiastormwater.com/vol2/3-1.pdf
Hawaii	Pond liners should be used in areas of karst topography, gravelly sands or fractured bedrock. http://www.stormwaterhawaii.com/pdfs/PermanentManual.pdf
Illinois	Improved sinkholes considered Class V Injection Wells. http://www.epa.state.il.us/land/regulatory-programs/permits-and-management/forms/class-v-well-types.pdf
Indiana	Measures should be used to reduce concentration of runoff. Storm water conveyance structures should allow increased infiltration and reduce pollutants generated. Investigate areas underlain by carbonate rock to identify sink holes. Where feasible, direct storm water runoff 1000 feet or more away from the edge of existing sinkholes and if possible, discharge it to an area that is not underlain by limestone bedrock. http://www.in.gov/idem/files/chap4.pdf
Kansas	Contaminated Runoff discharged to sinkhole considered Class I Disposal Well. http://www.kdheks.gov/uic/download/Class_I_Overview_Report.pdf

Regulating Authority	Regulatory Guidelines
Bowling Green, KY	Avoid; Prohibit Infiltration http://www.bgky.org/stormwater/pdf/bmp/Manualref.pdf
Lexington, KY	Development may occur in the immediate sinkhole drainage area if the developer provides alternative surface drainage away from the sinkhole, while keeping the water in the same surface drainage basin, and provided that the water shall not go into another sinkhole drainage area, nor into another stream of known flooding problems. The immediate sinkhole drainage system area (or portion thereof) which cannot have an alternative drainage system can be deleted from the development area and can be used to meet the normal open space requirements. The developer may request an increase in the density of the developable area, with the total resulting density no greater than if the entire area were developed to the permitted density. For portions of the immediate sinkhole drainage area where alternative surface drainage methods cannot be provided, the developer may choose one of the options described below. Section 4 Sinkhole Surface Drainage Analyses. The sinkhole can be used for surface runoff drainage of a proposed development if the conditions of either of the following alternatives are met: A. Alternative 1: A sinkhole can be used for surface runoff with or without retention or detention facilities, provided that any increase in the quantity of surface runoff due to development of the entire sinkhole drainage area in question will not aggravate flooding on the proposed development, adjacent existing development, or connected/adjacent sinkhole sub- surface systems. B. Alternative 2: A sinkhole can be used for surface drainage of a proposed development if all of the following conditions and provisions are met: 1. Runoff from the development area is either completely retained in a retention basin or detained in a detention basin. The flow rate out of the basin shall be no greater than the flow rate into the sinkhole of the development area prior to development of each of the following storms: 10 year/1-hour, 25year/24-hour storm or a 100 year/1-hour storm. The outflow rate shall not aggravate flooding on downstream properties for any of these storms. 2. The developer may elect to divert enough of the sinkhole drainage area so that the remaining area does not increase the total quality of the runoff into the sinkhole. 3. Where the sinkhole outlet is offsite, either the runoff leaving the subject property must be shown to be no greater in flow or in quantity than that which existed before development or written approvals must be submitted from owners of property where any increase in flow or quantity of water must go to reach the sinkhole outlet. http://www.stormwatercenter.net/Model%20Ordinances/Source_Water_Protection/Kentucky%20Sinkhole%20Ordinance.htm
Maine	Stormwater discharges to sinkholes are considered Class V injection wells. http://www.maine.gov/dep/blwq/docstand/uic/uichome.htm
Maryland	In general, stormwater runoff should not be concentrated and should be conveyed through vegetated areas; in addition, the facilities should be designed in accordance with the following standards: (1) Detention/retention ponds should be designed with a synthetic or clay liner. (2) Discharges from stormwater management facilities or from impervious surfaces should not be routed within 1000 feet of any existing unremediated sinkhole. (3) Sinkholes occurring within stormwater management structures should be repaired within 72 hours. (4) Liners: If natural soil permeabilities are $> 10^{-6}$ cm/sec (1.4×10^{-3} in/hr) for the two-foot interval below the depth of the proposed facility, a stable, low permeability liner shall be installed as follows: (a) One foot of clay with a permeability less than 10^{-7} cm/sec, or; (b) Two feet of clay with a permeability less than 10^{-6} cm/sec, or; (c) Two feet of compacted soil with a permeability less than 10^{-5} cm/sec plus a 30 mil thick artificial liner with a permeability less than 10^{-7} cm/sec, or; (d) A very low permeability base constructed of concrete. http://www.mde.state.md.us/assets/document/sedimentstormwater/Appnd_D2.pdf

Regulating Authority	Regulatory Guidelines
Massachusetts	Stormwater discharges to sinkholes are considered Class V injection wells. http://www.mass.gov/dep/water/approvals/ws06abc.pdf
Pennsylvania	Infiltration in karst topography is "recommended, but may not be feasible in all areas". The following basic principles must be considered in karst areas: • An initial site assessment that includes, but is not be limited to, the following: ○ Aerial photographs, geologic literature, sinkhole maps, borings (if available), existing well data, and municipal wellhead or aquifer protection plans. ○ Site reconnaissance, including a thorough field examination for features such as limestone pinnacles, sinkholes, closed depressions, fracture traces, faults, springs and seeps. ○ Drilling of boreholes. ○ Determination of groundwater elevations, especially with respect to the bedrock surface, and flow direction. To assess seasonal changes, it is necessary to obtain groundwater measurements over several months to a year. ○ Geophysical surveys to locate subsurface anomalies. • Observe the site under different weather conditions especially during heavy rain events and through different seasons. Identify and map the natural drainage ways. • A site design should be supported by a geotechnical or hydrogeologic report and should include: ○ Site reconnaissance discussion. ○ Identification and mapping of karst features and hydrogeologic conditions of the site. ○ Identification and mapping of existing drainage patterns and features. ○ Discussion of groundwater hydrology. ○ Survey of soil characteristics and thickness, plus an analysis of the site's infiltration capability. ○ A discussion of how infiltration will be handled to avoid contamination of the groundwater aquifer. ○ A plan view of the site, noting the locations of important features. This plan should delineate areas available for infiltration, areas not suitable for infiltration and areas where development should not occur. ○ A contingency plan if unexpected conditions or unmapped karst features are encountered. • Maintain the natural water balance for surfaces flows and groundwater recharge. Use these pre-development drainage ways to the maximum extent possible. • Maintain groundwater levels and hydrostatic pressure to the maximum extent possible – avoid large withdrawals, elimination of recharge areas or concentrated injection. • Establish a buffer zone around karst features that are not used for infiltration. Establish filter berms (with gabions or vegetation, for example), etc., to prevent contamination. (McCann & Smoot, 1999) • Designate aquifer recharge areas. Promote safe infiltration. Direct recharge into groundwater aquifers without proper infiltration of sediments and pollutants is prohibited. Improved sinkholes may be utilized as injection wells, but must be properly constructed. EPA categorizes these structures as Class 5 Underground Injection Wells. • Replicate natural hydrologic loading rates as much as possible. Minimize impervious surfaces. Drastically increasing or decreasing the loading rate may promote or accelerate sinkhole development. • Employ methods to reduce runoff volumes and velocity. • Implement numerous infiltration BMPs throughout the site instead of just one. • Stormwater should not be conveyed into concentrated runoff flow paths. • Impounded water causes soil saturation and loss of cohesion. Differences in hydraulic head and steep hydraulic gradients can result in sinkhole development. • Seal all exploratory boreholes to eliminate surface water entry. • Minimize earth disturbance when installing stormwater structures. • BMPs need to be inspected, cleaned, maintained, and possibly repaired. • Pay specific attention to the integrity of piping of all types. • All stormwater management designs for karst areas must include details for sinkhole repair during and after construction. http://www.depweb.state.pa.us/watershedmgmt/cwp/view.asp?a=1437&q=529063&watershedmgmtNav=

Regulating Authority	Regulatory Guidelines
City of Knoxville, TN	Areas containing karst topography and sinkholes may initially appear to have excellent infiltration, but should be considered as unreliable and will require very careful investigation and analysis. Natural sinkholes (or other evidences of karst topography and drainage) are not considered to be infiltration systems for use in treating stormwater quality or in providing stormwater detention. In general, stormwater drainage may continue to flow to a natural sinkhole at a rate that is representative of natural undeveloped conditions. For natural depressions and sinkholes, it is generally required that the postdeveloped peak flows and total stormwater runoff volume must be limited to the predeveloped values. The City of Knoxville also requires that any development near a sinkhole should include calculations demonstrating that no structures will be flooded from a 100-year storm assuming plugged conditions (zero outflow). http://www.ci.knoxville.tn.us/engineering/bmp_manual/knoxvilleBMP.pdf
West Virginia	The Groundwater Program requires any structure with a direct connection to ground water such as stormwater ponds, constructed wetlands, sinkholes, improved sinkholes, and infiltration trenches to obtain an Underground Injection Control Permit. All such structures should have a Groundwater Protection Plan even if they do not require an Underground Injection Control Permit. In addition, WVDEP would like all ponds to have a semi-permeable layer that allows for some attenuation of pollutants before the stormwater becomes ground water. http://www.wvca.us/flood/pdf/16_Appendix_J_Stormwater_Management.pdf

Several groups of researchers have been investigating the potential for infiltrating stormwater into karst. Examples include Hyland et al. (2006), who analyzed sinkhole susceptibility in the northern Shenandoah Valley after low impact development and infiltration practices were installed. Barner and Miller (1992) present several case studies on stormwater management in urban areas with karst terrain. Thomas Schueler of the Chesapeake Stormwater Network has developed guidance for infiltration in karst terrain and has posted it on the website www.chesapeakestormwater.net.

Preferential Flow Path and Impacts on Stormwater Infiltration Design. Karst terrain and soil aquifer heterogeneities between abutting materials have been documented as having preferential flow paths. Ives (1989) in an older filtration study used endoscopes to record the preferential flow paths in a sand filter. Clark et al. (1992) recommended that wall effects could cause a substantial amount of flow to bypass the filter/soil media in a column if the ratio of the column size to grain size was less than 40.

Preferential flow paths and the resultant short-circuiting of the treatment process has to be considered in the siting of an infiltration devices. When the vadose zone is saturated, these preferential flow paths have very high hydraulic conductivity and may transport pollutants rapidly to the groundwater. When the vadose zone is unsaturated, the capillary tension between the heterogeneous layers may be a barrier to flow and may cause one region to remain saturated longer than predicted. Goutaland et al. (2007a,b) highlight two methods, ground penetrating radar (GPR) and electrical resistivity, that could be used in combination to map the subsurface and identify where the preferential flow paths are likely to occur.

APPENDIX J

CASE STUDIES OF INFILTRATION

J.1 Field Infiltration Devices Treating Urban Stormwater Runoff

The historic case studies of stormwater infiltration focused primarily on characterizing the water quality below infiltration basins and providing fundamental descriptions of the soil based on physical characteristics, such as soil texture. Several historical and current field studies are summarized below. Additional studies have been performed on the infiltration of reclaimed water. Those studies (such as Bouwer et al. 1984; Bouwer, 1985, 1987; Crites, 1985; Schneider et al. 1987; Lloyd et al. 1988; Ehrlich et al. 1979a,b; Martin and Mohler, 1988; and the summary in Andleman et al. 1994), while not focusing on stormwater, also may provide indications as to the pollutant removal potential of vadose zone soils.

Case Study #1: Water Quality below Stormwater Infiltration Basins in Long Island, NY (Ku and Simmons, 1985)

To determine whether urban stormwater infiltration posed a threat to groundwater quality, forty-six storms were monitored at five recharge basins in different land-use areas (strip commercial, shopping-mall parking lot, major highway, low-density residential, and medium-density residential). The results for selected U.S. EPA priority pollutants in both the stormwater and groundwater are shown in Figure J-1. The indicator bacteria concentrations (fecal coliforms, fecal streptococci and total coliforms) also were monitored.

With the exception of the medium density residential site and lead, the soils were able to remove the pollutants. For chloride and total nitrogen, lags were seen between the high stormwater concentrations and the groundwater concentrations (time series data not shown). In terms of median concentrations over the monitoring period at each basin, the results were inconsistent. This may be an artifact of the lack of groundwater data during a few storm events for these parameters (typically six to ten storms for each site). For the indicator bacteria, stormwater median concentrations ranged from 10^8 to 10^{10} MPN/100 mL. No indicator bacteria were detected in the groundwater beneath any of the recharge basins.

Case Study #2: Water and Soil Quality below Wet and Dry Swales in Orlando, FL (Harper, 1988)

This case study monitored the pollutant treatment ability of a wet swale and a dry swale, each draining freeway runoff, in the Orlando metropolitan area (Florida). The wet swale was constructed in 1965 and the dry swale in 1972. The longitudinal slope in the wet swale is 0.23%, and in the dry swale, 0.45%. Surface water samples also were measured along each of the swales. For the wet swale, decreases in surface water concentration were noted for all metals, except iron, with the greatest decreases noted for zinc, aluminum and lead. For the dry swale, an increase in surface water concentration was seen for aluminum. A comparison of surface water to groundwater concentration for the metals shows that the swale soils are treating the total concentration of the metals, but that copper, aluminum and zinc have higher concentrations of dissolved metals in the groundwater at all sites measured than the swale water. This may be a

result of soil mineral dissolution or may indicate another source of these metals to the groundwater system. In comparison, the dry swale system soils removed all the metals measured except nickel and chromium. Dissolved manganese, aluminum, iron, nickel and chromium concentrations were greater in the groundwater at all measured sites than in the surface water.

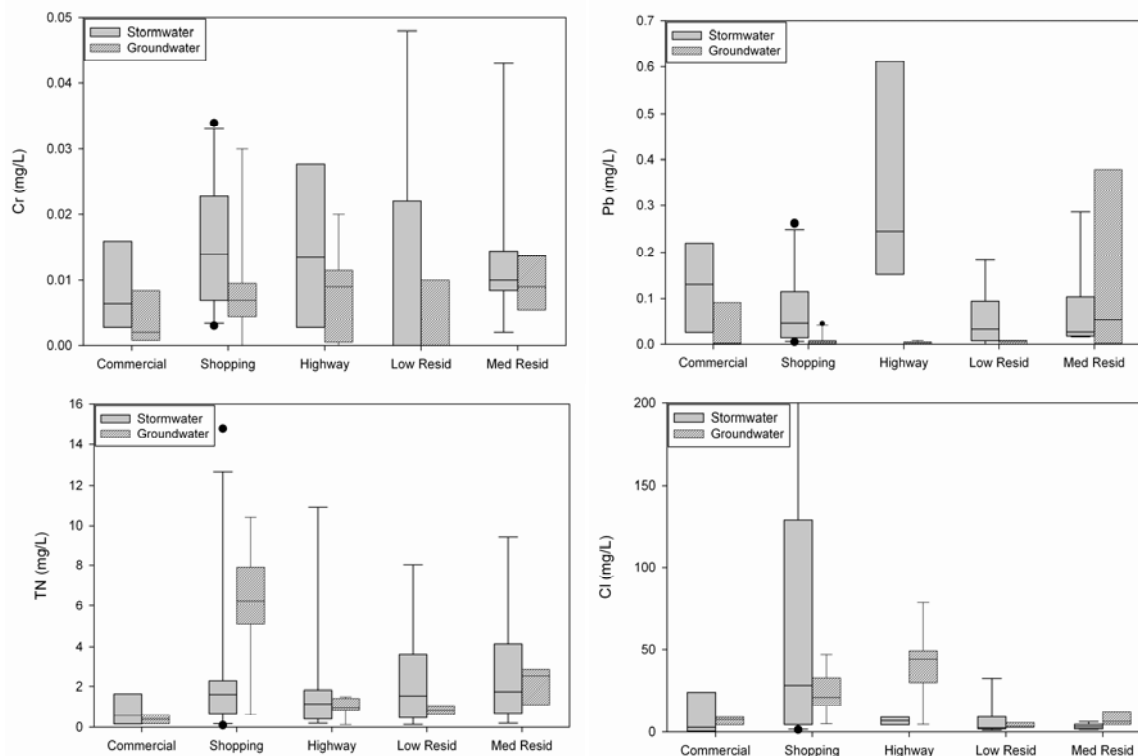


Figure J-1. Effects of Stormwater Infiltration on Groundwater Quality (adapted from Ku and Simmons, 1985).

Soil accumulations also were monitored and the results for representative nutrients and metals is shown in Figures J-2 and J-3. The results for the nutrients show accumulation of the nutrients in the top layer of the wet swale, but release of nutrients in the top layer of the dry swale. For nitrogen, the loss in the top layer may be a result of the leaching and downward migration of nitrogen into the lower layers, where it is trapped until it is flushed downward. For copper, lead and zinc, the upper layer of the soil showed a slight accumulation in the wet swale. For the dry swale, the accumulations were substantial in the top 10 cm, and not just the top 0-2 cm. Accumulation of aluminum also was seen in the dry swale, but the wet swale showed a slight release in the upper 5 cm with a resultant downward migration and accumulation in the 15-25 cm layer. This indicates that aluminum may be more mobile than the other metals in the likely saturated environment of the soils below the wet swale. Although it was not measured directly, it is likely that the soil water below the wet swale was a reducing environment, which converted aluminum to a more mobile species.

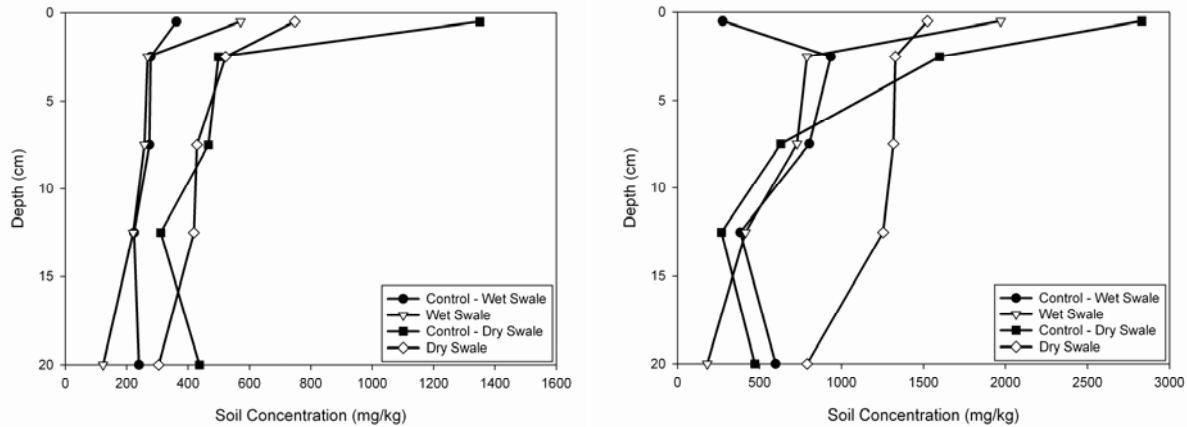


Figure J-2. Soil Accumulation of Nutrients. Left: Phosphorus; Right: Nitrogen (adapted from Harper, 1988).

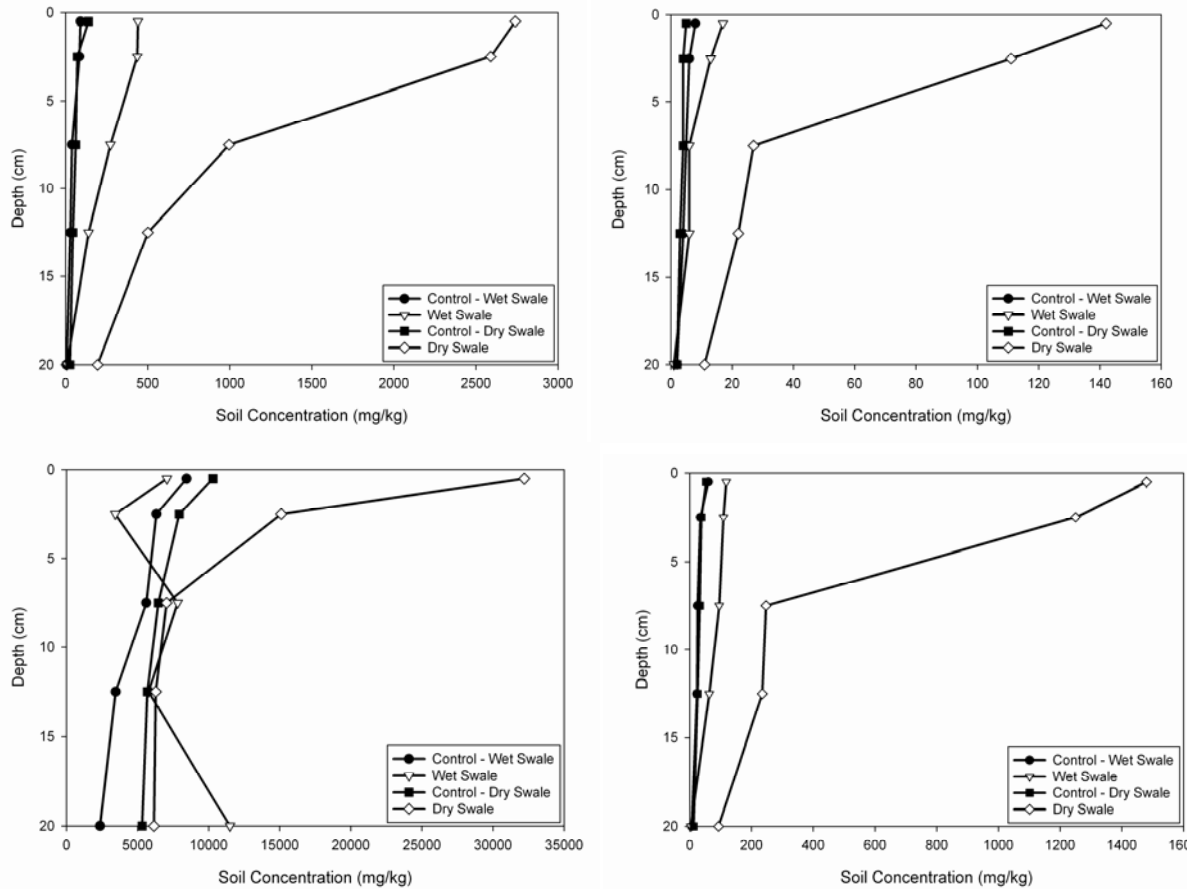


Figure J-3. Soil Accumulation of Metals. Top Left: Lead; Top Right: Copper; Bottom Left: Aluminum; Bottom Right: Zinc (adapted from Harper, 1988).

Case Study #3: Centre Routier in Lyon, France – Soil Accumulation over twenty-plus years of operation (Dechesne et al., 2004; Barraud, et al., 2005; Le Coustumer et al., 2007)

Soil samples were collected at ten locations throughout this infiltration basin. The soil was separated into depth profiles with each depth interval analyzed individually. These soil analyses allowed for comparisons of pollutant accumulation by depth and location in the basin

(Figures J-4 through J-7). The general results showed that the highest concentrations of many pollutants were found in the soils near the lowest elevation in the infiltration basin (area 7), likely because of the extended (comparatively) water ponding in that part of the basin. The other area of contamination was near the inlet (area 2). In addition, the buildup of runoff sediment was very visible and was also seen by the significant difference in the particle size distribution in the near surface soils compared to the three other soil depths analyzed.

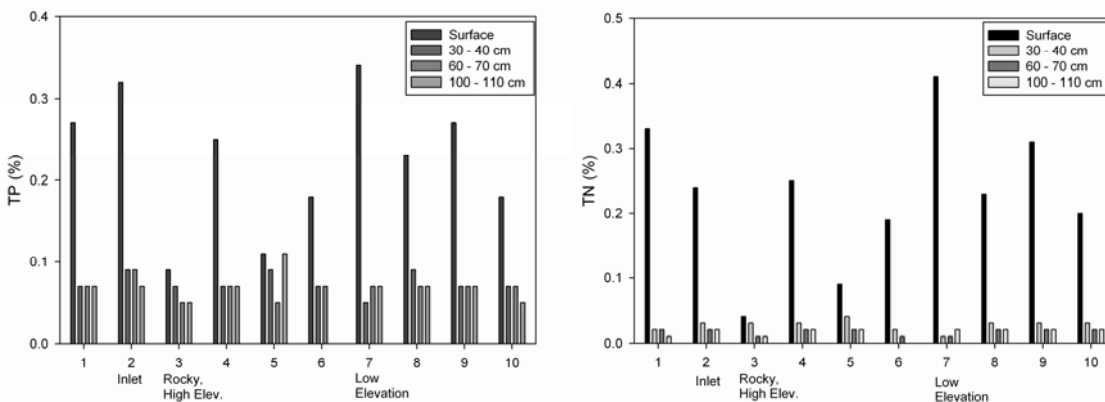


Figure J-4. Nutrient Concentration by Soil Depth beneath a 20+-year old Infiltration Basin
(adapted from Dechesne et al., 2004).

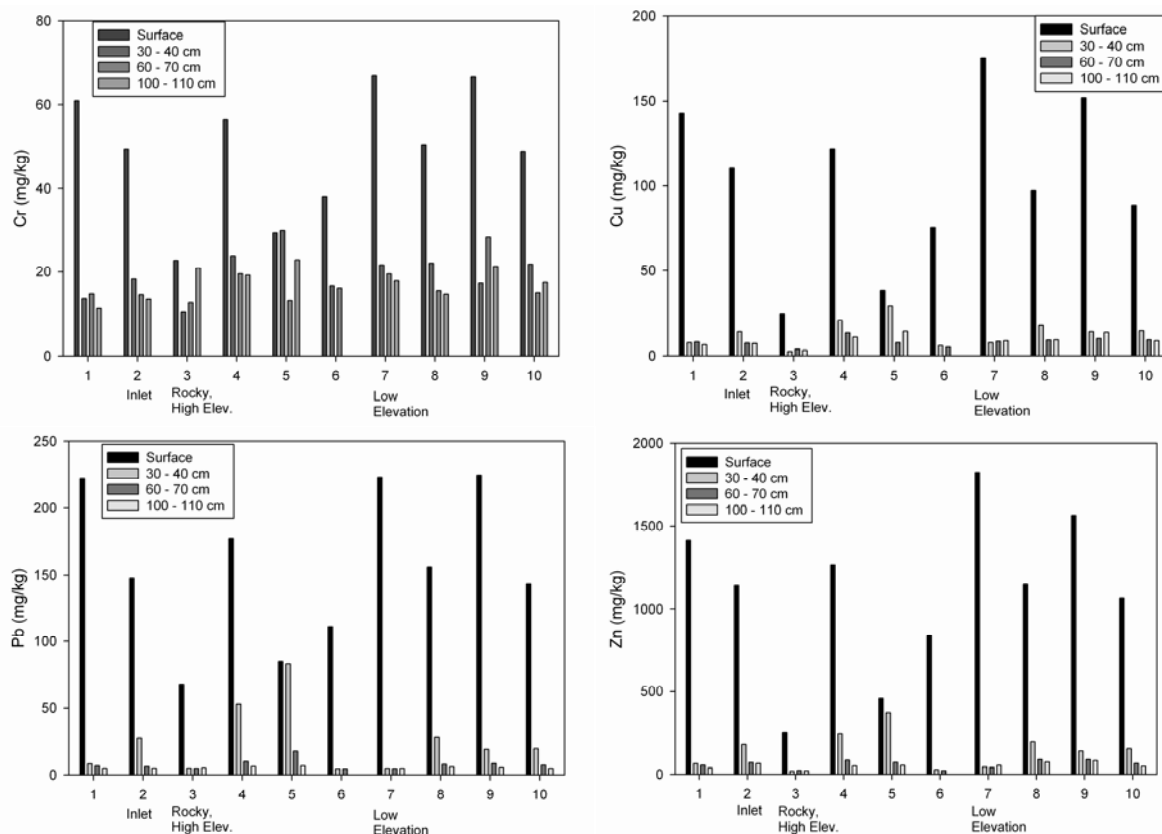


Figure J-5. Metal and Major Ion Concentrations in Soils beneath a 20+-year Infiltration Basin.
(adapted from Dechesne et al., 2004).

