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