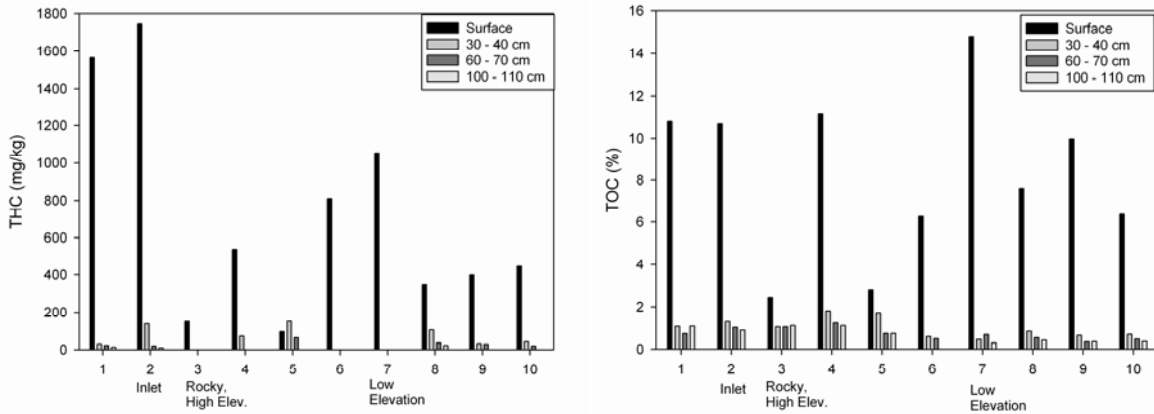


Figure J-6. Total Hydrocarbon and Organic Carbon Concentrations in Soils beneath a 20+-year Infiltration Basin.
(adapted from Dechesne et al., 2004).

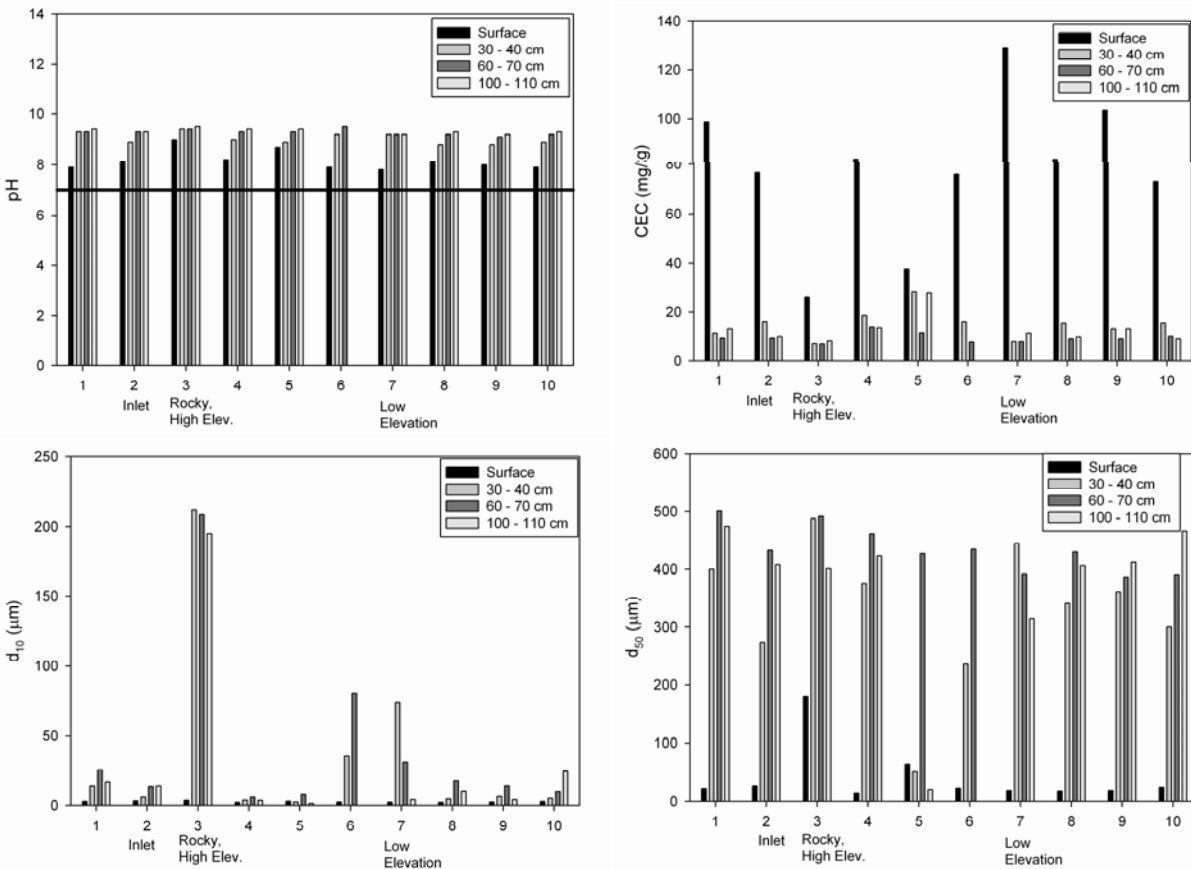


Figure J-7. Analysis of Soil Characteristics by Depth beneath a 20+-year-old Infiltration Basin.
(adapted from Dechesne et al., 2004).

The surface soil layer consisted of finer particles and had a higher organic content. Soil organic matter contains surface groups that retain many stormwater pollutants, including organics and positively charged metals. Therefore, pollutant retention was greatest in the surface layer with little accumulation in the lower layers. This surface accumulation of pollutants was noted also at a second infiltration basin, Django Reinhardt, over a 10-month period. The area of greatest accumulation of copper, lead and zinc was in the low-lying area of the basin, because this area

received the greatest water, and thus pollutant, loading. For small storms, only the lower-lying areas may have received water. No water monitoring data was available to indicate whether pollutants were passing through the system; however, the low levels of pollutants in the lower soil layers suggests that the surface layer to 30-40 cm layer treated the infiltrating water.

Case Study #3: North Carolina Field Bioretention Facility Assessment (Hunt et al., 2006)

Three North Carolina bioretention facilities were monitored for one year. The results described below focus on two of the facilities. The bioretention facilities had depths of 4 feet; one was built on a Madison clay loam soil with a post-construction saturated hydraulic conductivity of 3-15 in/hr and one on a White Store-urban complex soil of clay, clay loam, and silty clay with a post-construction saturated hydraulic conductivity of 1.3-3.1 in/hr. The clay loam soil had a pH of 6.2-6.6; a CEC of 5.6-7.0 meq; and a P-index of 86-100. The urban complex soil had a pH of 5.4-6.0; a CEC of 1.9-2.4 meq; and a P-index of 4-12. The P-index (phosphorus index) describes the relative risk of phosphorus being lost from a native soil. Eleven storms were monitored over the course of the year with an average rainfall of 1.32 inches per storm. Influent and effluent loads were compared for the two basins (Figure J-8 with clay loam labeled “high” and urban complex labeled “low”).

Both bioretention units produced a 40% reduction in total nitrogen, but $\text{NO}_3\text{-N}$ reduction varied from 13-75%; the higher $\text{NO}_3\text{-N}$ removal capacity of the Clay Loam unit may have been caused by anaerobic conditions present there but not in the Urban Complex unit. Total phosphorus reduction seemed to be related to the P-index of the bioretention unit’s soil; the unit with a P-index of 86-100 caused a 240% increase of total phosphorus while the unit with a P-index of 4-12 caused a 65% reduction of total phosphorus. The clay-loam soil cells caused increases in TKN, $\text{NH}_4\text{-N}$, TP, and ortho-P that were significant ($p < 0.05$). The outflow volumes were 50% less than the inflow volumes of the bioretention units. Outflow volume was significantly ($p < 0.05$) related to seasonal weather; the winter months had a lower reduction in inflow to outflow volumes. Pollutant mass removals are correlated with the volume reductions, and not with substantial concentration reductions.

Case Study #4: Effects of Compost Amendments in Hydraulically Poor Quality Soils (adapted from Pitt et al., 1999)

This research project, funded by the U.S. EPA and performed by the College of Forestry Resources (CFR) at the University of Washington (UW), measured the benefits of amending urban soils with compost. It was anticipated that compost-amended soils would improve infiltration characteristics of these problematic soils, along with removing pollutants by filtration/sorption. When these soils are disturbed (and particularly when disturbed with cut and fill techniques as with residential or commercial development), uneven water flow patterns develop due to restricted permeability. The testing used the Urban Water Resource Center design of large plywood beds for containing soil and soil-compost mixes. The test sites were at the University of Washington and two public schools. The compost was applied by adding 4 inches of compost onto the soil surface and tilling to a total depth of 12 inches, including the compost amendment (8 inches into the soil).

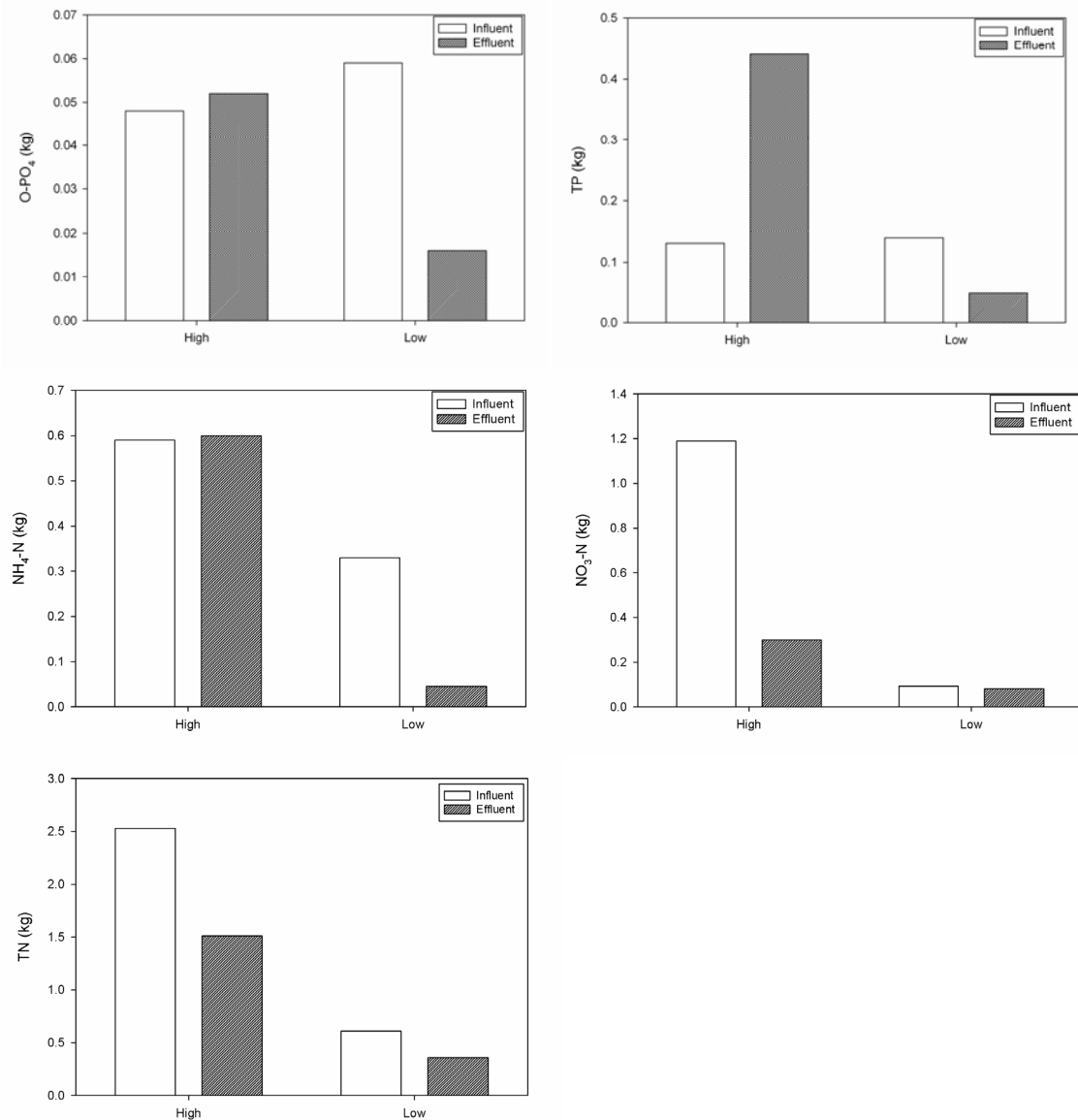


Figure J-8. Influent and effluent nutrient loads in one-year of monitoring at two bioretention facilities.
(adapted from Hunt, et al., 2006). NOTE: Clay loam soil = High; Urban complex soil = Low.

Both surface runoff and subsurface flow were separately collected following seven rainfall periods. The use of compost-amended soil resulted in significantly increased infiltration rates compared to soil alone. These infiltration rate increases (from 1.5 to 10 times the untreated rates) substantially decreased the runoff volumes and flow rates during rain storms from turf areas. The native soil structure below the amended depths likely would prevent much of this increased infiltrating water from reaching deeper groundwaters, but the compost amendments would still improve surface water flow characteristics (see also Harrison, et al., 1997).

Surface runoff and subsurface flows were also monitored over several extended periods at the test plot sites. The newer test plots at the schools showed significant decreases in surface runoff for the compost-amended test plots, compared to the soil-only test plots. These improvements also would be important from the perspective of reducing surface pollutant loads.

In addition, the evapotranspiration rates increased in compost-amended soils. The increase in evapotranspiration ranged from about 33-100% at the newer school sites.

The results showed that the subsurface flows in the soil-only test plots had lower concentrations than the associated surface runoff. For the compost-amended test plots, more constituents had higher concentrations in subsurface flows compared to the surface runoff. In addition, the increases were generally larger (as much as 2.5 times greater) than for the increases observed at the soil-only test plots.

The surface runoff from the compost-amended soil sites had greater concentrations for almost all constituents, compared to the surface runoff from the soil-only test sites. Interestingly, the exceptions were for the cations Al, Fe, Mn, Zn, and Si, plus toxicity, which were all lower in the surface runoff from the compost-amended soil test sites. The concentration increases in the surface runoff flows from the compost-amended soil test site were large, typically in the range of 5 to 10 times greater. Subsurface flow concentration increases for the compost-amended soil test sites were common and of similar magnitude. Toxicity tests indicated reduced toxicity with filtration at both the soil-only and at the compost-amended test sites.

The mass discharges of water and nutrients were calculated for each sampling period. As noted previously, compost-amended soils caused increases in concentrations of many constituents in the surface runoff. However, the compost amendments also significantly decreased the amount of surface runoff leaving the test plots, at least for the monitoring period. Table J-1 summarizes these expected changes in surface runoff and subsurface flow mass pollutant discharges associated with compost-amended soils, using the paired data only. The paired data concentration increases were multiplied by the runoff reduction factors to obtain these relative mass discharge changes. The newer sites had greater runoff reductions, while the older sites had smaller concentration increases associated with the added compost. All of the surface runoff mass discharges are reduced (by 2-50% of the unamended discharges). However, many of the subsurface flow mass discharges may increase, especially for ammonia (340% increase), phosphate (200% increase), plus TP, NO₃-N, and TN (all with 50% increases). Most of the other constituent mass discharges in the subsurface flows decreased.

The compost likely has significant sorption capacity and ion exchange capacity that is responsible for pollutant reductions in the infiltrating water. However, the compost also leached large amounts of nutrients to the surface and subsurface waters.

These results clearly show that amending soil with compost alters soil properties known to affect water relations of soils, including the water holding capacity, porosity, bulk density, and structure, as well as increasing soil C and N, and probably other nutrients as well. The mobilization of these constituents probably led to observed increases in P and N compounds in surface runoff compared to unamended soil plots. Results of the earlier Redmond-sponsored tests (Harrison et al., 1997) were somewhat different than obtained from the current tests. Some of these differences were likely associated with the age of the test plots, plus different rainfall conditions, and other site characteristics. The results of the earlier study clearly showed that compost amendment is likely an effective means of decreasing peak flows from all but the most severe storm events, even following very wet antecedent conditions. The increases in water holding capacity with compost amendment shows that storms up to 0.8 inches total rainfall would be well buffered in amended soils and not result in significant peak flows, whereas without the amendment, a storm about 0.4 inches total rainfall would be similarly buffered.

Table J-1. Pollutant Discharges from Surface Runoff and Subsurface Flows at New Compost-Amended Sites Compared to Soil-Only Sites (Ratio of Amended to Unamended Soil).

Constituent	Surface Runoff Discharges	Subsurface Flow Discharges
Runoff Volume	0.09	0.29
Phosphate	0.62	3.0
Total phosphorus	0.50	1.5
Ammonium nitrogen	0.56	4.4
Nitrate nitrogen	0.28	1.5
Total nitrogen	0.31	1.5
Chloride	0.25	0.67
Sulfate	0.20	0.73
Calcium	0.14	0.61
Potassium	0.50	2.2
Magnesium	0.13	0.58
Manganese	0.042	0.57
Sodium	0.077	0.40
Sulfur	0.21	1.0
Silica	0.014	0.37
Aluminum	0.006	0.40
Copper	0.33	1.2
Iron	0.023	0.27
Zinc	0.061	0.18

In conclusion, adding large amounts of compost to marginal soils enhances many desirable soil properties, including improved water infiltration (and attendant reduced surface runoff), increased fertility, and significantly enhanced aesthetics of the turf. Unfortunately, the compost also increased the concentrations of many nutrients in the runoff, especially when the site was newly developed, but with the increased infiltration of the soil, the nutrient mass runoff was likely significantly decreased. Further research is needed to determine if it is possible that less amounts of compost could be added to an urban soil and still obtain much of the observed benefits, but would have reduced problems associated with leaching.

Recent case studies have focused on newer infiltration-based treatment units, although several European researchers (Bardin et al. 2001; Barraud et al. 1999; Barraud, et al. 2005; Mikkelsen 1997) , plus Welker et al. (2006), have been investigating soil accumulation of pollutants in infiltration facilities that are several decades old. Research is ongoing at field installations and laboratories both in the U.S. and in other countries. Active researchers in the water-quality impacts of, and controlling factors for, infiltration through both engineered and natural soils include several researchers in Florida, Villanova University, the University of New Hampshire, North Carolina State University, the University of Maryland, the U.S. EPA Urban Watershed Management Branch (investigations in both New Jersey and Kansas City, Missouri), Australia, France, Germany, Japan, Norway, and Switzerland (Bao-rui, 1988; Chocat et al., 1998; Davis, 2008; Davis et al., 2009; Dechesne et al., 2005; Dechesne et al., 2001; Dierkes et al., 2006; Emerson and Traver, 2008; Ferguson, 1990; Fischer et al., 2003; Guo et al., 2006; Hathhorn and Yonge, 2005; Hatt et al., 2007; Hatt et al., 2008; Hsieh and Davis et al., 2007a,b; Hunt and Jarrett, 2004; Hunt et al., 2003; Hutter and Remmler, 1996; Imbe et al., 2002; Jayasuriya et al., 2007; Kutschke et al., 2005; Kumar et al., 2006; Kwiatkowski et al., 2007; Li and Davis, 2008a, b; Lucas and Greenway, 2008; Marcos et al., 2002; Marton and Mohler, 1988; Mason et al., 1999; McKenzie and Irwin, 1988; Mikkelsen et al., 1997; Morris and Stormont,

2000; Muthanna et al., 2007a,b; Murakami et al., 2008; Nogaro et al., 2007; Osenbruck et al., 2007; Sample and Heaney, 2006; Sansalone and Glenn, 2007; SRF Consulting Group, 2004; Sun and Davis, 2007; Thomas, 2000; Todorovick et al., 1999; Van Cuyk and Siegrist, 2007; van der Werf et al., 1999; Warnars et al., 1999; Welker et al., 2006; Wilde, 1994; Zhang and Ross, 2007; Zheng et al., 2006; Zomorodi, 2006).

J.2 Laboratory Investigations

The case studies described above indicated, first, that groundwater quality can be impacted from stormwater infiltration. They also indicate that certain soil properties, such as higher organic content, higher CEC, and low P-index, may be among the controlling characteristics of soils that decrease pollutant transport through the vadose zone. Research on stormwater filters (literature summarized in Clark, 2000) has shown that the following characteristics, in addition to those described above, can be linked to improved pollutant removal ability: specific surface area of media, surface organic acid concentration, humic and fulvic acid concentration, anion exchange capacity (AEC), depth of media, increased contact time (typically through deepening the filter media), and maintenance of aerobic conditions. Other researchers have shown that pollutant removal is increased in vegetated infiltration facilities, when compared to non-vegetated facilities. Because these field tests could not explicitly determine which factors controlled the pollutant removal, several research groups, using laboratory- and pilot-scale setups, are investigating the soil characteristics that affect pollutant removal, with two goals: first, producing guidance that will assist stormwater planners in determining where infiltration is acceptable in terms of groundwater protection, and second, creating an optimized bioretention/infiltration basin media.

Laboratory Study #1: Optimizing Bioretention Media (Hsieh and Davis, 2005)

The pollutant removal capabilities of eighteen soil columns were measured and compared with the results from six field bioretention units. The test water was a synthetic stormwater. Soil columns were composed of mulch (leaf litter and lawn clippings), two sands of differing particle size, and three soils of varying chemical properties and grain sizes. This infiltration media was created from various combinations of these sands, soils, and mulch. The soils showed high removals of oil and grease (O/G), total suspended solids (TSS), and lead for most media combinations. TSS increased during passage through one column where soil was the dominant portion of the media. Several media combinations that excluded soil resulted in lower Pb removal rates. Pb bonded to the solids in the synthetic runoff (56%), suggesting that removal of total suspended solids would remove a large portion of Pb. Total phosphorus removal ranged from 4-99%. Mulch did not assist in phosphorus removal; soil and sand had mixed impacts. Nitrate removal ranged from 1-43% with mixed results from various media combinations with higher removals in mulch-containing combinations and potentially lower removals in the sandier mixes. Ammonium removal was low, <26%, for all media combinations and no trends were seen. The field observations reflected column study results; but, unlike the columns studies, organic matter was correlated to phosphorus removal. Also, total suspended solids levels reflected the age of the units, with newer units having lower removal of TSS.

Laboratory Study #2: Multiple Evaluations of the Removal of Pollutants in Road Runoff by Soil Infiltration (Murakami et al., 2008)

The purpose of the project was to evaluate the ability of a natural loam soil from a park in Japan to treat simulated road runoff under continuous versus intermittent loading conditions.

Two depths of media were investigated in the continuous loading tests, 20 cm and 50 cm. The soil was collected from the park, air-dried, sieved to retain soil in the size range of 75 μm to 2,000 μm , and repacked into columns. Runoff water was created using pre-settled groundwater that had been spiked with sediments collected from an expressway drainage pit by road sweepers. Columns were pre-conditioned by pouring unspiked groundwater through the columns for approximately two weeks. This pre-conditioning removed many of the soluble pollutants from the media. Treese et al. (2009) (Laboratory Study #4) did not pre-condition the silt loam columns that were created in a similar manner and found that nutrient, cation and anion releases were very high during the first few flushings with stormwater. Since most field units are not pre-conditioned, early nutrient release must be addressed.

The results showed that the loam soil columns were able to remove organic matter, phosphorus species, and most heavy metals and PAHs. Nitrate was not removed. Nickel, manganese and some alkaline earth metals (strontium, barium, and magnesium) were released into the infiltration water. Toxicity tests showed that the soils were able to remove the pollutants causing toxicity during the later stages of the test.

Laboratory Study #3: Assessment of Sand and Soil-based Stormwater Filter/Bioretention Media (Hatt et al., 2008)

The purpose of project was to evaluate combinations of sand, soils and potential soil amendments for improving hydraulic and pollutant removal behavior in filtration and bioretention systems. The influence of time, cumulative sediment loading, cumulative water volume, wetting and drying cycles, and compaction on hydraulic conductivity was investigated. The test media included the following (designations relate to Column 1 in Table J-2):

- ◆ Sand (S)
- ◆ Sandy Loam (SL)
- ◆ 80% SL, 20% Hydrocell™ (a synthetic soil amendment) (SLH)
- ◆ 80% SL, 10% Vermiculite, 10% Perlite (SLVP)
- ◆ 80% SL, 10% Compost, 10% Mulch (SLCM)
- ◆ 60% SL, 20% Compost, 20% Mulch on a Charcoal Drainage Layer (SLCMCH)

The standard deviations in Table J-2 are based on three replicates of each media. Negative reductions indicate contributions from the media itself.

Table J-2. Percent Pollutant Reductions in Six Soil and Soil Combination Columns (Hatt et al., 2008).

Media	TSS	TP	TN	TOC	Cu	Mn	Pb	Zn
S	99 $\pm$ 1	97 $\pm$ 1	38 $\pm$ 1	59 $\pm$ 8	97 $\pm$ 1	94 $\pm$ 1	99 $\pm$ 1	99 $\pm$ 1
SL	93 $\pm$ 4	NR*	NR	NR	97 $\pm$ 1	NR	99 $\pm$ 1	99 $\pm$ 1
SLH	92 $\pm$ 3	NR	NR	NR	96 $\pm$ 1	NR	99 $\pm$ 1	98 $\pm$ 1
SLVP	90 $\pm$ 3	NR	NR	NR	94 $\pm$ 2	NR	95 $\pm$ 2	96 $\pm$ 4
SLCM	92 $\pm$ 4	NR	NR	NR	94 $\pm$ 1	NR	97 $\pm$ 1	96 $\pm$ 1
SLCMCH	96 $\pm$ 1	NR	NR	NR	93 $\pm$ 1	NR	97 $\pm$ 1	96 $\pm$ 1

*NR = Pollutant was not removed in these test columns. Pollutant was released from the media into the infiltrating water, resulting in effluent concentrations greater than the influent.

These results suggested that the primary cause of hydraulic failure was formation of a clogging layer at the filter surface. Sediment and heavy metals were effectively captured in the media; however, the soil-based filters leached nitrogen and phosphorus. The authors state that the release of manganese during testing may be an indication of changing chemical conditions in the media. Oxidized manganese would be expected to be well-retained; however, the development of anaerobic conditions could lead to release of certain pollutants. Similar results were seen by Clark (2000) and Clark and Pitt (2008a) for organic stormwater filter media.

After the testing was completed, the media columns were analyzed for pollutant accumulation by depth. The pollutant profiles revealed significant accumulation of all pollutants in the top 20% of the filter profile, suggesting that elevated discharges of nutrients was due to leaching of native material, rather than failure to remove incoming pollutants. The release of pollutants from the media itself indicates a need for a drainage or lower media layer in engineered infiltration systems that can capture those pollutants. One possibility is the installation of an expanded mineral drainage layer that has been chemically or heat-activated to improve its pollutant removal; Long et al. (2008) investigated several expanded minerals for their pollutant removal ability and found that an expanded slate worked well for a variety of pollutants.

Laboratory Study #4: Pollutant Removals by Horizon in a Silty Loam and Loamy Sand (Treese et al., 2009)

Two soils, a Wharton Silty Loam and Leetonia Loamy Sand were examined for their ability to remove pollutants from stormwater runoff. Twenty columns of each soil were collected intact in the field. In the laboratory, five columns were left undisturbed (with the exception described below), five columns retained only the O horizon, five retained the A horizon and five retained the A and B horizons for the loamy sand and the A1 and A2 horizons for the silty loam. Some of the tested columns also represented a disturbed soil, such as would be created when amending a natural soil to improve infiltration. The equivalent of a 3-inch rain was applied to each column approximately every week and the effluent analyzed. After every eight infiltration events, one column of each soil of each horizon was sacrificed for soil analysis. The results from the initial water testing are shown in Figures J-9 through J-12.

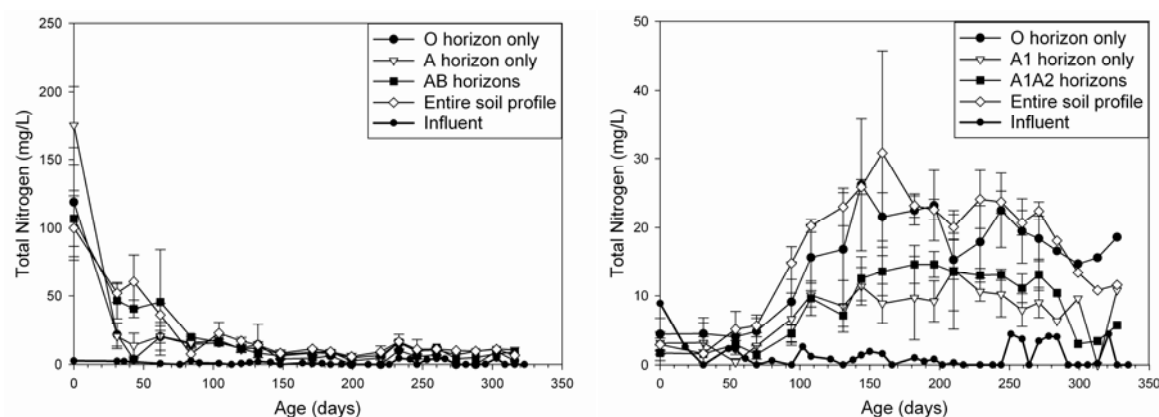


Figure J-9. Total Nitrogen: Wharton Silt Loam and Leetonia Loamy Sand.

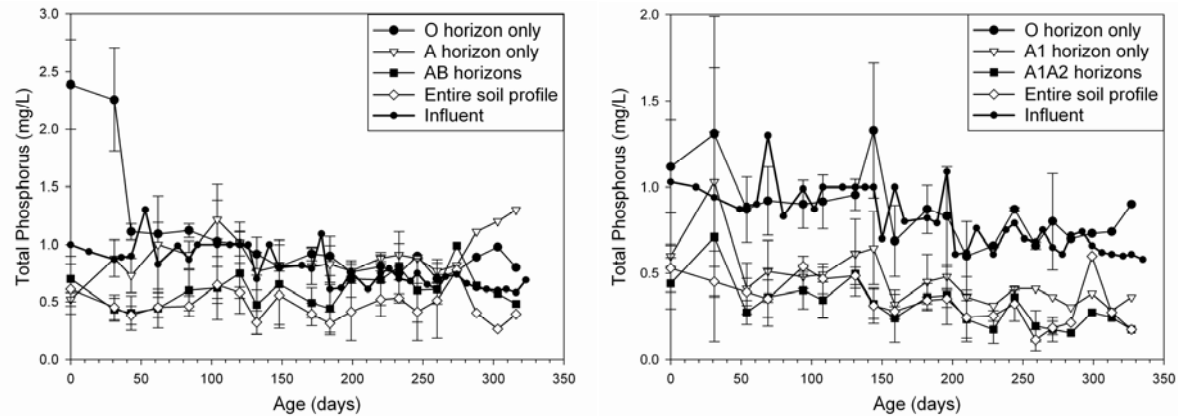


Figure J-10. Total Phosphorus: Wharton Silt Loam and Leetonia Loamy Sand.

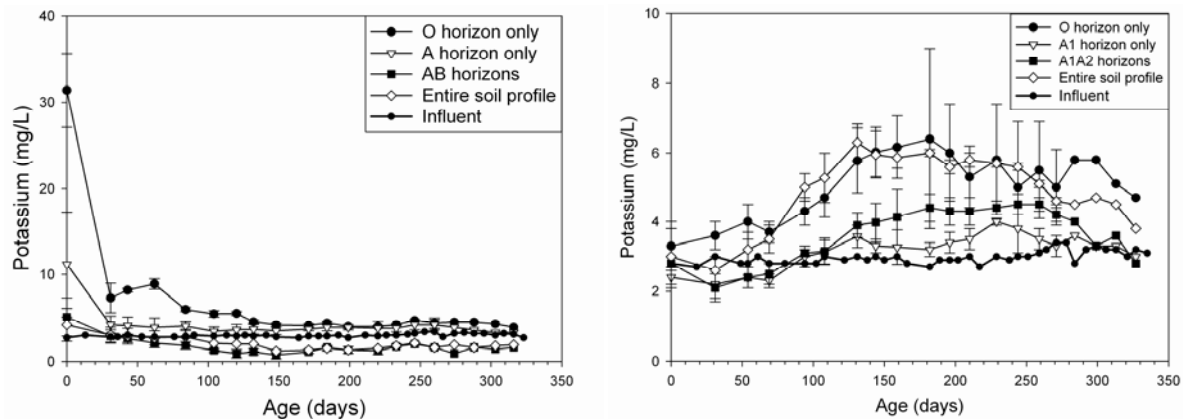


Figure J-11. Potassium: Wharton Silt Loam and Leetonia Loamy Sand.

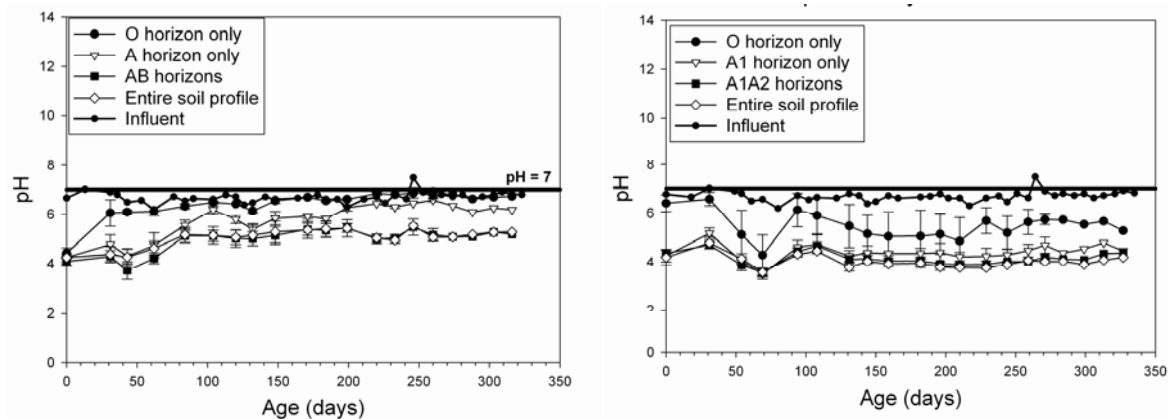


Figure J-12. pH: Wharton Silt Loam and Leetonia Loamy Sand.

These results showed leaching of total nitrogen and removal of total phosphorus by all soil horizons of both soil types, except for the early release of phosphorus from the silty loam (disturbed) soil. The phosphorus from this soil returned to levels similar to the influent after three infiltration events. This initial increase may have been the result of soil disturbance, which is being further investigated. Potassium and sulfate removal occurred early in the AB/A₁A₂ and OAB/OA₁A₂ soil horizon columns of both soils, but may only be temporary. The lower horizons and the entire profile are able to retain the leaching potassium and sulfate from the organic

horizon. All soil horizons of both soil types have lowered the pH of influent stormwater and increased conductivity, turbidity, color, and hardness.

The second question addressed by this research was the change in pollutant concentrations in the soil. Figures J-13 through J-15 highlight those results for the two soil types.

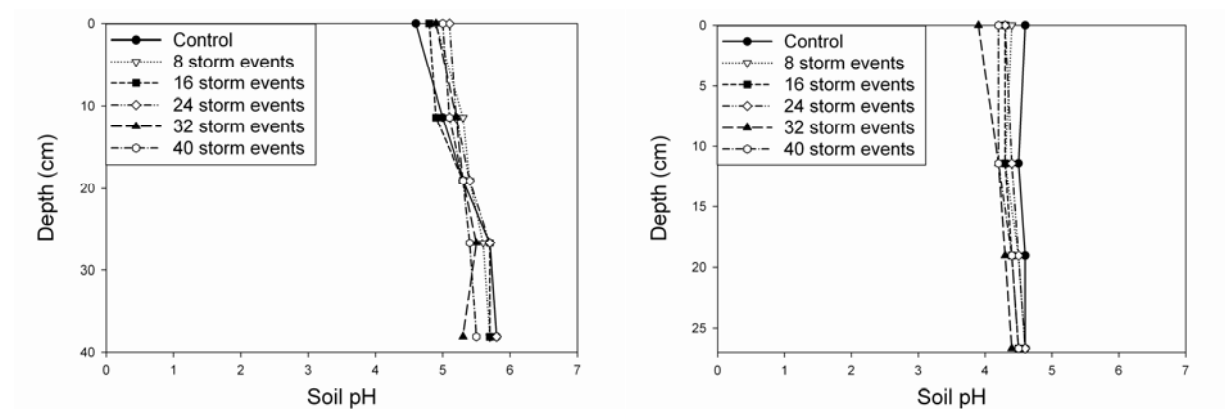


Figure J-13. Soil pH: Wharton Silt Loam and Leetonia Loamy Sand.

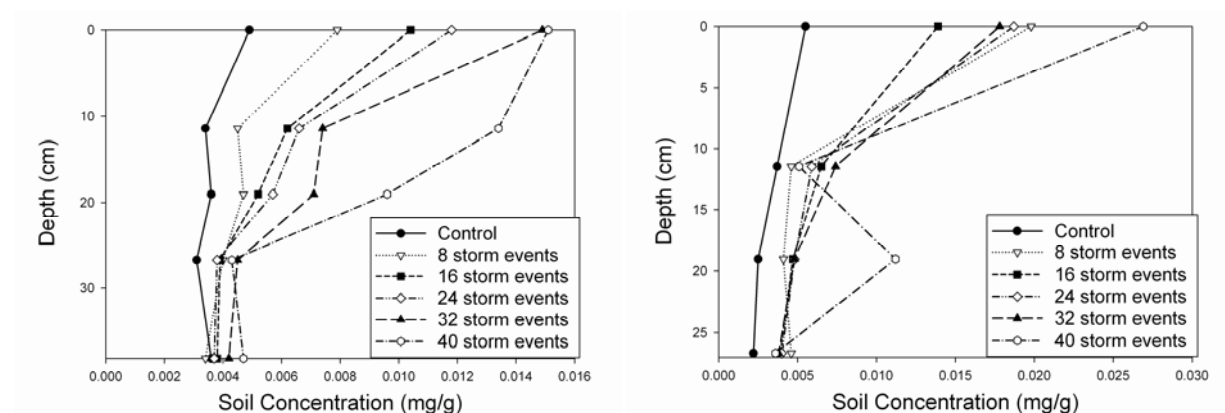


Figure J-14. Soil Copper Concentration: Wharton Silt Loam and Leetonia Loamy Sand (Extracted by Mehlich 3 Method).

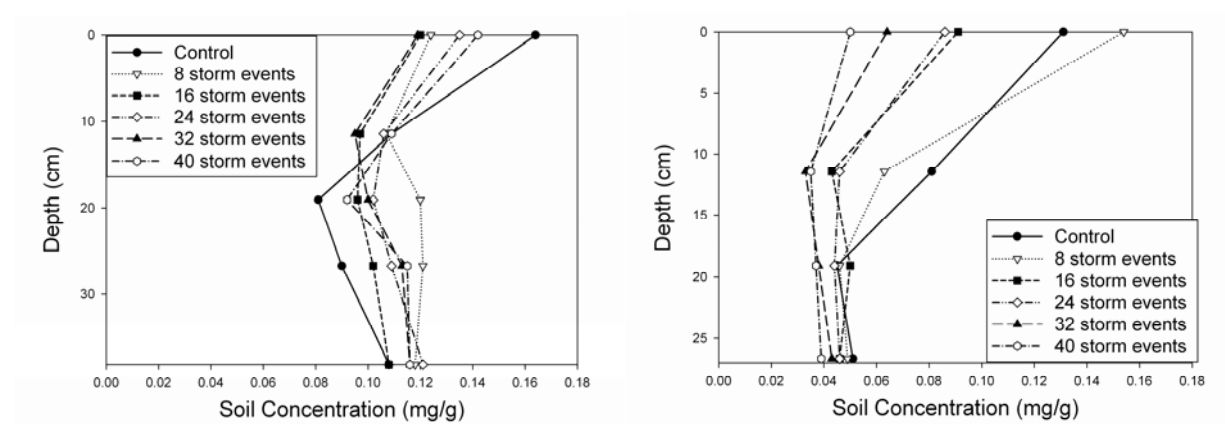


Figure J-15. Soil Magnesium Concentration: Wharton Silt Loam and Leetonia Loamy Sand.

The results indicate that the soil pH greatly affects the pH of the infiltrated water. The consistent pH results in the soil indicate that soil pH changes are not likely to occur. Passage through acidic soil horizons can be expected to decrease the water pH and potentially into a range where some metals may be more soluble. The copper and magnesium results shown here were from soil samples digested using the Mehlich 3 method rather than a nitric acid digestion. The Mehlich 3 method is used commonly in agronomy to extract those materials that are exchangeable and, therefore, bioavailable to the plants. The results for copper for both soils indicated an accumulation of copper in the upper layers during the early infiltration events with increasing depth penetration of the copper as additional soil filtering of the runoff water occurs. The opposite trend was seen with the magnesium but to a lesser extent and not seen in the silt loam. Magnesium in the loamy sand was lost from the column as the system aged. These columns received the equivalent of approximately 1-2 years of loading on the systems. The loss of magnesium, if accompanied by an increase in sodium, could change the SAR of the system and potentially reduce infiltration rate.

These laboratory studies confirm the importance of the organic content in removing pollutants from infiltrating stormwater runoff. However, as both the field and laboratory studies show, there appears to be an optimal organic content below which removal is not optimized. They also highlight the temporal accumulation or leaching of chemical constituents over relatively short operational times. Additional research would be needed to address both of these concerns. These will affect the lifespan of the system.

APPENDIX K

LITERATURE REFERENCE TABLE

Table K-1 summarizes some of the literature on stormwater management practices. This table was assembled from the literature databases using the following four search terms: stormwater infiltration, stormwater detention, stormwater wetlands, and stormwater filtration. This is not an exhaustive list but covers many of the pertinent studies published in the literature on stormwater treatment.

Table K-1. Literature Summary by Location, Activity, and Pertinent Conclusions.

Authors	Study Area	Treatment /Management Activity	Conclusions
Abbott and Comino-Mateos (2001)		Infiltration: perforated concrete-ring soakaway	Tested agreement of performance with design equations
Abida and Sabourin (2006)	Laboratory and survey in Ontario, Canada	Infiltration: grass swale-perforated pipe	Survey to determine acceptability to using grass swale-perforated pipe as part of storm sewer system Exfiltration rate from pipe not directly proportional to orifice area Flow through system about 1/13 th less than traditional storm sewer
Abida et al. (2007)	Laboratory and field	Infiltration: grass swale-perforated pipe	Model verification for flow through grass swale-perforated pipe system Parameters affecting system: lot size and imperviousness, swale dimensions and infiltration capacity, pipe length, number of orifices, soil infiltration capacity
Achleitner et al. (2007)	Tyrol parking lots	Infiltration	Investigated hydraulic permeabilities and soil pollutant accumulations in infiltration devices of various ages. No anticipated chemical accumulation failure for 15 year lifespan. No correlation seen between site specific parameters (age, traffic load).
Adams and Cahill (2003)		Infiltration: pervious asphalt	Discussed construction, performance with geotextile layer
Adamsson (2004)	Modeling	Detention tanks	Computational fluid dynamics modeling of detention tank hydraulics Analyzed flow patterns, residence times and sedimentation Results showed that bed shear stress boundary condition for particle contact with bottom can be used to estimate removal efficiency
Adolfson and Clark (1991)	Pierce County, Washington	Infiltration	Develop alternative dry well designs to improve pollutant removal in soil Three designs proposed for pollutant removal by sedimentation.
Adolfson and Clark (1992)	Pierce County, Washington	Infiltration: trenches	Pollutant removal improved in first 4 – 5 months of operation Improvements may result from fine sediment deposition in trench or on filter fabric Greatest pollutant removal for large-diameter particulates Limited removal for dissolved constituents
Akagawa et al. (1997)	Tokyo, Japan	Infiltration	Demonstrated flow control Investigated the transition of the groundwater table during recharge
Akan (1992)	Modeling	Infiltration	Explicit solution to Horton infiltration equation based on water penetration depth
Akan (2002)	Modeling	Infiltration devices	Design aid for sizing structures based on hydrological storage equation coupled with Green and Ampt infiltration equation Example design included
Akan and Yen (1984)	Modeling	Infiltration	Investigated effect of time distribution of rainfall on runoff and infiltration Showed that peak discharge and time of occurrence can vary significantly with temporal rainfall distribution
Aldrich (1993)	Lacey, Washington	Detention pond, wetland	Describes design parameters for treatment device
Alfakih et al. (1999)	France	Infiltration	Describes overview and feasibility criteria for choosing infiltration

Authors	Study Area	Treatment /Management Activity	Conclusions
Andersen (1999)	Eugene, Oregon	Stormwater Management – General	Describes multiple objectives planning approach to stormwater management design Focuses on community values and demonstration of multiple benefits
Anderson et al. (1996)	Great Lakes Basin	Detention pond	Designed integrated treatment system using existing detention pond Remedial measures included retrofitted flow baffles, effluent polishing by constructed wetlands and biofilm reactor, plus detoxifying pond sediments.
Anderson et al. (1997)		Filtration	Submerged aerobic biological filter evaluated in laboratory Found to be cost-effective Future work includes field installation and monitoring
Ando et al. (1984)	Tokyo, Japan	Infiltration	Final infiltration rates during field testing were related to land use Very high rates for forest, field, and fruit crop field; widely variable for garden, grass land, and lawn area; medium for open area in parks; low for open area in gardens; and very low for sports ground and cleared land.
Andoh (2007)		Filtration	Describes upflow filtration for stormwater treatment
Anonymous (1983)		Pervious concrete pavement	Describes ability of pervious concrete to reduce runoff peak rates and increase lag times to nearly pre-development conditions Describes two types of pervious concrete
Anonymous (1988)	South Africa	Detention pond prior to infiltration area	Describes detention pond-infiltration system used to treat urban runoff. Outlines pond siting requirements, including cost justifications
Anonymous (1991)	Tulsa, Oklahoma	Detention pond	Case study of incorporating detention pond into lake facility
Anonymous (2001)		Wetlands	Describes plans to improve the Las Vegas Wash, which is the primary drainage challenge for urban runoff in the Las Vegas Valley
Anonymous (2002a)	Vancouver, Canada	Wetland	Case study of integrating stormwater treatment wetland into existing lagoon area. Describes inlet pool to pre-settle larger particulates.
Anonymous (2002b)	Adelaide, Australia	Sediment traps	Describes the use of sediment traps to pre-settle particulates prior to further runoff treatment in a wetland
Anonymous (2003)	Toronto, Canada	Detention ponds	Case study of design of airport runoff combining ponds and underground storage tank
Anonymous (2005a)		Pervious pavement and other treatments	Describes several treatment devices Focuses on pervious pavement and describes benefits
Anonymous (2005b)	Gloucester	Concrete permeable paver system	Case study of Aquaflo's permeable paver systems
Apperson et al. (2005)	North Carolina	Retention ponds	Characterized seasonal occurrence and relative abundance of mosquitoes in relation to complexity and biological diversity of ponds Presence of mosquitofish and larvae/pupae were inversely related
Astebol et al. (2004)	Oslo, Norway	Ponds, Wetlands, Filter Strips, Swales	Case study of redevelopment of a closed airport into residential areas Presents concepts of sustainable stormwater management at site
Auger and James (2002)	Modeling		Describes optimization routines in SWMM used to select treatment devices based on lowest life-cycle costs and achieving acceptable effluent quality

Authors	Study Area	Treatment /Management Activity	Conclusions
Azzout et al. (1995)	Modeling	Detention ponds Infiltration	Presents development of decision aids for selecting between alternative techniques for urban drainage with consideration to needs of stakeholders
Bachhuber (1998)	Milwaukee, Wisconsin	Biofiltration, Filtration	Case studies to demonstrate feasibility to reduce flow and pollutant loads
Backstrom (2002)	Field studies and modeling	Grass swales	TSS reductions 79-98% from simulated runoff events Highest trapping efficiency in swales with dense, fully-developed turf. High infiltration rates and/or long swales aided in particle trapping. Model developed to describe particle removal as function of mean residence time in swale
Backstrom and Bergstrom (2000)	Laboratory	Pervious Asphalt	Demonstrated reductions in infiltration capacity of pervious asphalt when temperatures were reduced Simulations of snowmelt freeze-thaw reduced infiltration rates by 90%
Backstrom and Viklander (2000)	Lulea, Sweden	Pervious pavement, Grass swales, Wet ponds, Dry ponds, Infiltration basins/trenches	Created framework to evaluate suitability of stormwater systems to cold-climate operation
Backstrom et al. (2002)	Modeling Sweden	All treatment devices	Evaluated the relative contribution of stormwater to pollutant loads in a catchment. Suggested using sustainability tools/decision guides to select or eliminate specific practices in a design Questions whether traditional treatment (ponds, infiltration) can reduce pollutant loads sufficiently
Barbe and Poirrier (1991)	New Orleans, Louisiana Modeling		Describes methods of predicting and then planning to reduce the effects of urban runoff on Lake Pontchartrain
Barbosa and Hvitved-Jacobsen (1999)	Portugal Laboratory	Infiltration pond	Describes soil properties and experiments to determine metal retention in highway-runoff infiltration pond Soil pH played significant role in pollutant capture and retention
Barbosa and Hvitved-Jacobsen (2001)	Portugal	Infiltration pond	Describes design of infiltration ponds for semi-arid climates Soil hydraulic conductivity, pH, texture, CEC used to predict potential mobility of Zn
Bardin et al. (2001)	France	Infiltration	Case study of infiltration basin with pre-treatment
Bardin et al. (2002)	France	Infiltration	Developed 17 performance indicators to assess infiltration feasibility Application examples included
Barraud et al. (1999)	France	Infiltration	Case study Role of soil in pollutant migration, prevention of groundwater contamination
Barraud et al. (2002)	France	Infiltration	Describes the long-term project assessing the impacts of stormwater infiltration on groundwater quality and soil pollutant accumulation
Barraud et al. (2005)	France	Infiltration basin	Case study of 4 infiltration basins Pollutant concentration in soil decreased rapidly with depth with stable values reached at 50-cm.

Authors	Study Area	Treatment /Management Activity	Conclusions
Barrett (2000)	Multiple wood storage sites	Vegetated buffer strips, Sediment traps, Retention ponds, Site housekeeping	Describes practices for stormwater management at wood storage sites
Barrett (2004)	Multiple sites	Retention pond	International BMP database to assess factors affecting pollutant removal Design differences explained variability in pollutant removal Extended detention reduces variability
Barrett (2005a)	Multiple sites	Retention ponds, Extended detention ponds, Swales, Sand filters	International BMP database to compare performance of treatment devices Effluent quality was function of influent quality for many pollutants Differences noted when evaluated as function of influent quality
Barrett (2005b)	Multiple sites	Media filters Wet detention ponds	Used Caltrans database to compare performance of treatment devices Media filter and extended pond performance unrelated to influent quality
Barrett (2008)		Wet detention ponds, Vegetated swales, Sand filters, Extended detention basins	International BMP database to compare performance of treatment devices Some variability explained by design and watershed differences Differences noted when evaluated as function of influent quality
Barrett and Goldsmith (1998)	Massachusetts	Pond Wetland	Case study on bioengineered pond-wetland system Evaluating ecological benefits and improvements on pre-developed site of new biotreatment system
Barrett et al. (1997)	Texas	Grass swales Extended detention ponds Sedimentation/Filtration systems	Found general correlation between the pollutant removal efficiency and maintenance requirements Filtration requires high level of maintenance Grass swales had high level of treatment with minimal maintenance
Barton and Buchberger (2007)	Laboratory	Filtration	Compared effects of grain shape on particle retention. Angular media provided better removal than rounded media
Baun et al. (2006)	Modeling		Presented methodology for ranking and hazard identification of xenobiotic organics in stormwater
Bavor et al. (2001)		Constructed wetlands Detention pond	Compared wetlands and detention ponds for bacteria and other pollutants Removal efficiencies higher for wetland, but lower than reported values for treatment of municipal wastewater
Beale (1992)		Diversion, Infiltration, Detention, Flow Control	Reviewed methods for controlling urban runoff
Bean et al. (2007)	North Carolina, Maryland, Virginia, Delaware	Permeable pavement	Removal of top sediment layer significantly improved infiltration rate Demonstrated importance of permeable pavement location in maintaining good infiltration rates
Beatley and Wigfield (1993)		Detention control structure	Discuss design of outlet structures to meet multiple objectives of peak flow and pollutant control
Beecham and Myers (2007)		Pervious pavement Permeable block pavement	Describe research in Australia on permeable pavements as a treatment device for rainwater harvesting
Beisch et al. (2005)	Virginia	Low Impact Development	Case study of master plan for integrating LID in large-scale development Developed LID guidelines to aid design on large-scale Presented client and stakeholder perspectives

Authors	Study Area	Treatment /Management Activity	Conclusions
Bender (2004)	Chesterton, Indiana	Prairies and Wetlands Infiltration	Case study of development using prairie and wetlands to treat stormwater before infiltration
Berg (1998)		Constructed wetlands	Case study on wetlands and filter strip used to treat runoff from 1000 ac of residential, commercial and industrial runoff. Also treats runoff from snow disposal site
Bernard and Miramond (1998)	Modeling	Infiltration	Feasibility analysis of a simulation system to assess impact of stormwater infiltration on groundwater
Beyerlein et al. (2005)	Modeling	Detention pond, Infiltration pond, Tank, Stormwater vault	Describes Western Washington Hydrology Model (WWHM) Model sizes stormwater facilities based on flow duration curves HSPF is used to compute hourly runoff data from the rainfall record
Bibler (1991)	Tampa Bay, Florida		Describes Tampa Bay's stormwater program Describes roles of various governmental agencies and levels
Birch et al. (2005)	Australia	Infiltration	Removed 50% TSS, 68% Cu, 93% Pb, 52% Zn, 51% TP, 65% TKN Cr, Fe, Mn and Ni not removed Nitrate increased by 250% during infiltration Fecal coliform reduction was 96%
Bishop et al. (2000a)	Guelph, Ontario, Canada	Detention Ponds	Vegetated ponds had higher organic carbon and Cu concentrations
Bishop et al. (2000b)	Guelph, Ontario, Canada	Detention Ponds	Sediments had at least one contaminant exceeding 'lowest effects level' Statistically lower hatching success of northern leopard frogs eggs Larvae took longer to metamorphose into frogs
Blecken et al. (2007)	Laboratory	Biofiltration	Investigated temperature influence on cold-weather nutrient treatment TSS and phosphorus treatment not impacted by cold temperatures, but nitrogen was not removed
Bledsoe et al. (2001)	Modeling		Describes set of mechanical and statistical models to improve estimates of long-term changes in stream erosion potential, channel morphology and in-stream disturbance regime Goal to model land-use change impacts on streams
Bloom (2006)		Low Impact Development	Describes Low Impact Development's benefits
Bolender and Shuler (2003)		Infiltration	Design, including required soils information from test borings
Boller (2004)		Infiltration	Impact of pollutant sources, concentrations on design of infiltration facilities
Boller and Steiner (2002)		Filtration	Describes sources of copper in the watershed Describes a filtration system of iron hydroxide and calcium carbonate to treat copper-laden runoff
Bonilla-Warford and Zedler (2002)		Wetlands	Investigated potential of using native plants in stormwater wetlands Vegetation establishment was not limited by flow regime, including drought, but expansion of plants was drought sensitive

Authors	Study Area	Treatment /Management Activity	Conclusions
Booth and Jackson (1997)	Western Washington state	Detention ponds	Threshold of stream degradation at approximately 10% imperviousness with lower degradation levels seen in highly sensitive streams Noted limited effectiveness of ponds in mitigating flow impacts
Booth et al. (2002)	King County, Washington	Detention ponds Infiltration Wetlands	Described limitations of traditional practices in mitigating impacts on salmon of converting forest to rural area Advocated impervious surface limits to protect aquatic resources
Botts et al. (1994)	Peru		Incorporation of indigenous capabilities into stormwater management
Bourgues and Hart (2007)		Wetlands	Denitrification potential in stormwater wetland sediments and epiphyton Found that hydrocarbon levels could not predict ability to denitrify Epiphyton ability to denitrify similar to that of sediment
Boving and Neary (2007)	Pilot-scale field test	Filtration	PAHs were removed between 18 and 35% of dissolved PAHs PAH removal was not affected by water temperature or pH Effectiveness was directly correlated to filter size and whether part of the filter was submerged
Boving et al. (2008)	Laboratory	Filtration	Aspen wood filters for removing organic and inorganic pollutants PAH removal was positively correlated to increasing PAH molecular weight, but not to lignin content Barks high in tannin had greatest removal of copper
Bradford and Gharabaghi (2004)	Ontario, Canada	Stormwater management planning and design	Updates to Stormwater Management, Planning and Design Manual Need for in-stream erosion control and water balance considerations
Braga et al. (2007)	Pennsylvania	Infiltration	Temperature effects on infiltration rates below rock infiltration basin
Bratieres et al. (2008)	Pilot-scale Australia	Biofiltration	Vegetation selection critical to nitrogen removal performance Phosphorus removal improved in soil media with added organic matter Optimal biofilter is at least 2% of drainage area
Brattebo and Booth (2003)		Permeable pavements	Investigated four commercially available permeable pavements Noted no degradation in performance after 6 years and runoff quality was better than non-permeable asphalt
Braune and Middleton (1993)	Modeling		Damage ratings that identifies, quantifies, ranks areas by flood hazard Incorporates a Benefit Factor, which relates the risk of flooding to the capital cost of the drainage system
Brinkmann (1985)		Stormwater source	Identified sources of urban runoff pollutants and estimated loads
Brion (2005)		Stormwater pollutant sources	Describes ratio of atypical and typical coliforms as a measure of native versus introduced bacteria Suggested use of ratio in predicting risk and in locating sewage contamination of stormwater
Brown et al. (1999)	Sydney, Australia Modeling		Optimization scheme for sizing control options with cost as a limiting factor Uses LINGO, a nonlinear problem solver.
Browne (2003)		Ordinances	Describes use of ordinances to encourage implementation of desirable stormwater management practices

Authors	Study Area	Treatment /Management Activity	Conclusions
Brulo et al. (2004)		Detention pond	Evaluates two-stage outlet structure for detention basin
Bucheli et al. (1998)		Infiltration Stormwater sources	Investigated roofing as a pesticide source Found that infiltration may not reduce concentrations of mobile pesticides
Burak (2003)		Permeable Pavements	Selection of permeable pavements based on management objective Discusses criteria for design, construction and maintenance
Cabezas et al. (1998)	Florida	Stormwater planning	Describes risk-based approach to identify priority contaminants in urban runoff and to prioritize actions
Callander et al. (1999)	Christchurch, New Zealand	Infiltration Vegetated swales	Describes stormwater management in area where gravel soil strata also feeds drinking water aquifer Evaluated concerns of fecal coliform contamination, plus chemical spillage Describe designs that meet these criteria
Carleton et al. (2000)	Virginia	Constructed wetland	Effect of wetland size on pollutant removal with improving removal seen with increasing ratio of wetland area to drainage area OP, NH3 removals degraded when shallow sediments went anaerobic Baseflow nitrate concentrations lower than stormwater concentrations, indicating between-storm removals
Carlisle et al. (1991)	Ontario	Wetlands	Acceptance of public for stormwater wetlands for treatment and habitat
Casey et al. (2007)		Stormwater ponds	Temporal changes in sediment, macroinvertebrate Cu, Pb, Zn over 11 yr Sediment trace element levels did not significantly change, except for Zn from highways Trace metal body burdens varied among invertebrate groups, and to a lesser extent among land uses, but was a function of year
Chandrasena and Sim (1999)	Sydney	Wetlands	Described efforts to reduce weed (non-native plant) infestation of wetlands and restore wetland functionality
Chavan et al. (2008)	Nevada	Wetlands	Drying and rewetting produced noticeable, but short-term, effects on nutrient retention Longer HRT improved nutrient removal Increased nitrogen loading resulted in better nitrogen removal Similar results seen for TP and TSS
Chavez and Cunningham (2002)		Sediment traps	Describes use of concrete sediment traps/sediment boxes to treat runoff
Chen and Adams (2005)	Modeling	Detention	Probabilistic models in sizing storage facilities to be cost-effective Case study demonstration of method
Chen and Adams (2006)	Modeling	Detention	Methodologies for probabilistic design of water quality control measures Control measures include fraction of pollutant removed
Cheng (2008)	Modeling	Retention pond	Evaluated different pond inlet location's impacts on sediment removal
Cho (2007)	Maryland	Highway stormwater management	Describes Green Highways Partnership
Chouli et al. (2007)	Greece	Stormwater management	Evaluates stormwater management in Europe, issues in Greece, source control options, public policies, and strategies for implementation

Authors	Study Area	Treatment /Management Activity	Conclusions
Christianson et al. (2004)	Modeling	Bioretention	Modeling pollutant removal and degradation in bioretention columns Verifications to be performed using laboratory columns
Christianson et al. (2007)	Kansas	Biofiltration	Describes potential use of vegetated practices to treat runoff and for phytoremediation at military base
Clark and Pitt (2002)	Laboratory	Filtration	Compared upflow and downflow filtration Showed that upflow filtration had longer run times before clogging or effluent quality degradation
Clark and Pitt (2007)	Modeling	Groundwater contamination potential	Two model levels for predicting groundwater contamination concern
Clark et al. (1994)	New Jersey and Laboratory	Filtration	Compared three storm drain inlet filters, filter fabrics and filtration media
Clark et al. (2002)	Laboratory	Filtration	Results showed that anaerobic conditions in organic filter media caused release of previously-trapped nutrients and iron
Clark et al. (2004)	Laboratory	Filtration	Metal retention equal under both aerobic and anaerobic conditions
Clark et al. (2005)		Planning guidance	Reviewed concerns regarding implementation of infiltration practices by state, county and regional governments
Coffman (2003)	Modeling		Argues for new tools to address the protection of receiving waters as related to stormwater management
Cohen and Brown (2007)	Modeling	Wetlands	Model compares management using wetland network with standard incremental approach of site-specific design Improvements set with hierarchical network (flow retention increase of 31%, 36% increase for sediment, 27% for phosphorus)
Colandini et al. (1995)	Field testing	Pervious Pavement	Analyzed clogging materials in pervious pavement Pb, Zn, Cu, Cd sand contamination; concentrations related to road traffic
Conn and Fiedler (2006)	Modeling	Wetlands	Model effects of topographic bottom design on hydraulic residence time Baffled wetlands with multiple vertical-scale topography can increase HRT
Coombes et al. (2000)	Newcastle, New South Wales, Australia	Rainwater tanks, Infiltration, Detention pond	Case study of water sensitive urban design in residential area
Coppes (2002)	United States	Stormwater management	Outlines impact of NPDES on stormwater management Describes infiltration Outlines stormwater management approaches by geographic region of US
Crist (2006)	Virginia	Detention pond	Case study of piping system, conventional detention, under-wharf detention
Crosnier and Delolme (2003)	France Laboratory	Infiltration	Studied effects of wetting and drying on Zn mobility in infiltration basin soils Calcareous soil showed no impact of drying-wetting cycle, but other soils had effects depending on clay and organic matter fractions
Crowe et al. (2007)	Canada	Wetlands	Presented Canadian perspective on wetlands for stormwater treatment and creation of urban habitat

Authors	Study Area	Treatment /Management Activity	Conclusions
Culbertson and Hutchinson (2004)	Kansas Laboratory	Bioretention	Investigated plant species for runoff treatment Switchgrass enhanced infiltration and reduced discharge volume by 70%. Soil media leached nitrogen and phosphorus
Culp and Doering (1995)		Detention pond	Determine optimum volume for pond using standpipe as outlet control
D'Amato et al. (2004)		Stormwater management	Holistic stormwater and wastewater management design principles Describes techniques to overcome institutional barriers to implementation
Daniell and McCarty (1994)	Australia	Wetlands	Describes sedimentation efficiency in artificial urban wetlands and benefits of retrofitting small ponds for stormwater management
Daniell et al. (1994)	Australia	Wetlands	Characterized stormwater to be treated by 4 proposed wetlands
Datry et al. (2003)		Infiltration	Characterized sediments in 30-year-old infiltration basin Bed sediments had high concentrations of organic carbon, nitrogen, phosphorus, total hydrocarbons, and heavy metals. Development of anaerobic conditions in sediments led to release of ammonium, phosphates and dissolved organic carbon during dry-weather periods. Hydrocarbons and heavy metals rarely seem in pore water.
Datry et al. (2004)		Infiltration	Characterized solute dynamics below stormwater infiltration basin Rainfall produced low salinity plume for 2 m below basin Metal and hydrocarbon transport to shallow groundwater not seen
Dauber and Balzano (2005)	New Jersey	Wet pond, Wetland	Case study on multi-purpose regional BMPs for stormwater treatment
Davies et al. (2008)	Australia	Biofiltration, Storage tanks, Disinfection, Wetlands, Retention ponds	Evaluated stormwater treatment devices for microbial removal in light of water reuse standards
Davis et al. (2003)	Maryland Laboratory	Bioretention	Cu, Pb, Zn removal approximately 100% Effluent concentrations: less than 5 µg/L for Cu, Pb, and less than 25 µg/L for Zn. Removal decreased with shallower media depths Runoff pH, duration, intensity, and pollutant concentrations minimal effect
Deb-Moorjani et al. (2005)	Staten Island, New York	Wetlands	Describes Staten Island Bluebelt project which incorporates existing wetlands into drainage network Describes planning the Bluebelt network
Dechesne et al. (2001)	Modeling	Infiltration	Applies life-cycle modeling to evaluate system performance Models proposed for each performance indicator
Dechesne et al. (2002)	France	Infiltration	Context indicators for assessing infiltration basin state based on clogging, contamination Clogging function of time Topsoil acted as pollutant trap for metals with little penetration below 30 cm
Dechesne et al. (2004)	France	Infiltration	Metal pollutant concentrations decrease rapidly with depth pH, mineralization and grain size increase with depth Topsoil statistically different from lower layers Concentrations highest near inlet and at topographically low points

Authors	Study Area	Treatment /Management Activity	Conclusions
Dechesne et al. (2005)	France	Infiltration	Describes long-term clogging and soil pollution of basin Characterizes clogging by hydraulic resistance term No relationship seen between age, hydraulic resistance and pollution
Decker and Guo (2003)	New Jersey	Detention basin Subsurface wetland	Modeled retrofit of existing detention basin with sediment forebays and subsurface constructed wetlands to determine applicability Concerns necessitated new location, indicated need for H&H modeling
Dee (1997)	District of Columbia	Detention pond	Described design of detention basin retrofit with sand filter
Deletic and Fletcher (2006)	Aberdeen, Scotland Brisbane, Australia	Grass filter strips	Aberdeen strip reduced sediment by 61-86%, while Brisbane swale removed average of 69, 46, and 56% of TSS, TP, TN loads, respectively. TRAVA used to model both the strip and swale.
Dennett and Spurland (2001)	Steamboat Creek, Nevada	Constructed wetlands	Wetlands removed 65% to 99% for NO ₂ +NO ₃ , 30% to 80% for NH ₃ , 20% to 60% for TP, 20% to 75% for OP, and 80% to 95% for TSS.
Der (1999)	Maryland	Wetlands	Case study on balancing wetlands preservation and re-creation with highway stormwater management
Dierkes et al. (2002)	Germany	Hydrodynamic separator Multistage filter of pervious concrete	Pollution control pit of separator and filter suggested as underground method to pre-treat stormwater before infiltration Expected to remove >90% of the particulates and associated pollutants
Dietz (2007)		Low Impact Development	Reviewed current state and research results on LID
Doston (2006)		Subsurface Detention, Infiltration	Describes subsurface retention/detention/infiltration and storage chamber
Dougherty et al. (2007)	Alabama	Bioretention	Systems with and without internal storage zones (ISZ) for denitrification Particulate and sediment removal good Denitrification occurred, but late in the study period Significantly reduced outflow hydrograph
Dreelin et al. (2006)	Georgia	Pervious pavements	Pervious pavement over clay soils reduced runoff by 93% compared to asphalt lot during small storms Pervious pavement also reduced turbidity, Zn, Si, TP, Ca TN and conductivity higher at pervious pavement site
Driscoll (1989)	Multiple sites	Detention ponds	Summarizes performance of stormwater ponds as reported in NURP Discusses effects of storm runoff settling velocities, small storms, and analytical method for sediment analysis
Dunn et al. (1995)		Extended detention ponds, Wet ponds, Infiltration, Sand filters, Pervious pavement, Constructed wetlands, Swales	Documents current BMP design guidance and known removal efficiencies
Dunphy et al. (2007)	Sydney, Australia Laboratory	Infiltration	Developed model to describe treatment effectiveness of pervious pipe and soil with GAC to treat infiltrating water Experiments showed that sand/GAC ratio of 25:1 was ideal.
Dussaillant et al. (2003)	Wisconsin Modeling	Infiltration	Compared Green-Ampt and Richards models for rain garden Similar results seen with simpler G-A model

Authors	Study Area	Treatment /Management Activity	Conclusions
Dussaillant et al. (2004)	Wisconsin Modeling	Bioretention	Applied Richards equation to modeling rain garden flow Demonstrated effect of subsoil hydraulic conductivity on performance
Dussaillant et al. (2005a)	Wisconsin Modeling	Bioretention	Rain garden water flow modeled as three layers: root zone, storage layer of high hydraulic conductivity, subsoil lower layer Maximum groundwater recharge occurs when rain garden is 10% of impervious area
Dussaillant et al. (2005b,c)	Wisconsin Modeling	Bioretention	Groundwater recharge ability in Wisconsin, Nevada and Chile Optimum ratio of impervious area to rain garden area was 10 – 20% in Wisconsin and Chile and 5% in Nevada
Dzurik and Leszczynska (1995)		Constructed wetlands	Reviewed perspectives of constructed wetlands and potential applications
Echols (2008)	Pennsylvania	Split flow devices	Split flow theory where runoff is divided into evaporation, infiltration and discharge parts and managed to mimic pre-development hydrology
Eganhouse (1981)	Los Angeles, California	Pollutant transport	Analyzed transport of soluble organics in urban runoff No relation seen between organic concentrations and storm parameters
Elliott and Trowsdale (2007)	Modeling	Low Impact Development	Reviewed LID models for applicability for design and evaluation of sites
Ellis (1989)	United Kingdom	Detention pond	Design criteria to meet water quality, amenity, ecological functionality goals
Ellis (2000)	Multiple sites	Infiltration	Reviewed long-term performance of infiltration systems Reviewed acceptance matrix for infiltration
Ellis et al. (1994)	Laboratory	Wetlands	Evaluated macrophytes for pollutant treatment Typha and Juncus were able to uptake metals from simulated runoff Typha rhizome major metal bioaccumulation area
Emerson and Traver (2004)	Pennsylvania	Bioinfiltration	Case study of traffic island bioinfiltration area Removes 69% of annual runoff
Emerson and Traver (2008)	Pennsylvania	Infiltration	Case study on two infiltration devices Seasonal differences in flow performance noted and related to temperature impacts on water viscosity
Emmett et al. (1996)	Northfield, South Australia	Wetland-Detention basin	Wetland acts as flood control basin Infiltrated water withdrawn for summer irrigation and wetlands topping
England (1998)		Baffle boxes Inlet devices	Describes small footprint devices that can be retrofitted in-line for stormwater treatment
Eriksson et al. (2005)		Stormwater pollutant characterization	Describes an assessment protocol for hazardous pollutants (xenobiotic organic compounds) in stormwater runoff Presented a list of 16 priority pollutants to be included in runoff chemical hazard identification
Estime et al. (2002)		Wetlands	Presented method to use callus cells to estimate phosphorus absorption by cattail leaves

Authors	Study Area	Treatment /Management Activity	Conclusions
Evans (2004)	Cleveland, Ohio	Stream restoration	Describes stream restoration in heavily urban area and governmental partnerships required
Eyles et al. (2003)	Pickering, Ontario, Canada	Stormwater pollutant transport	Describes impacts of urbanization and increased stormwater on bay
Fach and Geiger (2005)		Permeable pavements	Demonstrated that pollutant retention ability varied greatly and depended on the material and specific reactive surface
Fan (2004)	Modeling	Extended detention Storm flow impacts characterization	Modeled using SWMM for storm flow regimes for stream erosion ability Modeled effects of control structures and source control on stream erosion
Farrel and Scheckenberger (2003)		Constructed wetlands	Describes 5-yr monitoring results (sediment, nutrients, metals) Describes operating conditions of wetland
Felstul and Montgomery (1991)	Modeling	Detention ponds	Spreadsheet model to estimate removal of particulate-associated toxicants Calculates dynamic, quiescent settling for 9 grain sizes, 7 toxicants
Ferguson and Suckling (1990)	Atlanta, Georgia	Stormwater management	Describes impacts of urbanization on baseflows and evapotranspiration Argues for inclusion of increasing ET and baseflows when planning
Fernandez (2006)	Scrapyards		Challenges of controlling stormwater runoff from scrapyard facilities
Ficquette (2004)	Shooting ranges, Florida		BMPs should incorporate lead removal and recycling, soil pH adjustment, and use of ground cover and dams to retain stormwater runoff Lead migration greatest in sand soils with low clay and organic content
Field and Lager (1975)		Multiple technologies	Summarizes treatment technologies for urban runoff
Field et al. (1995)		Multiple technologies	Summarizes BMPs for stormwater treatment
Finch and Macrina (1998)	Clearwater, Florida	Wetlands	Plan to use wetlands to control flow, biological treatment of runoff
Finkenbine et al. (2000)	Vancouver, British Columbia, Canada	Stream health evaluation	Impacted streams had large TIA, limited large woody debris, limited buffers Detention facilities constructed after the stream reacted to urbanization were not effective for prevention of flow damage
Finlay and Briertey (2000)	Modeling	Detention tanks	Development of computer program to design tanks
Finnemore and Lynard (1982)		Stormwater management planning	Management practices for urban runoff, including institutional, land use planning, street cleaning, erosion control, percolation ponds, sedimentation basins
Fischer et al. (2003)	New Jersey	Infiltration	Groundwater below infiltration basins had lower DO, which affected concentrations of major ions. VOC and pesticide occurrence was function of land use High recharge rates increase loading even when concentrations are low
Fischer et al. (2006)	Eastern United States	Infiltration	Addresses geotechnical investigations for development in karst terrain Requires understanding of variability in subsurface environment
Fisher and Street (2003)		Wetlands	Case study on transforming solid waste site into park, lake and wetlands for stormwater treatment
Flemming et al. (2008)	South Carolina	Detention ponds	PAH distribution in sediments and false dark mussels correlated Mussels may be good bioindicator of PAH pollution

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Fong and Nazarudeen (1996)	Singapore	Stormwater reuse reservoir	Case study on stormwater recycling for potable water supply Stormwater runoff comparable in quality to raw water supplies
Frechen et al. (2006)	Germany	Filtration	Describes use of plant-recovered retention filter to treat stormwater and combined sewer overflows Presents results of long-term observations
Freni et al. (2002)	Norway	Distributed stormwater practices	Proposes methodology to evaluate efficiency of complex distributed stormwater management practices Modeling performed with SWMM
Frentress (2006)	Portland, Oregon	Pervious pavement	Case study Monitoring infiltration rates, water quality, pavement durability, hydraulic properties, maintenance needs, and public acceptance
Fritioff and Greger (2006)		Wetlands	Measured uptake of Zn, Cu, Cd, Pb by Potamogeton natans. Uptake by leaves, stems and roots, with greatest uptake in roots Uptake of Cu by roots limited by competition with other metals
Fuchs (1984)		Detention basins Infiltration basins	Assessed renovation alternatives for storm sewers, including incorporation of infiltration and detention systems, through modeling
Fujita (1984)	Tokyo, Japan	Permeable pavement, Infiltration, Storage	Describes design philosophy for experimental sewer system that incorporates pipes, detention, storage and infiltration
Fujita (1993)	Tokyo, Japan	Infiltration	Describes infiltration methods and implementation in Tokyo
Fujita (1994)	Tokyo, Japan	Infiltration	Describes planning, design, construction, maintenance of infiltration systems. Implementation reducing contamination of receiving waters Case studies of Tokyo infiltration facilities
Fujita (1997)	Tokyo, Japan	Infiltration	Methods for distributing stormwater infiltration in heavily urbanized area
Fujita (2002)	Tokyo, Japan	Stormwater management	Describes modernization of stormwater practices in heavily urbanized area
Fulkerson et al. (2007)	Orlando, Florida	Stormwater characterization	Characterized mercury in urban runoff and its sources Noted removal of mercury from drainage system during transport to outfall
Furumai et al. (2005)	Modeling	Infiltration	Modeled dynamic runoff behavior for small storms Model used dynamic change in storage capacity and infiltration
Galatowitsch et al. (2000)		Wetlands	Plant guild suggested, rather than species, to describe impacts of land use changes on biota Changes include shifts away from native graminoid and herbaceous perennial abundance to annuals or non-native perennials
Geiger and Becker (1999)	Germany	Infiltration Source control	Describes feasibility studies for new drainage ideas Goal of balancing infiltration with collection and surface treatment of stormwater
Geldof et al. (1994)		Infiltration	Case studies on infiltration impacts on flooding and overflow events Groundwater recharge encouraged with infiltration

Authors	Study Area	Treatment /Management Activity	Conclusions
Genc-Fuhrman et al. (2007)	Laboratory	Filtration	Bauxsol-coated sand, fly ash, and spinel prefer cationic or non-charged metals i.e. Cd, Cu, Ni and Zn), compared to anionic species i.e. As and Cr). Iron-oxide coated sand, natural zeolite and sand prefer As and Cr, while alumina has equally high affinity to all tested heavy metals
Genc-Fuhrman et al. (2008)	Laboratory	Filtration	Iron based sorbent able to remove As, Cd, Cr, Cu, Ni, Zn from runoff Humic acid interfered with removal Lack of light reduced removal Used Thomas model to predict breakthrough sorption capacities
George et al. (2001)	Golf course	Wetlands	Discusses nitrogen flux in ecosystem adjacent to golf course Fiddler crab used as indicator of estuarine health
German (2003)		Retention ponds Street sweeping	Measured, modeled pollutant removal ability of pond and street sweeping Pond sediments correlated to runoff pollutant loads
Gharabaghi et al. (2006)	Ontario, Canada	Vegetated filter strips	Studied vegetation type, filter strip width, runoff flow rate, and influent sediment characteristics to sediment removal ability Sediment removal increased as filter strip width increased Most particles > 40 µm trapped within first 5 m
Gilbert and Clausen (2006)	Connecticut	Pervious pavements	Runoff quality from asphalt, permeable paver, crushed stone driveways Runoff rates and volumes: asphalt > paver > stone Average infiltration rates 0, 11.2 and 9.0 cm/h for asphalt, paver, and crushed stone driveways, respectively. Paver runoff quality better than asphalt, which was comparable to stone, except for TP which was lower in stone
Gironas et al. (2008)	Laboratory	Filtration	Studied expanded perlite, nonwoven geotextile to reduce solids load. Regression model developed to describe filter performance
Glenn et al. (2002)		Stormwater characterization	Examined associations of metals with stormwater solids Low alkalinity, low hardness and short pavement residence time (less than 30 minutes) resulted in majority of heavy metal mass remaining in solution
Gobel et al. (2004)	Germany	Infiltration	Effects of infiltration on groundwater surface modeled Both precipitation and infiltration rate affect groundwater surface Mounding should be expected in areas with low hydraulic conductivity
Goddard (2006)		Wetland	Used to treat stormwater for reuse in toilets Member bioreactor and UV disinfection also included in treatment scheme
Goebel et al. (2002)	Germany	Infiltration	Describes use of water balances to predict rising groundwater surface below intensive infiltration facilities
Goff and Gentry (2006)		Detention ponds	Watershed shape, stage of development, sequence of development had greatest effect on the cumulative impacts of ponds Development intensity, development size, and watershed slope contributed to the magnitude of the impacts which were created, but did not determine pattern of impacts

Authors	Study Area	Treatment /Management Activity	Conclusions
Goitom and Reischauer (1990)	Oman	Infiltration	Modification of wadis to detain water and promote infiltration described Case study included
Goransson (1999)		Detention Infiltration	Discusses improvements to aesthetics of stormwater drainage Case studies
Goutaland et al. (2007)	France	Infiltration	Modeled hydrostratigraphy of glaciofluvial deposit below basin Modeled effects of heterogeneities on water content distribution Heterogeneous facies may act as preferential flow paths
Graham and Lei (2000)		Detention ponds, Wetlands	Describes maintenance needs, including sediment removal
Graham et al. (2004)	Modeling	Low Impact Development	Demonstrates of water balance modeling to evaluate LID options
Graney and Eriksen (2004)	Broome County, New York	Detention ponds	Temporal changes in sediment Pb mimic rise, fall in leaded gasoline use As concentrations decreased as emissions tightened coal power plants
Grapentine et al. (2008)	Toronto, Ontario, Canada	Detention pond	Toxicological responses of benthic invertebrates exposed to sediment Toxicity decreases as water moved through facility
Grau and Harms (1986)	Germany	Infiltration	Standards and specifications for infiltration structures Site requirements compared to standards in other countries
Green et al. (1994)		Wetlands, Wet ponds, Grass swales	Monitoring programs for pollutant removals; provide process information
Greenway et al. (2002)	Brisbane, Australia	Detention pond Wetland Hydrodynamic separator	Case study examined performance of treatment train of devices Little reduction in TSS, but decrease in soluble nutrients During dry weather, wetland generated NH ₄ and organic particulates
Greenway et al. (2007)	Australia	Wetlands	Investigated plant establishment in new wetland Complete loss of macrophytes in marsh and ephemeral zones due to excess periods of inundation
Grizzard et al. (1986)	Laboratory and field studies	Extended detention ponds	Laboratory studies measured pollutant reductions in water with low, medium and high initial solids concentrations Field and lab data comparable
Groffman and Crawford (2003)	Baltimore, Maryland	Wetlands Riparian zones	Measured denitrification rates and microbial parameters Higher variability in urban zones Denitrification potential positively correlated with soil moisture, OM content Suggests wetlands may be effective at denitrification
Grout et al. (1999)	Houston, Texas	Wetlands bayou Stormwater characterization	Colloidal particles contained 17% of C, 32% of Si, 79% of Al, 85% of Fe, 52% of Cr, 43% of Mn, and 29% of Zn in runoff filtrates Composition of colloidal material changes over time
Guillory and Macrina (1998)	Pinellas County, Florida	Wetland	Describes retrofit of urban drainage basin as a wetlands
Gumb et al. (1995)	New York City, NY Modeling		Describes stormwater management plan and modeling to evaluate existing hydraulic structures and develop improvements
Guo (2008)		Low Impact Development	Model proposed that modifies conventional area-weighted method with a paved area reduction factor

Authors	Study Area	Treatment /Management Activity	Conclusions
Guo and Zhuge (2008)	Modeling	Detention pond	Methods presented to incorporate probabilistic flood routing into design Highlights problems with design storm approach
Guo et al. (2006)		Filtration	Higher rain intensity linked to higher diss. fraction of Zn, Cd, Cu, not Pb Transport through partial exfiltration reactor produced minimal changes in speciation of metals
Haasen et al. (2002)	London	Stormwater management planning Infiltration	Case study of stormwater management plan to promote infiltration and reduce impacts to sewer system Overland conveyance systems also heavily incorporated
Harada and Ichikawa (1994)	Tokyo, Japan	Infiltration	Artificial soil structure and pervious pavement for rate and volume control Modeling shows 42% volume reduction Model created for device to reflect strata in device
Hares and Ward (1999)	London, England	Biofiltration Dry detention	Motorway-derived contaminants directly related to traffic density Bioinfiltration has greater removals than pond
Hares and Ward (2004)	England	Vegetated treatment facilities	Heavy metals in pond sediments decreased in well-established reed bed. Postulated that reeds slowed flow and improved sedimentation.
Harms (1984)		Infiltration basin	Described stormwater infiltration at two sites Described model activities
Harned et al. (1992)	Savannah, Georgia	Wetlands	Case study of airport expansion with wetlands enhancement and creation for stormwater management
Harrell and Ranjithan (1997)	High Point, North Carolina Modeling	Wet detention ponds Stormwater management	Genetic algorithm optimization approach to determine most cost effective system of ponds and corresponding land use allocation
Harrington (1989)	Maryland	Infiltration	Describes feasibility, design and construction of infiltration trenches Describes design considerations to prolong useful life of trenches Survey of existing infiltration facilities
Hatoum (1998)	Florida	Wetlands	Describe oxbow retrofit to create additional wetlands and slow flow Goal to reduce suspended solids in creek
Hatt et al. (2006)	Australia Laboratory	Filtration	Pollutant removal did not improve as filters clogged and flow rate slowed Dissolved nutrient removal highly variable
Hatt et al. (2007a)	Australia Laboratory	Biofiltration	Evaluated 6 biofiltration media to remove pollutants, promote plant growth Soil-based filters removed 80% of solids, 90% of Pb, Cu, Zn 3 filters able to treat phosphorus Soil filters were net producers of nitrogen
Hatt et al. (2007b)	Australia Laboratory	Filtration	Tested 5 soil-based biofilters following extended dry periods Infiltration capacity reduced when soil wet but increased after drying period P, TSS, metals removal not affected by wetting and drying period Nitrogen release increased after extended dry periods

Authors	Study Area	Treatment /Management Activity	Conclusions
Hatt et al. (2007c)	Australia Laboratory	Filtration/Infiltration	Gravel infiltration system effectively removed sediment and heavy metals under all water regimes Depth of 0.5 m achieved adequate pollutant removal Physical clogging occurred before pollutant removal capacity exhausted Not effective at nutrient removal
Hatt et al. (2008)	Australia Laboratory	Filtration	Sand and soil-based filters failed primarily due to clogging after buildup of cake sediment layer on top of media Pollutant accumulation occurred primarily in top 20% of filter Nutrient releases likely due to degradation of native soil materials
Heasom (2005)	Pennsylvania	Bioinfiltration	HEC-HMS used to model bioinfiltration basin and its watershed Green-Ampt and kinematic wave methods used to calculate infiltration and runoff volumes and hydrograph shapes
Heasom et al. (2006)	Pennsylvania	Bioinfiltration	Hydrologic modeling of bioinfiltration basin HEC-HMS used to represent site and Green-Ampt and kinematic wave methods represented bioinfiltration island
Hebrard and Delolme (1999)		Infiltration	Showed that biofilm from <i>Pseudomonas putida</i> retarded zinc migration in sand infiltration media Adsorption was reversible (except at pH 6 and 7) and non-instantaneous
Heineman (2005)	Modeling	Structural practices	Long-term modeling of structural BMPs using STORM Used to size detention ponds
Heinzmann and Sarfert (1995)	Germany	Infiltration	Use of treatment prior to infiltration to artificially recharge groundwater for future water supply
Henderson et al. (2007)	Australia Laboratory	Biofiltration	Vegetated sand and vegetated sandy-loam removed 53 – 77% of N and 85 – 94% of P Carbon removal: 28 – 66% Tap water flushing, nutrients retained in vegetated systems, but not in unvegetated ones
Herath and Musiak (1994)	Modeling	Infiltration	Model with hydrological and infiltration components to simulate infiltration implementation in watershed Demonstration study in residential area presented
Heyvaert et al. (2006)	Tahoe, Nevada	Wetland	Wetland removed 49% or more of DP, DN, OP, TSS TP EMCs reduced from inflow 279 µg/l to outflow 94 µg/l TN EMCs reduced from inflow 1,599 µg/l to outflow 810 µg/l
Hicks and Larson (1997)		Wetlands	Evaluated impact of urban runoff on freshwater wetlands Describes application of macroinvertebrate assessment protocol to evaluate impacts Ecological integrity affected by amount of impervious surface

Authors	Study Area	Treatment /Management Activity	Conclusions
Hicks et al. (1993)	British Columbia, Canada	Wetlands	Case study of conceptual planning to construction and operation of stormwater wetlands Describes wetland functions of hydrology, ecology, recreational value, aesthetic value, education value
Higgins and Maclean (2002)	Edmonton, Canada	Subsurface wetland	Reviews feasibility study used to design wetland system at airport Compares Edmonton wetland with similar system at Heathrow Airport
Higgs (1978)	Virginia	Infiltration	Describes percolation storage for 10-year storm Percolation storage substituted for detention ponds
Hilding and Horner (1994)	Puget Sound region, Washington		Surveyed 23 infiltration basins to evaluate performance and degree of compliance with state guidelines Maintenance procedures also summarized
Hipp et al. (2006)	Laboratory	Filtration	Evaluated 10 curb-inlet filters for pollutant retention Removals ranged from 0% to >90% depending on the pollutant GIS system modeling optimal placement in case study watershed
Hitchcock and Williams (2007)	South Carolina	Constructed wetlands, Vegetated buffers, Bioretention systems	Evaluate potential use in coastal areas; effects on shallow groundwater
Hogan and Walbridge (2007)	Virginia	Detention pond Wetlands	Compared detention ponds designed for flood control and stormwater treatment with riparian wetlands Water-quality ponds had soil P adsorption similar to wetlands Surface soil P concentrations greater in detention ponds than wetlands
Holland et al. (2004)	Modeling	Wetland	Flow rate had little effect on residence time distribution, but water level did
Holland et al. (2005)	Modeling	Wetland	Using high-frequency data to calibrate, model was developed for pulsed flows and constituent fluxes in wetlands Residence time distribution (RTD) modeling with reaction kinetics of suspended solids better replicated outflow than plug-flow reactor models
Holmstrand (1984)	Laboratory	Infiltration	Describes research at Chalmers University of Technology
Hong et al. (2006)	Laboratory	Bioretention	Mulch layer of bioretention media trapped O&G Degradation of most of trapped organics occurred within one week of sorption to media
Hopkins and Argue (1994)	South Australia	Wetlands Swales	Describes where runoff collected, treated and used to sustain trees Swales used to recharge groundwater Two case studies presented
Horner (1989)	King County, Washington	Wetlands	Reviews expert panel working with King County to reduce impacts of stormwater runoff on wetlands and streams
Horner and Potts (2003)		Infiltration	Need to mimic pre-development hydrology in carbonate geology areas Recommendation charts developed to integrate site risk ratings and design parameters

Authors	Study Area	Treatment /Management Activity	Conclusions
Horner et al. (2002)		Structural control practices	Studied ability to mitigate impacts of runoff on streams Results showed little developed area served by treatment practices and inadequate design standards reduced their effectiveness
Hossain et al. (2005)	Spokane, Washington	Detention pond	TSS removal ranged from 68 – 99%, heavy metal removal: 55 – 65% Pond's flow regime varied with changing surface topography, which resulted from solids sedimentation
Hossain et al. (2007)	Tokyo, Japan	Infiltration	Heavy metals elevated in device sediment compared to background Substantial fraction of metals in potentially mobile fractions Decreases in potential sorption sites with depth noted
Hou et al. (2008)		Pervious pavement	3 pavement systems investigated for infiltration capability Optimum pavement system thickness 31 cm (6 cm pavement; 25-cm subbase) Rainfall of < 60 mm/h was completely infiltrated
Houston (1984)		Detention pond	Presented simple model to size urban detention ponds
Hoyt and Brown (2005)		Detention pond Wetlands	Described maintenance guidance developed for ponds and wetlands 8 common problem areas related to design, construction and post-construction operation identified
Hsieh and Davis (2005)	Maryland Laboratory	Bioretention	Evaluated bioretention media for pollutant removals >96% removal for O&G Lead removal inversely related to TSS removal TP removal related to preferential flow patterns bypassing treatment area Nitrate and ammonium had poor to moderate removals
Hsieh et al. (2007)	Maryland Laboratory	Bioretention	Showed that long-term phosphorus reactions in the media may open up short-term sorption sites (media regeneration) P removal increased when high infiltration media layered on top of low infiltration rate media
Huber et al. (2005)	Modeling	Low Impact Development	SWMM 5 used to model wet-weather controls and LID
Huhn and Stecker (1997)		Infiltration	Case study of using infiltration to mimic pre-development hydrology in area where traditional discharge system cannot be used
Hunt (2000)	North Carolina	Wetlands, Detention pond, Permeable pavement, Sand filter, Swales	Described demonstration sites Noted that some pollutant removal occurring in these devices
Hunt et al. (2002)	North Carolina	Permeable pavement	Runoff coefficients of block paver system to be between 0.20 and 0.50.
Hunt et al. (2003)	Mid-Atlantic region, USA	Bioretention	Presented design to optimize denitrification in biofiltration and data regarding design efficiency for nutrient removal
Hunt et al. (2005)	North Carolina	Bioretention, Dry detention, Green roofs, Permeable pavement, Sand filters, Wetlands	Determined inspection and maintenance costs of treatment practices Maintenance costs were higher than inspection costs Sand filters more expensive to maintain than ponds

Authors	Study Area	Treatment /Management Activity	Conclusions
Hunt et al. (2006a)	Modeling	Infiltration	Advocates incorporating infiltration into site design, not as retrofit Rating system for land development proposed that would quantifiably assess effectiveness of water resources use
Hunt et al. (2006b)	North Carolina	Retention ponds	Measures mosquito occurrence, relative abundance in ponds and wetlands Negative relationship between larvae/pupae and mosquitofish
Hwang et al. (2006)	Calgary, Canada	Retention ponds	Described strategy to use stormwater pond water to irrigate parks Described public attitudes toward stormwater recycling Users unwilling to accept much risk to health, but willing to consider irrigation use of stormwater
Ichikawa and Sakakibara (1984)	Tokyo, Japan	Infiltration	Grid Model used to evaluate effects of infiltration on peak flows
Illgen et al. (2007)		Permeable pavements	Goal to generate database of practices Database to be used to develop model of permeable pavement behavior
Ishizaki (1985)	Japan	Infiltration	Describes use of subsurface infiltration Case study presented
Jacobsen and Mikkelsen (1993)		Detention ponds Infiltration	Describes impact of ponds and infiltration to reduce CSOs Ponds adversely affect CSOs, while infiltration reduces loading to treatment plant
James and Auger (2003)	Modeling	Infiltration Detention and retention ponds	Uses PCSWMM to select most cost effective treatment that meets water quality and quantity goals
Jankowski and Knight (2001)	Sydney, Australia	Wetlands	Negative impact of polluted groundwater on wetlands chemistry Pond chemistry controlled by dilution, concentration, mixing, ion-exchange, dissolution-precipitation of carbonates, reduction processes
Jayasuriya et al. (2007)	Australia	Pervious pavements	Laboratory testing of permeable pavement infiltration behavior Established relations between rainfall intensity, infiltration rate and pavement runoff
Jenkins and Greenway (2007)	Australia	Wetlands	Ecological, hydrological assessment of stormwater wetland over 5 years Created bathymetric map of wetland Created time series plots of vegetation Frequency and duration of inundation affected vegetation distribution
Jewell (1985 a,b)	Modeling	Detention pond	Uses MULTIPLAN to analyze stormwater data and design detention pond
Jimenez et al. (2000)	Mexico	Infiltration Detention reservoir	Describes reuse of urban storm and wastewater for agricultural irrigation Assesses impact of infiltration on inter-connected shallow aquifers and drinking water supply
Johnson and Cave (2003)	Michigan	Stormwater practices	Describes management of stormwater as part of Rouge River restoration
Jokela and Pinks (1998)	Alaska	Detention pond	Describes use meet permit limits for Anchorage and AKDOT
Jonasson (1984a)	Sweden	Infiltration	Difficult to obtain accurate hydraulic conductivity values for sizing
Jonasson (1984b)	Sweden	Infiltration	Describes data needs for sizing infiltration basins

Authors	Study Area	Treatment /Management Activity	Conclusions
Jones (1984)		Detention ponds	Findings of ASCE task committee on outlet control structures
Jones (1990)		Detention pond	Summarizes multipurpose detention pond concepts for dry and wet ponds
Jones and Anderson (1994)		Detention ponds	Describes concerns about sediment toxicity under RCRA
Jones et al. (2004)		Multiple devices	Describes difficulty of monitoring treatment devices Describes International Stormwater BMP Database
Jones et al. (2007)	North Carolina	Bioretention Wetlands Wet detention pond	Investigated temperature changes through treatment devices Describes changes in temperature during soil and buried pipe transport Describes effects of shading on surface runoff temperature
Kalaba and Wilson (2005)	New Brunswick Modeling	Detention pond	Describes challenges of modeling compost runoff to determine needed size of detention pond to control organics, solids and nutrients
Kalli (2004)	Australia	Swales, Bioretention, Wetlands, Detention ponds	Describes treatment and reuse for augmenting potable water supplies
Kandasamy et al. (2008)	Sydney, Australia	Filtration	Investigates sand filters to treat stormwater for harvesting Results showed similar removals for many pollutants (compared to literature), and increased nutrient removal Modeled TSS and TP removal
Kang et al. (2007)		Filtration	Expanded polypropylene evaluated in upflow mode to remove TSS, COD Showed that removal improved with increasing expansion ratio but then required more frequent maintenance
Kao et al. (2001a)	Taiwan	Wetland	Removed 88% of nitrogen, 81% of COD, 60% of TSS
Kayhanian and Stenstrom (2005)	California	Multiple devices	Improved performance of treatment devices when treating first flush Models simulated first flushes through several devices and shows that focusing on first-flush treatment may be more cost-effective based on lower mass loadings later in storms that are harder to treat
Keane (2004)		Stream assessment	Describes database of reference streams Describes application of database to restoration planning and design
Kennedy et al. (2007)		Stormwater characterization	Determined elemental composition of stormwater particles P, S, Cl, Ca, Mn concentrations not related to land use in small size fraction, but related to industrial use in particle size range of 60 – 250 μm
Kerr-Upal et al. (2000)	Toronto, Canada	Wetlands	Case study of conceptual design combined with flow-balancing system Reviews policy implications of proposed facility
Kibler and Aron (1978)	Modeling	Runoff simulation	Sensitivity analysis of SWMM and PSRM Models extended to land surfaces to demonstrate need to improve models
Kim et al. (2003)	Maryland Laboratory	Bioretention	Created submerged anoxic zone over underdrain for N removal Newspaper was a good electron donor for denitrification
Kim et al. (2006a)	Laboratory	Permeable pavement	Lower-pore-size pervious pavements had higher pollutant reductions Water adsorption capability will decrease runoff temperature

Authors	Study Area	Treatment /Management Activity	Conclusions
Kim et al. (2006b)		Filtration	Evaluated fibrous materials as stormwater filters Needed chemical modifications to achieve satisfactory pollutant removal Combined with polymer filter media for treatment application
Kim et al. (2006c)		Filtration	Waste plastic was incorporated into stormwater treatment media Compared water retention and flow rates All media: similar TSS and PAH removal Heavy metal removal related to hydrophobicity of media.
Kim et al. (2007)		Filtration	Evaluated upflow filter of pervious polypropylene for TSS removal Removal efficiencies of > 90% when evaluating sump and filter; 70% removal in filter
King (1984)	Florida	Wetlands	Describes use of wetlands for treatment, habitat creation, education
Knuth et al. (2005)	Colorado	Extended detention pond Wetlands	System removing TSS, TN, TP, Cu, Cd E. coli removal not demonstrated
Kohler et al. (2004)		Wetlands	4-year study of golf course wetlands demonstrated removals of NO ₃ , NO ₂ , NH ₃ , P, COD, TOC, Ca, Cl, Mg, Mn, Na Recommended maximizing holding times/size as part of design
Koob and Barber (1998)	Washington state	Detention ponds	Describes O&M considerations for ponds treating highway runoff Pond in heavy snow area required more frequent dredging
Koob et al. (1999)		Wetlands	Describes hydrologic design considerations Outlet structures designed based on both storm size and dry periods to ensure healthy plant and phytoplankton growth
Krishnappan and Marsalek (2002)	Modeling	Detention pond	Applied model of flocc settling to predict sediment transport
Kumar (2004)	Virginia	Stormwater management planning	Classification scheme for subwatersheds based on management category Based on estimating ultimate imperviousness and establishing relationship with stream quality
Kuo et al. (1988)		Detention ponds Infiltration Pervious pavement	Presented model for preliminary design, evaluation and cost effectiveness analysis of treatment devices Extended detention provided most cost effective performance
Kutschke et al. (2005)	Maryland	Geotextile membrane, Swale, Detention pond	Case study describing stormwater treatment system for roadway development in karst
Kwiatkowski and Welker (2003)	Pennsylvania	Pervious pavement	Describes monitoring program for pervious pavement installation for water quantity and quality
Kwiatkowski et al. (2007)	Pennsylvania	Pervious pavement	Pervious pavement system able to remove Cu in first 0.3 m Cl not significant enough to impact groundwater
Lacoursier et al. (2003)		Vegetated stormwater treatment	Describes lessons learned from vegetation use Describes actions of developing countries to use non-vegetated practices instead of vegetated ones
Lai et al. (2005)		Low Impact Development	Development of decision-support system for device placement and LID

Authors	Study Area	Treatment /Management Activity	Conclusions
Lambert (2006)	Oregon	Filtration	Describes rainwater harvesting/stormwater treatment through StormFilter™
Lampe et al. (2004)	Multiple sites	Multiple devices	Compared treatment practices in U.S. and internationally Concluded that greater the natural value of receiving water, the greater the effort to protect it during stormwater management planning
Landers (2003)	Kentucky	Filtration	Describes filtration system for runoff treatment prior to cave discharge
Lantin and Barrett (2005)	Texas	Grass/vegetated swales	Evaluated by determining average differences between runoff at pavement edge and after passage through various strip widths; effect of site characteristics, effects of differences vegetation and coverage and climate. Swales could treat solids and metals and irreducible concentrations achieved within few meters of pavement edge.
Lantz (1998)	Arizona	Detention pond	Case study describing regional detention project with multiple basins Uses different configurations to establish different types of habitat
Lassabatere et al. (2004)	Laboratory	Infiltration	Investigated effect of geotextile on pollutant removal in calcareous soil When placed wet, needle-punched geotextile did not affect solids and metals removal, but when placed dry, it homogenized flow and created better contact between heavy metals and soil, Thermo-sealed geotextile, placed dry, homogenized the flow and increased retention over larger area
Lassabatere et al. (2005)	Laboratory	Infiltration	Showed that geotextiles modify heavy metal transfer to soils, depending on geotextile type, hydric conditions, hydraulic conditions, number installed
Lau and Stenstrom (2005)	California	Stormwater characterization	Showed smaller particles had higher solid-phase concentrations, but not as high as the specific-surface area ratios Relative PAHs concentrations higher on small particles than metals Single-family residential areas lowest in metals and PAHs Greatest pollutant mass associated with particles in 100-250 µm range.
Lau et al. (2000)	Laboratory	Biofiltration	3-day biofilm on filter media able to remove 90% of TSS and metals
Laughland (1996)	Modeling	Stormwater runoff	Describes adjustment of hydrology models such as TR-55 for karst geology
Lawrence and Phillips (2001)	Modeling Australia	Detention ponds Wetlands	Described development of separate pond and wetland models that address physical, chemical and biological pollutant removal processes
Lawrence et al. (1996)	Multiple sites	Detention ponds	Outlines considerations in hydrological and pollutant mobilization processes, and selection of detention and water quality treatment devices
Le Boultilier et al. (1999)	Modeling	Stormwater characterization	Describes pollutant build-up functions to estimate pollutant loads in runoff Describes washoff efficiency functions to address non-ideal transport Case study of residential catchment
Le Coustumer and Barraud (2007)	France	Infiltration	Long-term study of hydraulic and pollutant removal performance Describes model calibration for study device

Authors	Study Area	Treatment /Management Activity	Conclusions
Le Coustumer et al. (2007a)	Australia	Biofiltration	Investigated improvements for hydraulic performance Noted decrease in hydraulic conductivity early in life Examines ratio of biofilter size to drainage area size Examines influence of media type on hydraulic performance
Le Coustumer et al. (2007b)	France	Infiltration	Temporal evolution and spatial distribution of heavy metals in top soil layer Buildup of metals over time noted Increased concentrations seen in older areas of device
Lee et al. (1989)	Modeling	Grass swales	Used GRAPH and SEDIMOT II to predict phosphorus transport
Lee et al. (2005)	Modeling	Multiple devices	Life-cycle optimization techniques for selecting highway practices
Leeftang et al. (1998)	Netherlands	Infiltration	Describes design graphs for facility sizing Permeability related directly to device length and impervious drainage area
Lefers et al. (2005)	Wisconsin	Stormwater management planning	Used lake water level response to runoff to develop criteria for detention Also used to create model ordinances that focus on infiltration
Legret et al. (1999)		Pervious pavement	Modeled heavy metal retention using LEACHM Laboratory results confirmed retention of metals by clogging particles Cd migration maximum but not visible below 30 cm
Lemonsu et al. (2007)	Modeling France		Evaluated hydrological component of energy-water balance model Performed 6-year simulation of soil-biosphere-atmosphere interaction
Li and Davis (2008a)	Modeling	Bioretention	Modeled particle capture in bioretention media Used 3-layer model to simulate capture: cake layer, capture/depth layer, and pristine layer
Li and Davis (2008b)	Laboratory	Bioretention	Analyzed particle clogging in media in laboratory and field studies
Li et al. (2007)	Modeling	Wetlands	Modeled solids removal in wetlands Sedimentation not related to Turbulent and Particle Shear Velocity Reynolds number, indicating resuspension not a factor Vegetation density not important factor Sedimentation correlated with particle fall number
Liao et al. (1998)	Modeling	Wetlands	Used VASWETS to model fate and transport of pollutants in wetlands Model used to compare design criteria
Liaw et al. (2007)	Field studies	Infiltration	Permeability of infiltration gutters analyzed
Liebens (2002)		Detention ponds, Swales, Street Sweeping	Analyzed sediment metal contamination Particle size dependent on erosion processes and limitations of sweepers Pond and swale sediment more contaminated compared to background Land use factor in metal contamination
Lilley and Labatiuk (2001)	Edmonton, Alberta, Canada	Wetlands	Reviews draft guidelines for constructed stormwater wetlands Addresses water quality improvements, drainage area, soil permeability, vegetation, water depth, wetland area and volume, length-to-width ratio, forebays, inlets, outlets, grading, maintenance, monitoring, signage, secondary uses, land ownership, access, fencing, wildlife and mosquitoes

Authors	Study Area	Treatment /Management Activity	Conclusions
Line et al. (2008)	North Carolina	Wetlands	Compared two wetlands for P, N, and sediment removal Both wetlands exceeded removals reported in literature Greater efficiencies may be related to high ratio of wetland area to drainage area
Livingston (1989)	Florida Maryland	Wetlands	Discusses design variables Compares criteria in Florida and Maryland Discusses unknowns in wetlands design
Lloyd et al. (2002)	Australia	Biofiltration Wetlands	Outlines process of translating concepts to practice Discusses construction activities, costs, and public acceptance
Loftin (2001)		Stormwater management	Compared practices used by governments to guide land development Compares stormwater management practices in hypothetical case studies Shows that impervious area disconnections and cluster development increases density development without receiving water degradation compared to traditional storm systems
Loganathan et al. (1994)	Modeling	Detention pond	Formula for basin detention time as function of captured runoff volume Curve generated using SWMM
Looper (1980)	Florida	Stormwater planning	Discusses calibration of TR-20 for a coastal area
Lucas (2003)	Delaware Modeling	Infiltration	Describes hydraulics of DURMM Describes how infiltration/interception is affected by soil and land cover
Lund et al. (2001)	Perth, Australia		Analyzed removal of filterable reactive phosphorus in wetlands Uptake initially in plant biomass with sediment later important sink Anoxia in sediments did not cause P release
Maestri and Lord (1986)	US Federal Highway Administration	Vegetated swales, Detention pond, Infiltration, Wetlands	Describes FHWA's guidelines for managing stormwater runoff Identifies impractical or ineffective measures for highways Identifies general design principles and practices
Maimone et al. (2005)	Modeling Philadelphia, Pennsylvania	Stormwater and receiving water characterization	SWMM model developed to simulate storm sewer and COS controls Modeled potential treatment practices to reduce CSOs
Malin et al. (2001)	North Carolina	Receiving water characterization	Correlations between tidal creek microbial concentrations and populations, percent watershed development, and percent impervious cover Fecal coliform and turbidity positively correlated and to rainfall within previous 24 h in developed watersheds
Marcos et al. (2002)	Modeling Laboratory	Infiltration	Binary and tertiary exchanges in soil control Pb, Zn migration in sands Numerical model proposed
Maristany (1989)		Retention pond, Detention pond, Filtration	Describes variables controlling performance for nutrients, other pollutants Recommendations system design based on watershed characteristics
Maristany (1993)	Lake Munson	Wet detention pond	Compares new and older wet detention ponds Removal in older pond comparable to new pond removal

Authors	Study Area	Treatment /Management Activity	Conclusions
Marsalek (2003)		Infiltration, Oil and grit separators, Ponds, Wetlands	Discusses impact of road salt on pollutant retention in treatment devices Concerns are for chloride contamination of groundwater, leaching of metals, and densimetric stratification of ponds and wetlands
Marsalek et al. (2002)	Ontario, Canada	Detention pond	Assessed stormwater impacts on stream with in-line detention pond Toxicity not seen in creek water, but in pond sediment Sediment toxicity seen across the pond
Marsalek et al. (2006)	Ontario, Canada	Detention pond, Wetlands, Infiltration, Biofiltration, Clarifier, Oil and grit separator	Greatest metal sediment pollution in oil and grit separator, clarifier, biofilter, industrial pond All sediments considered moderately polluted Sediment toxicity confirmed
Martin (1989)		Detention pond Wetlands	Used tracer studies to determine mixing and residence times At low discharges, pond moderately mixed, residence near theoretical At higher discharges, short-circuiting occurs In wetlands, mixing increases with decreasing discharge, increasing storage
Matsushita et al. (2001)	Japan	Infiltration	Describes "Rainwater Recycle Sewer System", which is supported by "Rainwater Storage and Infiltration Technology (RSIT)"
Matthews et al. (1997)	Ontario	Detention pond	Describes use of baffles to increase retention time in pond Anticipates increased sedimentation
Maxted and Shaver (1997)		Retention pond	Ponds unable to prevent loss of sensitive stream species in almost all cases where pond installed to treat commercial development runoff
May and Horner (2002)	Pacific Northwest	Multiple practices	Describe limitations of devices at mitigating stormwater impacts Survey found that little watershed area was served by treatment devices Design standards not ensure devices operate at maximum efficiency Low Impact Development promising concept for development
Mayer et al. (2008)	Michigan	Detention pond	Investigated impact of road salt on benthos of detention pond Sediment porewater retains salt with Cl affecting Cd complexation, which increases Cd concentration in porewater Toxicity result of metals and other pollutants, but not chloride itself
Mazza (2006)	New Jersey	Filtration	Use of StormFilter with StormGate Separator for stormwater treatment
McCuen (1984)	Modeling	Detention pond	Inaccuracies in hydrologic models used to compute design discharges Describes concerns in hydraulic modeling used to size detention facilities
McCuskey et al. (1994)	Ohio South Carolina	Wetlands	Presents components of wetlands restoration and creation Case studies
McDonough and Liner (2007)		Multiple practices, planning	Describes components of stormwater pollution prevention plan
Mensing and Chapman (2004)		Stormwater management	Conservation development as an ecological approach to development Uses Stormwater Treatment Train to manage stormwater Include swales, prairies, wetlands to control rate, volume, promote infiltration

Authors	Study Area	Treatment /Management Activity	Conclusions
Merly and Shoberg (2005)	Clearwater, Florida	Detention pond Wetland	Regional detention facility for treatment and reducing stream degradation Case study
Mermillod-Blondin et al. (2008)	Laboratory	Retention pond	Describes impact of bioturbation and sediment thickness on nutrient and PAH dynamics in retention systems
Middleton and Barrett (2008)	Austin, Texas	Detention pond	Modified basin to operate in batch flow Effluent EMC of TSS: 7 mg/L TSS removal efficiency: 91% Statistically significant removal of total metals, COD, TN, TP, TSS
Mikkelsen and Jacobsen (1993)	Denmark	Infiltration	Describes infiltration design based on rainfall statistics and soil hydraulics
Mikkelsen (1997)	Multiple locations	Infiltration	Describes design procedures for infiltration systems in various countries Describes conceptual design methodology Evaluates errors with simplified method
Mikkelsen et al. (1994)		Infiltration	Assesses state-of-the-art on infiltration Proposes methods to address inherent problems Describes soil processes affecting water transport and pollutant removal
Mikkelsen et al. (1996)		Infiltration	Reviews recent developments in infiltration Design parameters require local information Information on clogging required Notes concerns about surface soil pollution
Mikkelsen et al. (1997)		Infiltration	Soil pollution concentration exceeded background concentrations Contamination decreased rapidly with depth. Simulated soil water was cleaner than drinking water standards
Mikkelsen et al. (2002)	Denmark Sweden	Multiple practices	Reviews recent experiences in Denmark and Sweden
Millikan (1991)		Stormwater management planning, Detention ponds, Wetlands	Case study on stormwater management at commercial facility Includes stormwater reuse
Milly and Ferrard (1984)		Infiltration	Models movement of water through layer of low permeability, such as clogging layer in infiltration
Mitchell et al. (2007)	Australia	Rainwater harvesting	Describes multi-functional benefits of stormwater harvesting Describes research program to develop guidance on harvesting
Moller et al. (2002)	Laboratory	Filtration	Iron-oxide coated sand (IOCS) removed metals, but released most of them in weak acid conditions (allowing media regeneration)
Molzahn (1993)	Kensington	Retention pond	Describes maintenance costs of retention pond Case study
Monde (1998)		Stream restoration	Case study of suburban stream restoration Describes evaluation phase of study

Authors	Study Area	Treatment /Management Activity	Conclusions
Montalto et al. (2007)	Brooklyn, New York	Low Impact Development	Modeled potential cost-effectiveness of LID for CSO control Addressed green roofs, pervious pavement, stormwater treatment wetlands Individual LID systems have differing levels of cost-effectiveness
Montes and Haselbach (2006)	Laboratory	Pervious concrete	Hydraulic conductivity using computerized falling head permeameter Used Carmen-Kozeny equation to describe relationship between porosity and hydraulic conductivity Porosities of 15% or less indicated limited hydraulic conductivity
Montgomery et al. (2005)	Wisconsin	Infiltration	Used infiltration to recharge groundwater to compensate for new cogeneration facility Case study that describes site selection process
Moore and Barrack (2005)	Cub Run watershed	Low Impact Development	Case study of LID implementation Describes process of evaluating effectiveness of LID implementation Modeling used SWMM
Moore et al. (2005)	Modeling Virginia	Stormwater management planning	Management planning models used include combination of SWMM's RUNOFF and TRANSPORT modules, HEC-RAS Procedures and protocols developed for storing, analyzing results in GIS
Morgan et al. (2004)	Rogers, Arkansas	Greenway development	Case study of greenway development as part of stormwater management Describes initial assessment of biological, chemical, physical stream health
Morioka and Sueishi (1984)	Modeling	Stormwater system	Describes role of models in evaluating drainage design alternatives Compares advantages and disadvantages of various runoff models
Morquecho et al. (2005)	Laboratory	Stormwater characterization	P, COD associated with larger particulates Metals present in < 0.45 µm phase with Zn having highest concentration UV light exposure increased most metals concentration, indicating dissociation from organic complexes or colloids
Morrison et al. (1983)		Stormwater characterization	Variation in particulate associations of Cd, Cu, Pb, Zn throughout storms
Mothersill et al. (1998)	Kingston, Canada	Filtration	Describes submerged aerobic biological filter to treat stormwater Sediment accumulation interfered with dissolved nutrient removal through bacterial assimilation TOC, P removal efficiencies decreased over time NH ₄ removal independent of time
Mothersill et al. (2000)	Kingston, Canada	Filtration	Backwash used in submerged biological filter to remove sediment Sediment accumulation interfering with performance
Moustafa (2000)		Wetlands	Extended relationship between P dynamics and lakes to wetlands Wetlands characterized by trophic status
Muherm and Steele (1989)	Denver, Colorado	Detention ponds	Case study of in-stream ponds for P removal
Mullen (2003)		Structural stormwater practices	Modifications to current structural devices for water quality improvement Describes use of deep catch basin sumps and baffles to promote sedimentation and O&G removal

Authors	Study Area	Treatment /Management Activity	Conclusions
Muthanna et al. (2007a)	Norway	Bioretention	Water, metal removal in bioretention areas during summer and spring Spring water removals were lower than summer Metals removal good in both seasons Adsorption and filtration primary metals removal processes
Muthanna et al. (2007b)	Norway	Bioretention	Evaluated current bioretention sizing methods for cold climate applications Modeled methods using RECARGA Snow volume storage was a primary design factor
Muthukrishnan and Oleske (2008)	Laboratory	Filtration	Evaluated impact of lime amendments on pH of bioretention media Goal to improve metals removal by sorption onto dolomitic limestone
Nakai and Carr (1993)	Skokie, Illinois	Detention pond	Case study of using detention to control runoff and reduce CSOs
Nakanishi (2002)	Japan	Infiltration	Describes functional evaluation of stormwater infiltration Uses equi-risk curves for Japan to evaluate effects of infiltration
Nehrke and Roesner (2002 a,b)		Detention pond	Examined flow control in detention systems on peak flow frequency curve
Nelson et al. (2006)	Washington state	Multiple devices	Evaluate metal removal in devices in cold weather Metals concentration decrease within upper 30 cm of soil/sediments Snowmelt contains more chloride and solids than rainfall events Laboratory testing showed that road salt enhanced metals mobility in soils
Neukrug et al. (2003)	Philadelphia, Pennsylvania	Infiltration, Bioretention, Pervious pavement	Case study of stormwater management at school
Nietch et al. (2002)		Wetlands Detention pond	Compared wet ponds and wetlands Wetlands were inefficient at removing nitrogen, but preferentially retained P Modeled effect of vegetation uptake
Nietch et al. (2005)	Laboratory	Wetlands Detention pond	Neither device removed total nutrients to a large extent Nitrate removal controlled by influent concentration and explained by nature of primary production in device
Nimmer et al. (2007)		Infiltration	Addresses groundwater mounding concerns beneath infiltration basins Mounds may reduce soil pollutant removal and decrease infiltration rate Modeled using HYDRUS, which was most sensitive to basin sedimentation layer and hydraulic conductivity
Nnadi et al. (1999)	Florida Modeling	Stormwater runoff generation	Compared design storm distributions to actual rainfall patterns and compared runoff rates from methods to measured runoff data Showed that design storm distribution behavior varies with watershed characteristics and throughout state

Authors	Study Area	Treatment /Management Activity	Conclusions
Nogaro et al. (2007a)		Infiltration	Studied OM and pollutant content influence on mineralization processes, microbial characteristics, release of solutes Results showed that biogeochemical processes (aerobic respiration, denitrification, fermentative processes), the microbial metabolism (enzymatic activities), and solute release (NH ₄ ⁺ and DOC) were stimulated in presence of the stormwater deposit
Nogaro et al. (2007b)		Infiltration	Tubificid worms affected organic matter processing but not pollutant fate
Nolde (2007)	Germany	Filtration Rainwater harvesting	Describes possibilities for rainwater harvesting, inc. from traffic surfaces Treatment consists of biological filter and eventual UV disinfection Rainwater used in non-potable ways
Nordeide et al. (2004)	Oslo, Norway	Stormwater management	Describes process to rank subcatchment areas for study Ranking includes pollutant discharge loads, existing stormwater discharge Highest ranked areas strongly influenced by highway runoff Results incorporated into GIS
Norman et al. (2003)		Detention pond	Characterized Erwinia populations in ponds used for nursery irrigation Erwinia greater in ponds used for irrigation and reuse
Novotny (1984)		Source control, Pervious pavement, Infiltration, Grass swales, Erosion control, Detention ponds, Wetlands	Describes the pollutant control efficiency of low-cost treatment practices Retention basins, grass filters, enhanced infiltration most effective in medium impervious areas Pervious pavement, surface detention-retention effective for highly impervious areas Case study provided
Nowakowska-Blaszczyk and Blaszczyk (1997)		Infiltration	Describes procedures for designing infiltration systems in Poland Suggests infiltration for roof runoff and treatment plant for dirtier road runoff Describes need for solids pretreatment to prevent infiltration clogging
O'Leary (1997)	Maryland	Detention pond	Use of Groundwater Syphon to decrease temperature of release water Release water drawn from groundwater mixing and pond water used to recharge it
O'Leary et al. (1997)	Baltimore County, Maryland	Detention pond Bioretention Erosion control	Case study Documents steps to assess water quality needs, device retrofit option, and prioritize retrofits Constraints were feasibility, aesthetics, cost, neighborhood acceptance
Obropta and Kallin (2003)	New Jersey	Floodplain restoration	Case study of Rahway River watershed restoration Analyzes stormwaters, groundwater, surface water, and soil amendments
Olcott and Gill (2004)	Nashua, New Hampshire	Detention pond	Case study describing conversion of pond to recreational area
Olenik (1995)	New Jersey		Effect of water resource planning on land available for affordable housing Describes NJDEP move to watershed-based permitting
Olenik and Cheng (2002)	New Jersey		Describes effect of land development regulations on affordable housing

Authors	Study Area	Treatment /Management Activity	Conclusions
Oost (2004)		Manufactured treatment device	Describes Rainstore3 system
Osenbruck et al. (2007)	Halle, Germany	Infiltration	Investigates sources and transport of pollutants in urban groundwater Stormwater infiltration may be source of bisphenol-A
Ostendorf et al. (2008)	Massachusetts	Infiltration	Describes groundwater transport of deicers beneath an infiltration basins Uses advective transport model and field data for model calibration
Pack et al. (2004)		Infiltration	Describes optimization of infiltration to treat highway runoff Used continuous simulation to illustrate optimization routine Optimization includes cost
Pack et al. (2005)	Field studies	Infiltration	Describes modeling framework using continuous simulation to predict annual pollutant removal in vegetated buffer strips Compared traditional drainage systems shows improvement with grassed systems
Papa and Adams (1997)	Modeling	Detention pond	Probabilistic model and dynamic programming to optimize stormwater pond
Papa et al. (1999)	Ontario, Canada	Detention pond	Addresses dichotomy of extended detention design: increased removal with increased retention, but decreased available storage for next storm Modeled maximum attainable pollutant control at optimal detention time
Park and Stenstrom (2006)	Modeling Santa Monica, California	Stormwater characterization	Used Bayesian networks and GIS to estimate spatial stormwater pollutant loads and identify areas of high loads Major sources were multi-family residential, commercial, industrial and transportation
Parmer et al. (1994)		Infiltration	Literature review on stormwater infiltration and impacts on groundwater
Parsons (2006)	Canadian golf courses	Stormwater management planning	Describes new guidance on golf course development that considers stormwater management
Patwardhan et al. (2005a)	Tennessee Valley Authority site Modeling	Low Impact Development	Case study of LID applied to industrial site Modeling performed using LIFE™ Describes planned demonstration projects
Patwardhan et al. (2005a)	Modeling	Low Impact Development	Evaluated LID's impacts on CSO Modeling performed using LIFE™ Advocates LID for ecosystem health and aquatic resource protection
Pazwash (1990)		Stormwater management	Describes concepts and misconceptions associated with stormwater management planning and practices
Pazwash (1991)		Stormwater devices	Discusses maintenance requirements of treatment devices
Pazwash (1993)	New Jersey	Stormwater management practices	Summarizes stormwater practices used in NJ Includes suggestions for improvement
Pazwash and Boswell (1995)		Stormwater management practices	Summarizes current practices and their effectiveness Suggests improvements, including multistage detention pond control

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Perez-Pedini et al. (2005a)	Northeast United States	Infiltration	Describes optimal placing of infiltration practices Hydrological model used to guide placement for maximum effectiveness Results showed placement affected by watershed connectivity, flow travel time, land use, distance to channel, contributing area
Perez-Pedini et al. (2005b)	Modeling	Infiltration	Distributed hydrologic model with genetic algorithm used to determine optimal location and number of stormwater treatment practices
Perniel et al. (1998)	Minnesota	Detention pond	Describes nutrient removal from pond using duckweed
Persson (1999)		Detention pond Wetlands	Evaluated hydraulic efficiency in detention pond Two-dimensional vertically integrated model used to simulate pond performance
Persson and Wittgren (2003)		Detention pond Wetlands	Summarizes knowledge about pond hydraulics in terms of effective volume ratio and dispersion Modeled N removal, showing that effective volume ratio influenced removal
Persson et al. (1999)		Wetlands Detention ponds	Present new measure for hydraulic efficiency that combines existing measures of flow uniformity and effective volume. Case studies presented to assess effects of pond and wetland shapes, inlet/outlet locations, botanical layouts and basin morphology
Petavy et al. (2007)		Retention pond Infiltration pond Street sweeping	Evaluated treatments for stormwater sediments Treatment concentrates pollutants in fine particles with goal of reusing coarser particles
Petterson (1998)	Sweden	Detention pond	Small pond removed particles, particle-associated pollutants, but not dissolved pollutants Advocates sizing pond to contain storm volume to avoid short-circuiting
Petterson (1999a)	Sweden	Detention pond	Studied effects of water chemistry (pH, DO, conductivity) on associations of pollutants and solids Variability seen in heavy-metal partitioning
Petterson (1999b)	Sweden	Detention pond	Small pond removed particles and particle-associated pollutants but not dissolved pollutants Advocates sizing pond to contain storm volume to avoid short-circuiting
Petterson (1999c)	Sweden	Detention pond	FEM-model used to describe flow patterns in small detention pond Sedimentation approach was added to flow field
Petterson and Svensson (1999)	Modeling Sweden	Detention pond	Modeled particle removal in ponds by particle settling method Removal efficiency affected by inter-event sedimentation
Petterson et al. (1999a)	Sweden Modeling	Detention pond	FEM-model used to describe flow patterns in small detention pond
Petterson et al. (1999b)	Sweden	Detention pond	Cumulative effects of outlet discharges shows independence of inflow load to outflow Comparison of two ponds shows that increasing pond size increases pollutant removal up to 250 m ² /ha

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Petterson (1999d)	Sweden	Detention pond	Modeling showed that 3-D characterization best represents flow field Pond geometry critical to proper function
Phelps (2001)		Hydrodynamic separator	StormVault™ Paper describes device testing
Phillips (2005)		Detention pond	Describes how to use aquascapes for stormwater management Case study of residential area
Piccolo (1991)	Puget Sound, Washington	Stormwater management	Describes stormwater management plan to improve water quality Describes Authority that oversees plan implementation
Pitcher et al. (2004)	Laboratory	Filtration	Describes zeolite filters for treating metals in highway runoff Synthetic zeolite removed > 91% of metals, but increased sodium and decreased calcium levels Potential inhibition of metals uptake because of other dissolved pollutants
Pitt and Field (2004)	New Jersey	Filtration	Evaluated storm drain inlets and sump configuration for pollutant removal Sediment trapped in sump but may degrade
Pitt et al. (1993)	Birmingham, Alabama	Stormwater characterization and treatability	Identified critical source areas for pollutants Treatment effectiveness varied, beneficial treatments included 24-hr settling (40 – 90%), screening through 40-µm mesh (20 – 70%), aeration, photodegradation
Pitt et al. (1995)		Infiltration	Concerns about groundwater contamination from stormwater infiltration Recommends infiltration guidance
Pitt et al. (1999)		Infiltration	Addresses potential effects of stormwater infiltration on groundwater Proposes simple method to evaluate site potential for infiltration
Pitt et al. (2002a,b)	Birmingham, Alabama	Infiltration	Describes impacts of construction compaction on soil infiltration rate
Pitt et al. (2004)	Laboratory	Filtration	Describes high-level treatment for metals Heavy metal binding to particulates not sensitive to pH changes likely in stream and pond sediments
Pitt et al. (2005)	Alabama Washington state	Infiltration	Describes impacts of construction and urbanization on soil structure Presents results of soil amendments to improve infiltration in glacial till
Pitt et al. (2008)	Alabama	Infiltration	Impacts of compaction, saturation on clay and sandy soil infiltration rates
Pittman (1991)	Carolinas	Detention pond, Wetlands	Describes requirement to use detention pond outflow to recharge wetlands
Pomeroy et al. (2008)	Kansas City	Stormwater management	Used SWMM to model stormwater treatment devices designed to maintain geomorphic stability Advocates regional analysis to determine stormwater control needs
Pond and Pawlowicz (1995)	Bolingbrook, Illinois	Stormwater management planning	Case study of watershed and stormwater management planning
Poole and Yu (1997)	Virginia		Advocates revaluing common areas of infrastructure and aesthetics Case study

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Pope and Hess (1989)	Kansas	Dry detention pond	NH ₃ , Organic-N, TOC: negative removals TSS: 2.5%; COD: 15.5%; NO ₂ +NO ₃ : 20%; TP: 18.5%; DP: 0%; Pb: 66%; Zn: 65%
Pope et al. (1988)	Kansas	Dry detention pond	Describes monitoring instrumentation
Ports and Jermeland (1988)	Phoenix, Arizona Washington, D.C.	Stormwater management	Compares systems for two transportation-related sites
Pratap et al. (2005)	Laboratory	Filtration	Examined upflow filtration for stormwater solids removal Statistical comparisons made between peat, compost, sand filters at different points of filter life Better performing filter depends on where in filter life analysis is performed
Pratt (1996)	United Kingdom	Infiltration	Describes recent research and design principles for soakaways Field data show difficulty in determining soil infiltration rate and highlight pollution issues
Pratt (1999)		Pervious pavements	Described design guidelines for pervious and permeable pavements Recounts experiences with pavements
Pratt and Horstead (1986)		Infiltration	Case study on pervious pavement for surface-water pollution reduction Cost savings given for concrete block paving system
Radbone and Hamnett (2002)	Adelaide, Australia	Stormwater management	Outlines the initiatives used in stormwater management for water reuse Describes key factors needed to implement projects Assesses project's impacts on water sustainability
Raimbault and Legret (1997)		Infiltration	Reservoir structure of streets used to store stormwater prior to infiltration
Raimbault et al. (2002)	Modeling	Infiltration	Describes temporal variability in soil infiltration capacity Evaluates effects of soil drainage on infiltration capacity and facility sizing
Randall (1984)		Detention pond	Describes task committee report on pond outlet structures Describes purpose of outlet control
Rangsivek and Jekel (2005)	Laboratory	Filtration	Evaluated zero-valent iron for metals removal in stormwater runoff Performed kinetics, capacity tests Noted slight change in removal for Cu, but Zn removals increased with increasing DO, ionic strength, temperature, pH DOC formed complexes with iron, reducing sorption capacity Large organics competed for adsorption sites
Rauch and Morrison		Detention pond	Evaluated platinum uptake by freshwater isopod Pt binds to sediment, which then is taken up by isopod Speciation affects uptake
Rea and Traver (2005)	Pennsylvania	Wetland	Wetlands provided nearly 70% TSS removal RP, CI little or no removal Good removals of TP during baseflow First-flush flows and concentrations reduced substantially in wetland

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Read et al. (2008)	Australia	Biofiltration	Evaluated plant species for pollutant removal in bioinfiltration systems Removals varied by species per unit root mass
Reese (1993)	Pennsylvania Modeling	Detention pond	Describes linking of PSRM to detention pond routing software to test Release Rates for detention pond control
Revitt et al. (2008)	Modeling	Infiltration, Wetlands, Pervious asphalt, Detention tanks	Prioritized after modeling 15 devices in terms of pollutant removals Infiltration, subsurface wetlands performed best for most pollutants
Ristenpart (1999)	Modeling Germany	Stormwater management	Presents new concept for planning Dimensioning and performance of treatment devices evaluated using rainfall-runoff model
Rochfort et al. (1997)	Canada	Wetlands	Wetlands removed 39% OP, 46% TSS, 50% dissolved metals Compared traditional sizing methods with kinetic sizing approach and showed that latter method most versatile
Rodriguez and Pardo (2005)	Venezuela	Filtration	Described devices for stormwater treatment at petroleum facilities Categorizes stormwater into uncontaminated, potentially contaminated and contaminated Used sedimenter-filter to treat stormwater
Rohrer (1992)		Infiltration	Fate of noxious substances from basin overflows during infiltration During infiltration, COD reduced from 80 – 100 mg/L to < 30 mg/L
Rose and Peters (2001)	Atlanta, Georgia	Stormwater impacts	Describe impacts of urbanization on hydrological regime in creeks compared to reference streams
Roseen et al. (2005)	New Hampshire	Infiltration, Filtration, Wetlands, Detention ponds, Manufactured devices	Compared treatment performance of variety of devices Describes test setup Range of devices have distinct trends and performance differences
Roseen et al. (2006)	New Hampshire	Infiltration, Filtration, Wetlands, Detention ponds, Manufactured devices	Compares devices in setup to treat 90% of annual rainfall Structural devices have poorer removals, except for TSS Manufactured devices vary widely and depend on pollutant Infiltration devices perform well
Roseen et al. (2007)	New Hampshire	Infiltration, Filtration, Wetlands, Detention ponds, Manufactured devices	Evaluated cold weather performance of series of devices Infiltration devices continue to function well in winter Frozen filter media not seen Chloride attenuation complex
Rosted Peterson et al. (1994)	Denmark	Infiltration	Relates desired CSO control level to return period for infiltration trench size
Rousseau et al. (2008)		Constructed wetlands	Provides overview of treatment processes and water reuse possibilities Describes O&M requirements, costs, and constraints
Roy et al. (2008)	Australia United States	Stormwater management	Describes impediments and solutions to implementing sustainable watershed-scale stormwater management Compares Australia and U.S. activities to propose solutions to impediments

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Royal (1998)	Lake County, Illinois	Stormwater management	Case study on flood mitigation and stormwater management in multi-jurisdictional area Design encourages detention and wetland modifications
Rozis and Rahman (2002)	Modeling Brisbane, Australia	Low Impact Development/Water Sensitive Urban Design	Presents method for life-cycle assessment Case study shows lower construction but higher maintenance cost with WSUD. Benefits of flooding control outweigh slightly increased O&M costs
Rusciano and Obropta (2007)	Laboratory	Bioretention	Fecal coliform removal: > 90%; TSS removal: > 91%; pH: 6.8 to 4.6 Removal mechanisms likely adsorption and filtration
Rushton (2001)	Tampa, Florida	Pervious pavement	Compared three paving surfaces, basins with/without swales Swales reduce runoff amount 30% Pervious paving removes additional 15% Rain significant source of inorganic nitrogen Vegetated swales had higher P Metals, PAHs higher from asphalt versus cement, pervious paving
Rushton (2002)	Florida	Swales Wet detention pond	Treatment train for parking lot that quickly moves runoff from asphalt P discharges increased in swales with vegetation
Rushton and Carr (1993)	Florida	Wetlands	pH, DO, conductivity increased during wetlands flow Effective solids removal
Rushton and Teague (2005)	Florida	Wet detention pond with side bank filters	System ineffective at removing dissolved nutrients May be dewatering groundwater TSS, metals significant removals (79% to 89%) Outflow samples mostly met water quality standards in first year, with lesser compliance in second year Noncompliance related to rain amount when pond water softer and standards stricter
Rutherford (1981)		Detention ponds	Case studied compared dry and wet ponds for cost, performance, O&M
Sample and Heaney (2003)	Modeling	Low Impact Development	Describes modeling approach at parcel level Incorporates decentralized options for managing stormwater, water supply Evaluate irrigation policies and rainwater harvesting
Sample and Heaney (2006)	Modeling	Low Impact Development	Describes modeling approach at parcel level Incorporates decentralized options for managing stormwater, water supply Evaluate irrigation policies and rainwater harvesting
Sandvik (1985)		Detention ponds	Evaluates proportional weirs for stormwater pond outlets
Sansalone (1999a)	Laboratory	Filtration	Describes partial exfiltration trench to remove metals from highway runoff Media is oxide-coated sand, amphoteric media with high surface area OCS compared to sand; OCS better able to remove and retain metals Metals retention improved as pH increased to 8.0
Sansalone (1999b)	Ohio	Filtration	Field performance of partial exfiltration reactor for treating highway runoff Mass removals > 80% after 1 year

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Saravanapavan et al. (2005)	Prince George's County, Maryland	Low Impact Development	Case study of integrating on-site stormwater management Describes evaluation of practices for implementation using criteria of technical feasibility, economics, social acceptance Included recommendations for site landscaping
Schaad et al. (2008)	Midwest U.S.	Wetlands Detention pond	Describes design and performance of wetlands and flow equalization basin for stormwater treatment at rail yard. TSS, O&G concentrations reduced approximately 45% compared to old retention pond treatment
Schaefer (1997)		Multiple devices	Compares treatment device performance for construction projects
Schauer and Barmoy (1995)	Carroll County, Maryland	Stream restoration and management	Case study of integrated stream management Incorporates stormwater control in plan
Scher et al. (2004)	France	Detention pond	Evaluated biodiversity in ponds treating highway runoff
Scher et al. (2005)	France	Detention pond	Cu, Zn concentrations high in surface sediment layer Dragonfly richness higher in natural-bottom ponds compared to lined ponds Amphibian richness related to structure of surrounding landscape
Scholz (2002)	United Kingdom	Detention pond	Described design and management guidelines for ponds Public acceptance of ponds investigated
Scholz (2003)	United Kingdom	Wetlands	Evaluated wetlands for treating gully pot effluent
Scholz (2004a)		Detention pond	Evaluated algae control and water quality treatment in sustainable pond
Scholz (2004b)		Wetlands	Evaluated wetlands treatment of gully pot effluent during cold weather Ni not trapped in presence of road salt
Scholz and Anderson (2003)		Detention pond	Pond contains sediment trap, wet pond and dry pond Evaluated pond performance to aid in developing design guidelines Compared performance to existing guidelines Dry pond infiltration function logarithmic Seasonal variations in BOD, DO, pH seen
Scholz et al. (2005)	Glasgow, Scotland	Stormwater management	Case studies assessing use of SUDS to reduce CSOs
Scholz et al. (2006)	Modeling	Low Impact Development/Sustainable Urban Drainage System	Describes decision support model for SUDS management Developed detailed design guidelines for vegetated treatment systems
Schroeter and Watt (1989)	Modeling		Simulated sediment transport in urban runoff Model uses concept of "equivalent solids reservoir" Module incorporated into Q'URM
Schueler (1993)	Multiple sites	Detention ponds Wetlands	Compares 58 monitoring studies on pond and wetland performance Results suggest importance of certain design parameters in performance: pretreatment, long flow paths, basin geometry Pollutant removal dependent on type of pollutant
Schueler and Helfrich (1989)	Washington, D.C.	Extended detention pond	Presents concept of extended detention Design to maximize removal and minimize maintenance while meeting environmental requirements

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Schwartz and Terry (1998)	Lake Munson	Detention pond	Case study describes lake restoration Problems result of urbanization and channelization of upstream pond
Sear and van Ravenswaay (1992)	Florida	Detention pond	Describes sizing methodology for ponds SWMM4 modeled range of pond parameters and create design curves
Sela and Chidananda (1997)	New Jersey	Detention pond	Describes planning and management issues associated with urban ponds Case study of transportation facility
Semadeni-Davies (2006)	Sweden	Detention pond	Cd, Cu removals similar winter and spring Pb, Zn, TSS removals dropped in winter
Shafer and Westfall (1991)		Wetlands	Discusses wetlands legislation that influences wetland design Outlines permitting process Analyzes design considerations
Shammaa and Zhu (2001)		Infiltration, Filtration, Detention pond	Evaluated TSS removal in treatment devices
Shammaa et al. (2002)	Edmonton, Canada	Dry detention ponds	Evaluated dry ponds for TSS removal Detention time most important factor in TSS removal Two-stage facilities and multi-level outlet control enhances TSS removal
Shapiro (2002)	Santa Monica, California	Stormwater impacts	Described initiatives to change view of stormwater as nuisance to resource
Shasti Annambhotla and Bryant (2005)	Greensboro, North Carolina	Wetlands	Describes riparian wetland for regional stormwater treatment Sensors and control gates to maintain water levels in stream and wetland
Shatwell and Cordery (1999)	Sydney, Australia	Wetlands	Evaluated nutrient storage in wetlands P, sediment accumulate in pond during small events (60% P removal, 80% TSS removal)
Shaver (1986)	Maryland	Infiltration	Discusses implementation of infiltration, regulatory background Describes standards for infiltration design and construction
Shaw et al. (1997)	Kingston, Ontario	Detention pond	Characterized flow patterns and evaluated impacts on water quality Water quality concerns in times of high wind and low inflow Length to width ratio of case study pond promoted short-circuiting
Shelley and Mudgett (1999)	Modeling	Wetlands	Simulated wetland's ability to remove organic matter from runoff Results showed importance of biofilm development in pollutant removal
Shelton and Vogel	Modeling	Detention pond Infiltration	Compares cost-effectiveness of infiltration vs. detention ponds for stormwater management Describes evaluation methodology Relates cost-effectiveness to climate, soil, land-use conditions
Sherrard et al. (2004)	Laboratory	Wetlands	Evaluated removal ability of wetlands for chlorpyrifos and chlorothalonil Substantial (almost 100%) toxicity declines seen after wetlands treatment
Shirahama et al. (2002)		Infiltration	Developed evaluation method for incorporating infiltration facilities into storm drainage system Case study using infiltration map to rank potential sites

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Shuster et al. (2008)	Modeling Laboratory		Evaluated runoff response from pervious-impervious systems Increase in percent impervious area reduced infiltration, decreased lag time Runoff rate ratios affected by antecedent moisture conditions ratios Connectivity important only early in simulation events
Sieker (1984)	Germany	Infiltration	Describes four methods of infiltration and dimensioning rules for sizing Addresses data and understanding gaps
Sieker (1988)	Germany	Infiltration	Describes short swale-long infiltration trench device to promote infiltration and replace storm sewer system Describes materials to be used in infiltration trench
Sieker and Klein (1998)	Germany	Stormwater management	Presents the constraints of using de-centralized management techniques in highly developed area as retrofit Case study of structural and non-structural treatments Showed that 30% impervious disconnect can be achieved in urban area
Sieker et al. (1986)	Germany	Infiltration	Describes use of vegetated depressions to infiltration stormwater runoff 2 case studies
Sim et al. (2002)		Wetland	Describes wetland restoration, stormwater management practices, weed control programs, and blue-green algae management
Simon et al. (2003)		Stormwater management	Describes implementation of sustainable water management, including stormwater management
Singhal et al. (2008)	Laboratory	Filtration	Evaluates sediment retention in alternative media Sediment removals > 90% Lower sediment removal seen with smaller particles in water, decreasing influent concentration, and well-mixed influent Retention occurred primarily in top 22mm
Siriwardene et al. (2007a)	Laboratory	Filtration Infiltration	Described buildup of clogging layer on media surface Clogging reduced if constant head maintained on system Clogging caused by migration of small sediment (< 6 µm) Regression model developed
Siriwardene et al. (2007b)	Modeling	Filtration Infiltration	Tested two models for sediment behavior in filtration media Modified Yao model to describe behavior of filter over lifespan
Skinnerland et al. (2007)	Puget Sound, Washington	Stormwater management	Describes Puget Sound Water Quality Management Plan
Smaill (1994)	Auckland, New Zealand	Infiltration	Describes program to treat stormwater prior to groundwater recharge to prevent further groundwater degradation
Smith (2003)		Permeable pavement	Describes permeable interlocking concrete pavements
Smith (2008)	Laboratory	Biofiltration	Describes passive biological filtration system to remove inorganic nitrogen Media contains mix of ion exchange and electron donors (expanded clay and sulfur pastille) Nitrate reduction 98% with removals decreasing with increasing flow rate

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Smith and Cook (1985)	Rye, New York	Detention pond	Case study on installing detention pond in flood plain to treat runoff
Smith and DiToro (1979)		Multiple devices	Presents statistical method of analysis that estimates device performance Analyzes treatment devices sensitive to flow and influent concentration Addresses bypass, flow and concentration variations, CSO issues
Smith et al. (2005)	Charlotte, North Carolina	Multiple treatment devices	Describes performance monitoring for 12 treatment devices Monitoring program designed so data could be included in the National Stormwater BMP database.
Smith et al. (2007)	Modeling	Filtration	Developed decision support system to assist in meeting TMDLs Modeled wet weather flows and pollutant discharges using SWMM 5.0 Filtration most effective to meet TMDLs, but decision system needed to optimize placement
Smolenska et al. (2003)	Australia	Low Impact Development/Water Sensitive Design	Outlines investigations used to create Water Sensitive Road Design for case study at Park and Ride facility Challenges of spatial constraints and open waterway at site boundary Incorporates infiltration to treat runoff, plus litter traps
Snodgrass et al. (2008)	Laboratory	Detention pond	Investigated susceptibility of tolerant and sensitive organisms to pond sediments with elevated chloride and metals Sensitive organisms had 100% mortality, but tolerant organisms had only sublethal effects
Somes and Wong (1994)		Wetland	Discusses wetlands processes that could improve water quality Reviews current guidelines on wetland design
Somes and Wong (1997)		Wetland	Describes outlet characteristics that optimize wetland performance Modeling showed that culverts, risers, and siphons could effectively control wetlands ability to runoff, but had different effects on hydrologic regime Siphon kept inundation depth evenly distributed
Somes et al. (2000)		Wetlands	Tracked pollutant detention in wetlands Presents methodology for tracking Modeling highlights influence of outlet structures on detention time 2 case studies
Sotir (2001)		Stormwater management	Addresses need for soil bioengineering in watershed management Case studies of 2 stream restorations
Sparling et al. (2004)		Retention ponds	Elevated Zn, Cu in sediments and carcasses of red-winged blackbirds Sediment Zn correlated with clutch size, hatching success, fledgling success, nest success
Spingarn (1993)	Virginia	Detention pond	Describes ecological concerns associated with regional facilities Evaluating several smaller-scale, on-site devices for stormwater treatment
Stahre and Urbonas (1989)	Sweden	Infiltration	Describes design of infiltration and percolation devices Design similar to detention facilities

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Stanley (1996)	Greenville, North Carolina	Dry detention pond	Presented removal efficiencies for TSS, N, P, TOC, and selected metals
Starzec et al. (2005)	Sweden	Detention ponds	Evaluated functioning of highway detention ponds Pollutant retention capacity not optimal for most ponds Sediment accumulation was low, indicating turbulent resuspension Relationship between sediment metal content and pond size, but not shape Maintenance deficiencies noted
Stead-Dexter and Ward (2004)		Detention pond	Heavy metals associated with carbonate and residual fractions. Ni, Cd highly associated Cu, Zn associated with carbonates and iron-manganese oxides Pb associated with iron-manganese oxides Changes in fractionation seen through lake system for Cu, Ni, Pb, Zn
Stedman (2004)	England Wales	Stormwater management	Plan to implement stormwater management and protect wetlands
Stenmark (1995)	Sweden	Infiltration Detention pond	Describes residential road construction that increases infiltration through pervious pavement Describes concerns with snowmelt and needs for further monitoring
Stenstrom and Carlander (2001)	Sweden	Wetlands	Investigated occurrence and die-off of indicator organisms in sediment Fecal coliforms and enterococci reduced by 97 – 99.9% Coliphages reduced by 70% Suspended particles removal main factor for bacteria elimination Long sediment survival of E. coli, fecal enterococci, Clostridium, coliphages
Stephenson (1989a)		Stormwater management	Uses kinematic type model to model stormwater system elements Modules include infiltration, aquifer, conduits, storage reservoirs
Stephenson (1989b)	Modeling		Comparison of calibration parameters versus field hydrologic data Showed only overland flow time needed adjustment during calibration Small-scale discretization required longer lag times and Manning's n than large-scale discretization
Stephenson (2004)	United Kingdom	Detention tanks	Describes Stormbloc™ and Stormcell™, which treat water and require minimal maintenance Describes infiltration to recharge groundwater
Stephenson (2005)		Low Impact Development/Sustainable Urban Drainage Systems	Describes why SUDS not effective at solving runoff problems Presents Hydro-Brake Flow Control, to be used in conjunction with structural controls for retrofit treatment
Stidger (2005)	Virginia	Multiple devices	Reviews ultra-urban treatment devices Case study
Stidger (2006a)		Low Impact Development, Infiltration	Describes infiltration as a part of LID
Stidger (2006b)		Multiple devices	Describes manufactured treatment devices

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Stockdale and Horner (1987)	Pacific Northwest, U.S.	Wetlands	Summarizes wetlands improvement principles in the literature Addresses research needs and areas of uncertainty for use of wetlands in Pacific Northwest
Stovin and Swan (2007)		Low Impact Development, Sustainable Urban Drainage Systems	Addresses costs estimates and decision-support tools for retrofitting LID/SuDS devices Developed comparisons based on land use area Infiltration basins cheapest to construct
Strecker and Hesse (2005)	Southern California	Low Impact Development	Case study of LID in coastal resort Simulation modeling using SWMM to size and develop system components Incorporated rainwater harvesting to aid in reducing runoff volumes and footprint of surface treatment devices
Strecker et al. (2005)	Nevada/California	Multiple devices	Effectiveness and cost of current and improved devices on urban runoff pollutant discharges Describes approach to data collection and analysis and plan for long-term simulation modeling
Stribling et al. (2002)		Detention pond Riparian vegetation Bank stabilization	Evaluated use of biological indicators to determine success of stormwater management practices Two case studies on use of calibrated reference conditions
Strosnider et al. (2007)	South Carolina	Wetlands Detention ponds	STELLA used to determine hydraulic capacity and stormwater management potential of wetlands designs Wetland designed to surround detention pond to improve nutrient treatment
Struck et al. (2004)	Laboratory New Jersey	Wetlands Retention ponds	Compared wetlands vs. pond for processes providing runoff treatment Wetlands had greater removals of TSS, TKN Pond had higher removals of NO ₃ Goal of developing models to explain pollutant removals
Struck et al. (2005)	Laboratory	Wetlands Retention pond	Investigated removal of indicators in two devices Retention ponds had greater removal in warm weather Appears to be irreducible microbial concentration in these devices
Struck et al. (2008)	Laboratory New Jersey	Wetlands Retention pond	Showed that water temperature, light, and a combination of other environmental factors affected bacterial concentration Bacteria inactivation generally followed the first-order, KC* model Noted that models that ignore irreducible concentration may underestimate actual concentrations. Turbidity reductions may predict bacterial reductions
Sullivan and Borst (2004)	Laboratory	Multiple devices	Describes U.S. EPA research on control practices Describes state of knowledge on treatment devices
Sulsbruck (1999)	Denmark	Stormwater management	Case study of incorporating stormwater management into sustainable development in sensitive watersheds

Authors	Study Area	Treatment /Management Activity	Conclusions
Sutton-Grier et al. (2005)	North Carolina	Wetlands	Investigated whether addition of compost would increase plant growth in wetlands Water quality data shows limited removal of nutrients Soils data shows high variability among sites for parameters such as OM
Syme et al. (2001)	Australia	Wetlands	Evaluated impact of smaller lots on quality of life and use of open space Small lots did not affect the interest and recreation values of gardens, or visitation to local parks and wetlands Perceived environmental control factor governing wetland visitations
Taebe and Droste (2004)	Iran	Stormwater characterization Detention ponds	Urban runoff pollutant load higher than sanitary wastewater loads in areas with high precipitation, but lower in drier areas Evaluated treatment options for runoff and wastewater
Takasou et al. (2002)	Japan	Infiltration	Evaluation method for predicting stormwater improvement from infiltration, which includes calculating infiltration area and number of facilities
Tan et al. (2008)	Modeling Shanghai, China	Stormwater characterization	Calibrated 3 rainfall-runoff models for residential area Runoff volume, peak most sensitive to fixed runoff percentage, impervious Impact of parameter changes of Horton Infiltration Model larger than those of Green-Ampt Infiltration Model and New UK Percentage Model.
Tanaka and Zaizen (1995)	Japan	Detention ponds Infiltration	Reviews current state-of-the-art of stormwater control Addresses two concerns of stormwater infiltration: groundwater contamination and subgrade strength
Tatalovich and Harbor (1998)	Indiana	Wetland Biofiltration	Case study of parking lot treatment Describes monitoring program to confirm pollutant removal of wetland/biofiltration facility
Taur et al. (1985)	Texas	Detention pond	Described model for least-cost design of regional detention facilities
Taylor (1991)	Tennessee	Wetlands Detention ponds	Evaluated treatment efficiency of design parameters (hydraulic loading rate, rainfall intensity, vegetation) on treatment from power plants
Thomas (2000)	Michigan	Infiltration	Compared new residential development impacts on groundwater quality New groundwater increase in NO ₃ , Cl, TDS Sources were septic leakage and stormwater runoff
Thompson and Vandermuss (2004)	Laboratory	Rock cribs	Size and depth affected time for runoff to cool Rock cribs could reduce temperature of runoff prior to discharge
Thompson et al. (2008)	Laboratory	Bioretention	Infiltration rate: sand and compost only > sand, compost, and sandy soil > sand, compost, and silt loam soil. Bulk density inversely related to proportion of compost Moisture holding capacity increased with the proportion of compost Compaction resulting from initial wetting testing increased bulk density and decreased moisture holding capacity
Tilley and Brown (2006)	Florida	Wetlands	Uses eco-hydrological model to predict that installing wetlands for stormwater management increased landscape productivity

Authors	Study Area	Treatment /Management Activity	Conclusions
Toet et al. (1990)		Detention pond	Used POND model to predict eutrophication in urban stormwater ponds Model describes removal and accumulation of pollutants and processes concerning phytoplankton seasonal growth Evaluated impact of volume on pollutant removal, eutrophication
Townsend et al. (1998)		Wetlands	Identifies some differences between constructed and natural surface-flow wetlands for stormwater treatment. Include wetland objectives, physical and operational differences, pollutant removal capability, and considerations for selection of wetland type
Traver (2002)	Modeling	Wetlands	Compares routing techniques for a stormwater wetland Results indicate that storage-indication routing does not work in a wetland
Traver (2004)		Infiltration Low Impact Development	Describes relationship between LID goals and capture volume, device placement, and general use of infiltration
Traver and DeBarry (2003)	Pennsylvania	Infiltration	Discusses development of criteria to meet recharge, treatment, and downstream protection goals of stormwater management
Traver and Ermilio (2005)	Pennsylvania	Bioinfiltration	Presents monitoring results for bioinfiltration traffic island
Traver and Woodruff (2005)	Pennsylvania	Wetlands	Presents monitoring results for stormwater wetlands
Traver et al. (2003)	Pennsylvania	Biofiltration, Infiltration	Describes monitoring program
Traver et al. (2005)	Pennsylvania	Infiltration	Presents design, construction, monitoring of infiltration trench treating parking garage runoff
Trejo-Gaytan et al. (2006)	Nevada	Chemical treatment	Evaluated improved sedimentation of particles after chemical dosing Evaluated effect of temperature, coagulant type, dose, mixing, quality Dosing based on streaming current values resulted in turbidities of less than 10.9 ± 0.35 NTU and filterable and total phosphorus concentrations of less than 9.83 ± 0.54 and 25.6 ± 5.71 $\mu\text{g/L}$, respectively. Polyaluminum chlorides modified with silica or sulfate, with low to medium basicity, consistently best for removing P and fine particles
Tsai (1993)		Retention basin	Case study of stormwater management at petrochemical facility Separated stormwater by degree of contamination Used oxidation ditches as detention facilities for clean stormwater
Tsihrintzis and Hamid (1998)	Modeling	Stormwater management planning	Used SWMM 5 to model small urban catchment Impervious depression storage was most sensitive calibration parameter, followed by Manning's n values
Tsihrintzis et al. (1990)	Modeling	Wetlands Stormwater management planning	Case study of modeling to support restoration and site development SWMM model used to size storm drains and wetland circulation pipes
Tsihrintzis et al. (1996)	California	Wetlands	Case study of wetland restoration for multiple objectives – biotic habitat, flood control, runoff treatment
Tuccillo (2006)	New Jersey	Stormwater characterization	Cu, Zn dissolved (20-100%) or particulate associated > 5 μm (0->70%). Pb, Cr associated exclusively with particles > 5 μm in size. Fe, Al, Si mostly in larger size fractions (>70%)

Authors	Study Area	Treatment /Management Activity	Conclusions
Uchimura et al. (1997)	Japan	Detention pond	Describes simulation models for predicting sewer overflows Ponds installed to reduce overflows by reducing stormwater in system
Urban and Claborn (1989)	Texas	Infiltration	Describes installation of geotextiles and sand trenches in bottom of playa lakes to prevent clogging and promote recharge
Urbonas (1984a,b)		Detention pond	Describes committee report on detention outlet control structures
Urbonas (1999)	Colorado	Sand filtration	Model to describe flow rate as a function of suspended solids loading Reviews current work in media filtration for stormwater treatment
Urbonas (2003)	Colorado	Stormwater management	Reviews the effectiveness of traditional BMPs in a semi-arid climate
Urbonas et al. (1985)		Detention pond	Describes committee report on detention outlet control structures
van Dam and van de Ven (1984)	Netherlands	Pervious pavement	Evaluated infiltration models for effectiveness on pervious pavements Hillel and Gardner model best able to replicate field data
Veldkamp et al. (1997)	Modeling	Stormwater management	Describes decision network for stormwater management Advocates source control and that rainwater harvesting and infiltration are more sustainable than end-of-pipe solutions
Venkata Rathnam et al. (2002)	India	Detention ponds	Case study of detention pond design using design storm approach
Villareal et al. (2004)	Malmö, Sweden Modeling	Green roofs Open channels Detention ponds	Investigated benefits of disconnecting older impervious areas from sewer system to new surface drainage system consisting of combinations of green roofs, channels and detention ponds Modeling demonstrated that devices in series should be effective
Vogel et al. (2005)	Northeastern United States Modeling		Distributed watershed model of nutrient and stormwater transport Model uses curve number method with genetic algorithm to optimize number and placement of treatment devices
Von Braun (1985)	Modeling		GIS to determine whether stormwater infiltrated into hazardous waste site
Vorreiter and Hickey (1994)	Sydney, Australia	First flush evaluation	First flush for TSS, fecal coliforms, TP, but not seen for filterable P Antecedent dry period (less than 5 mm of rain) was highly correlated to first flush occurrence
Wada and Miura (1990)	Modeling	Infiltration facilities	Presents combinations of devices at a site to improve infiltration capacity Build simulation model to estimate overall effectiveness of combination treatments on stormwater runoff control Case study presented
Wada et al. (2006)		Measurement of organics	Characterized organic matter in first flush from road Soil infiltration effectively treated refractory organics
Wakelin et al. (2003)	Winnipeg, Canada	Retention basins	Monitored water quality after nuisance-plant treatment with herbicides Neither herbicide effective as natural regulation to limit plant growth Monitored TSS, chlorophyll-a, temperature, DO, pH
Wang et al. (2004)	Modeling	Wet detention pond	Model based on mass balance and release-storage equation. Pollutant removal and flow routing tested with highway runoff pond

Authors	Study Area	Treatment /Management Activity	Conclusions
Wanielista and Yousef (1986)		Retention ponds, Detention ponds, Vegetated Swales, Street Cleaning, Catch basin cleaning, Infiltration, Erosion Control	Summarizes efficiencies and designs of practices
Wanielista and Yousef (1993)		Detention pond	Used mass balance on storage to determine irrigation water available as function of impervious area, temporary storage volume, and irrigation rate Design curves created and tested
Warnaars et al. (1999)	Copenhagen, Denmark	Infiltration trench	Describes monitoring of two infiltration trenches Found slight clogging, but greatest hydrology impact was soil permeability Indicated need for better soils information during design Infiltration possible in areas with compressed soils and backfill
Warner and Li (2000)	Canada	Wetlands	Presents matrix of issues when considering wetlands for treatment
Weeks and Crockett (1983)	Australia	Modeling runoff pollution	Presents annual export rates and concentrations for several pollutants Treatment options that can be retrofit are discussed
Wegener et al. (1990)	Denver, Colorado	Wetlands, Extended detention ponds, Infiltration basins	Describes design, construction, operation and monitoring during first year of operation
Weijland et al. (1990)		Infiltration basins Retention basins	Presents flow chart of decision process to select stormwater management system to reduce sanitary sewer I&I Includes constraints such as water quality standards, site limitations and managements considerations
Weiss et al. (2006)	Laboratory Field studies Modeling	Detention ponds	Laboratory and field studies to generate model parameters to predict heavy metal removal in plants and sediments First order kinetic model could describe plant uptake Growth of plants and removal rates were species specific. Metals stratified at sediment water interface
Weiss et al. (2007)	United States	Dry extended detention ponds, Wet detention ponds, Sand filters, Constructed wetlands, Bioretention filters, Infiltration trenches	Related pollutant removal ability to device cost, construction, annual O&M Total present cost presented as function of water quality design volume Total mass of pollutants removed function of water quality design volume Wetlands least expensive to construct and maintain
Wen and Yu (1997)	Taiwan	Swale Wetlands Ponds	Treatment train reduced flood peaks by 50 – 75%. TSS removal (-14 to 99%); BOD (72 – 85%); COD (-90 to 88%); TKN (23 – 72%); TP (20 – 80%).
Westerstrom (1984)	Lulea, Sweden	Snowmelt characterization	Describes hydrologic parameters of snowmelt runoff
Whitaker et al. (2002)	Oregon	Dry detention basins, Wetlands , Bioretention areas	Describes integration of practices to treat, improve aesthetics and habitat
White and Meyers (1997)	Alabama	Wetland	Golf course treatment Described vegetation selection and design Predicted removal of up to 60% of nitrogen, phosphorus and sediment

Authors	Study Area	Treatment /Management Activity	Conclusions
Whitehouse (1984)	Mining reclamation locations	Wetlands	Wetlands act as sediment traps and water filtration systems
Williams et al. (2007)	South Carolina	TMDL Development	Describes need and plan for stakeholder buy-in during TMDL development Describes activities to characterize and model watershed to ensure one group is not bearing disproportionate share of load reductions
Wilson et al. (2004)	Modeling Laboratory Compost facilities	Detention ponds	Found that approximately 68% of rainfall passes through the compost and is transported to detention pond
Wiseman et al. (1993)	Orange County, Florida	Wetlands	Used water budget modeling to improve treatment performance Wetland water budget compared to regional groundwater flow model Characterized evapotranspiration, surface water outflow, groundwater outflow, hydraulic gradients and storage volume
Witt (2000)	Alabama	Wetlands with sediment forebay	Examine impacts of development on natural wetlands and wildlife refuge Described design of wetlands with sediment forebay to treat runoff
Wojtenko et al. (2002)	Laboratory	Filtration	Described flow rates through natural organic media individually versus in combination with sand
Wong (1995)	Melbourne, Australia Modeling	Wetlands	Describes stochastic approach to designing stormwater wetlands Design chart created relating wetland size, prescribed stormwater retention time, and hydrologic performance
Wong (2002)	Australia	Wetlands	Describe concepts of Water Sensitive Urban Design (WSUD) to meet multiple stormwater management objectives Presents design of stormwater wetlands in urban areas
Wong and Breen (2002)	Australia	Wetlands	Describes design practices, including compartmentalization Analyzed stormwater PSD Describes use of hydrologic effectiveness curves to select appropriate extended storage volume Encourages use of landscape designer to meet aesthetic criteria
Wong et al. (2006)	Modeling	Wetlands, Pond, Vegetated swales, Sediment basins, Biofilters	Presents model development to predict device performance \ Water quality described using first-order kinetic decay model ("k-C" model) CSTR model used to describe hydrodynamics
Wong et al. (2008)	Model Australia	Rainwater harvesting Infiltration Effective Impervious prediction	Use of hydrologic, water quality, geomorphic indicators of catchment effective imperviousness. Indicators then could be used to predict effectiveness of stormwater control strategies Discusses rainwater harvesting as part of strategy Showed that reducing 1.5-year peak flow could reduce post-development erosion potential index

Authors	Study Area	Treatment /Management Activity	Conclusions
Woodhouse and Duff (2004)	Laboratory	Aerobic trickling filter	Influent runoffs toxic, but toxicity reduced after 24 hours of treatment Reductions at 34°C: BOD (94 – 100%), COD (86 – 93%), tannins and lignins (91 – 97%) Slightly lower removals at lower temperatures (5°C)
Wright et al. (2007a)	Wilmington, North Carolina	Pervious pavement, Rain gardens, Bioretention cells	Described retrofit stormwater practices in urbanized, impacted watershed
Wright et al. (2007b)	Holden Beach, NC	Infiltration basins	Describes conversion of never-used septic tanks to subsurface infiltration devices or rainwater harvesting tanks Tanks captured 75 to 90% of storm runoff during 1-year monitoring period
Wu (1989)	Charlotte, North Carolina	Detention pond	Pond area > 1 – 2% of land area required for 70% sediment removal. Calculated removal efficiencies for TSS, TP, OP, TKN, Fe, Zn, Cu, Pb Used SWMM to derive relationships relating pond size to pollutant removal
Wu et al. (1989)	North Carolina	Detention pond	Pond short-circuiting noted Ponds not designed for water-quality treatment, but are providing treatment
Wulliman et al. (1989)		Detention ponds Wetlands Infiltration Basins	Design recommendations for using combination of ponds, wetlands, infiltration to remove at least 50% of phosphorus load Guidelines for designing detention ponds and wetland/infiltration areas for water quality treatment Issues of integrating project into natural prairie landscape highlighted
Wulliman et al. (1998)	Denver, Colorado	Wetlands	Case studies of stream restoration and water quality projects
Xiao et al. (2006)		Infiltration basins	Investigated interaction of micro- and macro-organic on biogeochemical function at sediment-water interface Sediments with macroinvertebrates had higher rates of nutrient removals through stimulation of biological processes
Yaman et al. (2006)	Laboratory	Geotextile	Investigated permeability and clogging in geotextiles used to treat CSO Only nonwoven geotextiles with complex structures were able to support biomass growth and retain permeability
Yousef et al. (1983)	Central Florida, USA	Highway bridge runoff pollution Infiltration and detention	Runoff water had Pb, Zn, Cu, Cr, Fe, Ni, Cd Metals concentrate in soils and biota Runoff should not be discharged directly to receiving waters
Yousef and Lin (1990)	Florida	Detention pond	Presents sedimentation rates and leaching characteristics of bottom sediments from six detention ponds
Yousef et al. (1986)	Florida	Detention/retention pond	Summarizes existing design considerations and removal efficiencies of selected pollutants
Yousefi et al. (2001)		Constructed wetlands and detention ponds	Use of bacteriophages to predict removal of viruses in constructed wetlands and detention ponds Bacteriophage (and potentially virus) removal more effective in wetlands Removal likely due to association with particulate matter

Authors	Study Area	Treatment /Management Activity	Conclusions
Yu and Zhen (2001)	Modeling	All	Evaluate placement of BMP analysis at three spatial levels (on-site, sub-regional, regional) using AGNPS Developed BMP optimization approach for cost-effective placement Hypothetical case study included
Yu et al. (1994)	Field	Dry detention pond Grass swale	Modified dry pond had 50% TSS, 40% TP, 30% COD and Zn removal. Slightly higher removals for grass swale with check dams Best removals obtained when storm flows are small
Yu et al. (1998)		Constructed wetlands	Three wetland sites monitored TSS, COD, TP, OP, Zn removals ranged from -30% to > 80%, with significant variability between sites Model being developed
Zavoda (2006)	New York City	Rainwater harvesting	Rainwater collection tank combined with sand filter and chlorine treatment to provide additional water for high-rise building 50% water reduction compared to similar residential buildings without reclamation system
Zeigler and Emmanuel (1985)	Pennsylvania	Management Planning	Described need for watershed planning with urban runoff and wastewater treatment plant discharges Need to protect trout population
Zhang and Mitsch (2005)	Modeling Ohio	Wetlands	Used simple daily mass-balance water budget model for inflow, outflow, precipitation, evapotranspiration and groundwater seepage Model: STELLA 7.0
Zhang et al. (2008)	Laboratory	Filtration/Biofiltration	Increase in pollutant removal ability in sandy soils by amending with fly ash Modeling showed that treatment layer had life of 10 years if unamended sand is used, but over 100 years if fly ash-sand mixture is used
Zhen and Yu (2001)	Modeling	All	Methodology to optimize device placement in watershed Used unit pollutant removal cost as index to evaluate effectiveness
Zhen et al. (2004)	Modeling	Detention ponds	Heuristic optimization techniques coupled with a watershed model (AnnAGNPS and BMP module) to predict least-cost placement that meet the pollutant load reduction requirements. Impoundment module modified to address sediment accumulation and resuspension
Zheng et al. (2006)		Infiltration pond and wetlands	Case study to assess constraints of planning, design and operation Vegetation did not improve drainage properties Water quality after treatment not acceptable for reuse Problems with filamentous green algae development in unplanted pond

Authors	Study Area	Treatment /Management Activity	Conclusions
Zhu and Ehrenfeld (2000)	Laboratory	Wetlands	Wetlands sediments assessed for N removal ability Peat removed N after week 1 but all soils released N after weeks 2 and 3 Soils from hollows and most hummocks retained nitrate but all soils released ammonium Patterns correlated with N mineralization and nitrification rates of soils
Zimmer et al. (2007)	Modeling Kitchner, Ontario	Low Impact Development (LID)	Watershed modeling to evaluate water quality, quantity impacts of development Applied to retrofit
Zimmerman et al. (2005)	Laboratory and Modeling	Infiltration	Modeled impacts of roof runoff infiltration Laboratory-generated isotherms used for modeling parameters Groundwater concerns only for soils with low adsorption potential Soil accumulations in near surface layers of soil
Zitomer and Tonuk (2003)		Anaerobic completely-mixed stirred tank reactors and filters	Investigated ability of reactors and filters to treat aircraft deicing fluids Increasing COD removal rates required increased biomass and biomass immobilization

APPENDIX L

CHECKLISTS

L.1 Introduction

This appendix contains the checklists in the body of the document. The purpose of creating a separate appendix is to create a single location in the document where they may be obtained as a package for use in project evaluations.

Table L-1. Documentation of Regulatory Requirements for Sustainable Site Stormwater Management.

Regulation Type	Regulation: Yes or No	Regulating Authority or Authorities
Federal		
State		
Local/Regional		
Total Maximum Daily Load (TMDL)		
High-Value Water		
Drinking Water Source Protection		

Table L-2. Checklist for Calculating Stormwater Volume, Peak Flow Rate, or Exceedence Storm.

Design Storm	Yes (size, yrs) No		Continuous Simulation	Years of Record:
Method of Calculation for Site Stormwater:				
	Units		Pre-development	Post-development
Peak Flow Rate	cfs	cms		
Peak Volume	cf	cm		
Method of Calc				
Water Quality Volume	cf	cm		

Table L-3. Checklist for Evaluating Stormwater and Receiving Water Quality Compared to Standards.

WATER QUALITY CONSIDERATIONS

Regulatory based discharge limits: Yes No

TMDL imposed on outfall: Yes No

Sources of Data:

Stormwater _____

Stormwater Quality Limits _____

Receiving Water _____

Receiving Water Limits _____

Groundwater Quality _____

Groundwater Limits _____

General Quality Parameters

Parameter	Units* (Circle One)	Receiving Water (Actual)	Receiving Water Limits	Stormwater Quality (Actual)	Stormwater Quality Limits	Groundwater Quality (Actual)	Groundwater Quality Limits**
pH							
Temperature	°C °F						
Specific Conductance	µS/cm						
Suspended Solids (TSS)	mg/L						
Suspended Solids (SSC)	mg/L						
Dissolved Solids	mg/L						
Turbidity	NTU						
Hardness	mg/L as CaCO ₃						
Alkalinity	mg/L as CaCO ₃						
Dissolved Oxygen	mg/L						
Toxicity, Total	LD ₅₀ LC ₅₀						
Toxicity, Dissolved	LD ₅₀ LC ₅₀						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable.

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Nutrients

Parameter	Units* (Circle One)	Receiving Water (Actual)	Receiving Water Limits	Stormwater Quality (Actual)	Stormwater Quality Limits	Groundwater Quality (Actual)	Groundwater Quality Limits**
Ammonia/Ammonium	mg/L as NH ₄ NH ₃ N						
Nitrate	mg/L as NO ₃ N						
Nitrite + Nitrate	mg/L as NO ₃ N						
Total Kjeldahl Nitrogen	mg/L as N						
Dissolved Nitrogen	mg/L as N						
Total Nitrogen	mg/L as N						
Orthophosphate	mg/L as PO ₄ P						
Dissolved Phosphorus	mg/L as PO ₄ P						
Total Phosphorus	mg/L as PO ₄ P						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Metals

Parameter	Units* (Circle One)	Receiving Water (Actual)	Receiving Water Limits	Stormwater Quality (Actual)	Stormwater Quality Limits	Groundwater Quality (Actual)	Groundwater Quality Limits**
Arsenic, Total	µg/L mg/L						
Arsenic, Dissolved	µg/L mg/L						
Cadmium, Total	µg/L mg/L						
Cadmium, Dissolved	µg/L mg/L						
Chromium, Total	µg/L mg/L						
Chromium, Dissolved	µg/L mg/L						
Copper, Total	µg/L mg/L						
Copper, Dissolved	µg/L mg/L						
Iron, Total	µg/L mg/L						
Iron, Dissolved	µg/L mg/L						
Lead, Total	µg/L mg/L						
Lead, Dissolved	µg/L mg/L						
Mercury, Total	µg/L mg/L						
Mercury, Dissolved	µg/L mg/L						
Nickel, Total	µg/L mg/L						
Nickel, Dissolved	µg/L mg/L						
Zinc, Total	µg/L mg/L						
Zinc, Dissolved	µg/L mg/L						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Organics

Parameter	Units* (Circle One)	Receiving Water (Actual)	Receiving Water Limits	Stormwater Quality (Actual)	Stormwater Quality Limits	Groundwater Quality (Actual)	Groundwater Quality Limits**
Total Organic Carbon (TOC)	mg/L						
Oil & Grease	mg/L						
Total Petroleum Hydrocarbons	mg/L						
5-day Biochemical Oxygen Demand (BOD ₅)	mg/L						
7-day Biochemical Oxygen Demand (BOD ₇)	mg/L						
Chemical Oxygen Demand (COD)	mg/L						
1,3-Dichlorobenzene	µg/L						
Benzo(a)anthracene	µg/L						
Bis(2-ethylhexyl) phthalate	µg/L						
Butyl benzyl phthalate	µg/L						
Chlorobenzene	µg/L						
Ethylbenzene	µg/L						
Fluoranthene	µg/L						
Pentachlorophenol	µg/L						
Pyrene	µg/L						
Toluene	µg/L						
Atrazine	µg/L						
Lindane	µg/L						
Chlordane	µg/L						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Microbiological Water Quality

Parameter	Units* (Circle One)	Receiving Water (Actual)	Receiving Water Limits	Stormwater Quality (Actual)	Stormwater Quality Limits	Groundwater Quality (Actual)	Groundwater Quality Limits**
Total Coliforms	CFU/100 mL						
<i>E. coli</i>	CFU/100 mL						
Enterococci	CFU/100 mL						
<i>Clostridium perfringens</i>	CFU/100 mL						
Somatic coliphage	PFU/100 mL						
<i>Giardia lamblia</i>	cysts/100 mL						
<i>Cryptosporidium parvum</i>	cysts/100 mL						

* Use one set of measurement units for consistent comparisons and circle selected set of units, where applicable

** Groundwater quality limits should be included if infiltration may be considered as a stormwater management practice.

Receiving Water Biology and Habitat

Habitat Evaluation	Percent		
Pool			
Riffle			
Parameter	Units* (Circle One)	Receiving Water (Actual)	Receiving Water Limits
Chlorophyll a	mg/L		
Biotic Integrity Indices			
Index of Biotic Integrity (IBI)	n/a		
EPT Index	n/a		
Primary Production	n/a		
Gross Primary Productivity (GPP) and CR			
Fish Community: Taxa Richness & Diversity			

Table L-4. Checklist for Determining Whether to Use Infiltration, Surface Treatment, or a Combination.

Selecting a Control Practice: Water Quantity

Is post-development flow rate control required for the entire site?	Yes	No
If Yes, how much flow requires control? cfs cms	_____	
Is post-development volume control required for the entire site?	Yes	No
If Yes, how much volume requires control? cf cm	_____	

If both flow rate and volume control are required, select treatment device from Group A.

If only flow rate control is required, select treatment device from either Group A or B.

If quantity control is not required, select treatment device from Groups A, B or C.

GROUP A: Stormwater Control Practices Appropriate for Control of Both Flow Rate and Volume

Infiltration Basins, Infiltration Trenches, Pervious Pavement, Bioinfiltration Devices (Rain Gardens), Infiltrating Grass Swales, Underground Injection Control (UIC) (clean water only)

NOTE: The sizing of these devices is dependent on the desired flow rate of infiltration.

GROUP B: Stormwater Control Practices Appropriate for Rate Control Only

Detention Basins, Retention Basins, Grass Swales (limited infiltration), Underground Injection (clean water only)

NOTE: The sizing of these devices depends on the rate attenuation desired.

GROUP C: Stormwater Control Practices Designed Primarily for Water Quality Control

Manufactured Hydrodynamic Devices, Manufactured Filtration Devices

Selecting a Stormwater Control Practice: Water Quality

List the water quality parameters that require control starting with the primary criterion (rank in order of importance).

Water quality parameter	Potential Treatment Device (Table 5-6, based on Tables 5-3 through 5-7)

The process now becomes iterative as described below. If the local guidance does not provide checklists, generic checklists for the steps are found in the appropriate chapters.

1. Tentatively site the planned infiltration devices.
2. Calculate the surface area available for infiltration at each device and in total for the site.
3. Estimate the approximate flow rate and volume that can be controlled through infiltration (Chapter 6).
4. Estimate the approximate pollutant treatment provided by the infiltration devices (Chapter 7).
5. Calculate the flow rate, volume, and pollutant levels requiring treatment in non-infiltrative (surface) devices.
6. Estimate the approximate water quantity and quality improvements with the surface treatment devices (Chapter 8).
7. Predict the water quantity, flow rate, and pollutant treatment provided by the selected design practices (Chapter 9).
8. Compare to the required treatment level.
9. Repeat Steps 1 – 8 until the required treatment meets or exceeds the volume, flow rate, or pollutant reductions required for low/no impact development.
10. Where groundwater depletion is an issue or where additional infiltration is needed to reduce post-development flow rates, investigate potential infiltration locations for surface-treated runoff.

Table L-5. Predicting Effluent Quality from Stormwater Treatment Devices.

Device	Influent Quality (mg/L) for Critical Constituent(s)	Individual Device Estimated Effluent Quality (mg/L) for Critical Constituent(s)*	Individual Device Performance (% Removal)	Critical Particle Size (µm), typically d ₅₀	Effluent Concentration based on Percent removal*	Predicted Effluent Quality (mg/L) – Use greater value from % removal calculation or literature
Sedimentation*						
Filtration						
Infiltration						

* For sedimentation devices, removal efficiency and effluent concentration can be predicted from sedimentation theory if discrete particle settling and ideal behavior can be assumed, or a correction factor should be applied to account for short-circuiting (for example, inclined plate settlers are assumed to be 60% efficient compared to ideal discrete particle settling).

Table L-6. Predicting Treatment Performance for Devices Installed in Series.

Pollutant:	Effluent Quality (mg/L µg/L cfu/100 mL)
Sketch the treatment train used at the site (Device A is the first device in series and Device B is the second device):	
Calculate the performance for the Device A in series (using the calculations described in Table 9-1 and repeated here)	
Flow Rate or Water Quality Volume Being Treated (note units)	
Influent Quality to Device A	
Calculate effluent quality based on removal efficiency: Influent Concentration – (Percent Removal)(Influent Concentration) = Effluent Quality	
Predict effluent quality from literature (such as the International BMP database):	
Predict effluent quality from theory for sedimentation devices.	
Use greater of Effluent Quality based on Percent Removal and Literature Effluent Concentrations.	
Calculate the performance for the Device A in series (using the calculations described in Table 9-1 and repeated here)	
Influent Quality to Device B (= Effluent Quality from Device A)	
Calculate effluent quality based on removal efficiency: Influent Concentration – (Percent Removal)(Influent Concentration) = Effluent Quality	
Predict effluent quality from literature (such as the International BMP database):	
Predict effluent quality from theory for sedimentation devices.	
Use greater of Effluent Quality based on Percent Removal and Literature Effluent Concentrations.	

Table L-7. Predicting Treatment Performance for Devices Installed in Parallel.

Pollutant:	Effluent Quality (mg/L μ g/L cfu/100 mL)
Sketch the layout of the devices in parallel (Device A is the first device in series and Device B is the second device):	
Flow Rate or Water Quality Volume to Treatment Area (note units):	
Calculate the performance for the Device A in parallel (using the calculations described in Table 9-1 and repeated here)	
Flow Rate or Water Quality Volume to Device A (note units)	
Influent Quality to Device A	
Calculate effluent quality based on removal efficiency: Influent Concentration – (Percent Removal)(Influent Concentration) = Effluent Quality	
Predict effluent quality from literature (such as the International BMP database):	
Predict effluent quality from theory for sedimentation devices.	
Use greater of Effluent Quality based on Percent Removal and Literature Effluent Concentrations.	
Calculate the performance for the Device B in parallel (using the calculations described in Table 9-1 and repeated here)	
Flow Rate or Water Quality Volume to Device B (note units)	
Influent Quality to Device B (= Effluent Quality from Device A)	
Calculate effluent quality based on removal efficiency: Influent Concentration – (Percent Removal)(Influent Concentration) = Effluent Quality	
Predict effluent quality from literature (such as the International BMP database):	
Predict effluent quality from theory for sedimentation devices.	
Use greater of Effluent Quality based on Percent Removal and Literature Effluent Concentrations.	
COMBINE the Effluent Qualities from Devices A and B	
Effluent Quality from Device A	
Flow Rate or Water Quality Volume from Device A	
Calculate the Effluent Load from Device A (Flow Rate x Time x Concentration) or (Water Quality Volume x Concentration)	
Effluent Quality from Device B	
Flow Rate or Water Quality Volume from Device B	
Calculate the Effluent Load from Device B	
Add the Effluent Loads from Devices A and B	
Calculate the Weighted Average Effluent Quality (Load Sum divided by Sum of Volumes from Devices A and B)	

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WASTEWATER UTILITY

Alabama

Montgomery Water Works & Sanitary Sewer Board

Alaska

Anchorage Water & Wastewater Utility

Arizona

Avondale, City of
Glendale, City of, Utilities Department
Mesa, City of
Peoria, City of
Phoenix Water Services Dept.
Pima County Wastewater Management
Safford, City of
Tempe, City of

Arkansas

Little Rock Wastewater Utility

California

Central Contra Costa Sanitary District
Corona, City of
Crestline Sanitation District
Delta Diablo Sanitation District
Dublin San Ramon Services District
East Bay Dischargers Authority
East Bay Municipal Utility District
El Dorado Irrigation District
Fairfield-Suisun Sewer District
Fresno Department of Public Utilities
Inland Empire Utilities Agency
Irvine Ranch Water District
Las Gallinas Valley Sanitary District
Las Virgenes Municipal Water District
Livermore, City of
Los Angeles, City of
Los Angeles County, Sanitation Districts of
Napa Sanitation District
Novato Sanitary District
Orange County Sanitation District
Palo Alto, City of
Riverside, City of
Sacramento Regional County Sanitation District
San Diego Metropolitan Wastewater Department, City of
San Francisco, City & County of
San Jose, City of
Santa Barbara, City of
Santa Cruz, City of
Santa Rosa, City of
South Bayside System Authority
South Coast Water District

South Orange County Wastewater Authority
South Tahoe Public Utility District
Stege Sanitary District
Sunnyvale, City of
Union Sanitary District
West Valley Sanitation District

Colorado

Aurora, City of
Boulder, City of
Greeley, City of
Littleton/Englewood Water Pollution Control Plant
Metro Wastewater Reclamation District, Denver

Connecticut

Greater New Haven WPCA
Stamford, City of

District of Columbia

District of Columbia Water & Sewer Authority

Florida

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Fort Lauderdale, City of
Jacksonville Electric Authority (JEA)
Miami-Dade Water & Sewer Authority
Orange County Utilities Department
Pinellas, County of
Reedy Creek Improvement District
Seminole County Environmental Services
St. Petersburg, City of
Tallahassee, City of
Toho Water Authority
West Palm Beach, City of

Georgia

Atlanta Department of Watershed Management
Augusta, City of
Clayton County Water Authority
Cobb County Water System
Columbus Water Works
Fulton County
Gwinnett County Department of Public Utilities
Savannah, City of

Hawaii

Honolulu, City & County of

Idaho

Boise, City of

Illinois

Decatur, Sanitary District of
Greater Peoria Sanitary District
Kankakee River Metropolitan Agency
Metropolitan Water Reclamation District of Greater Chicago
Wheaton Sanitary District

Indiana

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Iowa

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Des Moines, City of
Iowa City

Kansas

Johnson County Wastewater
Unified Government of Wyandotte County/
Kansas City, City of

Kentucky

Louisville & Jefferson County Metropolitan Sewer District
Sanitation District No. 1

Louisiana

Sewerage & Water Board of New Orleans

Maine

Bangor, City of
Portland Water District

Maryland

Anne Arundel County Bureau of Utility Operations
Howard County Bureau of Utilities
Washington Suburban Sanitary Commission

Massachusetts

Boston Water & Sewer Commission
Massachusetts Water Resources Authority (MWRA)
Upper Blackstone Water Pollution Abatement District

Michigan

Ann Arbor, City of
Detroit, City of
Holland Board of Public Works
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Wayne County Department of Environment
Wyoming, City of

Minnesota

Rochester, City of
Western Lake Superior Sanitary District

Missouri

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Metropolitan St. Louis Sewer District

Nebraska

Lincoln Wastewater & Solid Waste System

Nevada

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Las Vegas, City of
Reno, City of

New Jersey

Bergen County Utilities Authority
Ocean County Utilities Authority

New York

New York City Department of Environmental Protection

North Carolina

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Metropolitan Sewerage District of Buncombe County
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Ohio

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Oklahoma

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Oregon

Albany, City of
Clean Water Services
Eugene, City of
Gresham, City of
Portland, City of Bureau of Environmental Services
Lake Oswego, City of
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Water Environment Services

Pennsylvania

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Philadelphia, City of
University Area Joint Authority

South Carolina

Charleston Water System
Mount Pleasant Waterworks & Sewer Commission
Spartanburg Water

Tennessee

Cleveland Utilities
Murfreesboro Water & Sewer Department
Nashville Metro Water Services

Texas

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Dallas Water Utilities
Denton, City of
El Paso Water Utilities

Fort Worth, City of
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Trinity River Authority

Utah

Salt Lake City Corporation

Virginia

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Washington

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Wisconsin

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Water Services Association of Australia

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Cradle Mountain Water
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Water Corporation
Water Distribution Brisbane City Council
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Canada

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Lethbridge, City of
Regina, City of, Saskatchewan
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STORMWATER UTILITY

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Colorado

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Florida

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Iowa

Cedar Rapids Wastewater Facility
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STATE

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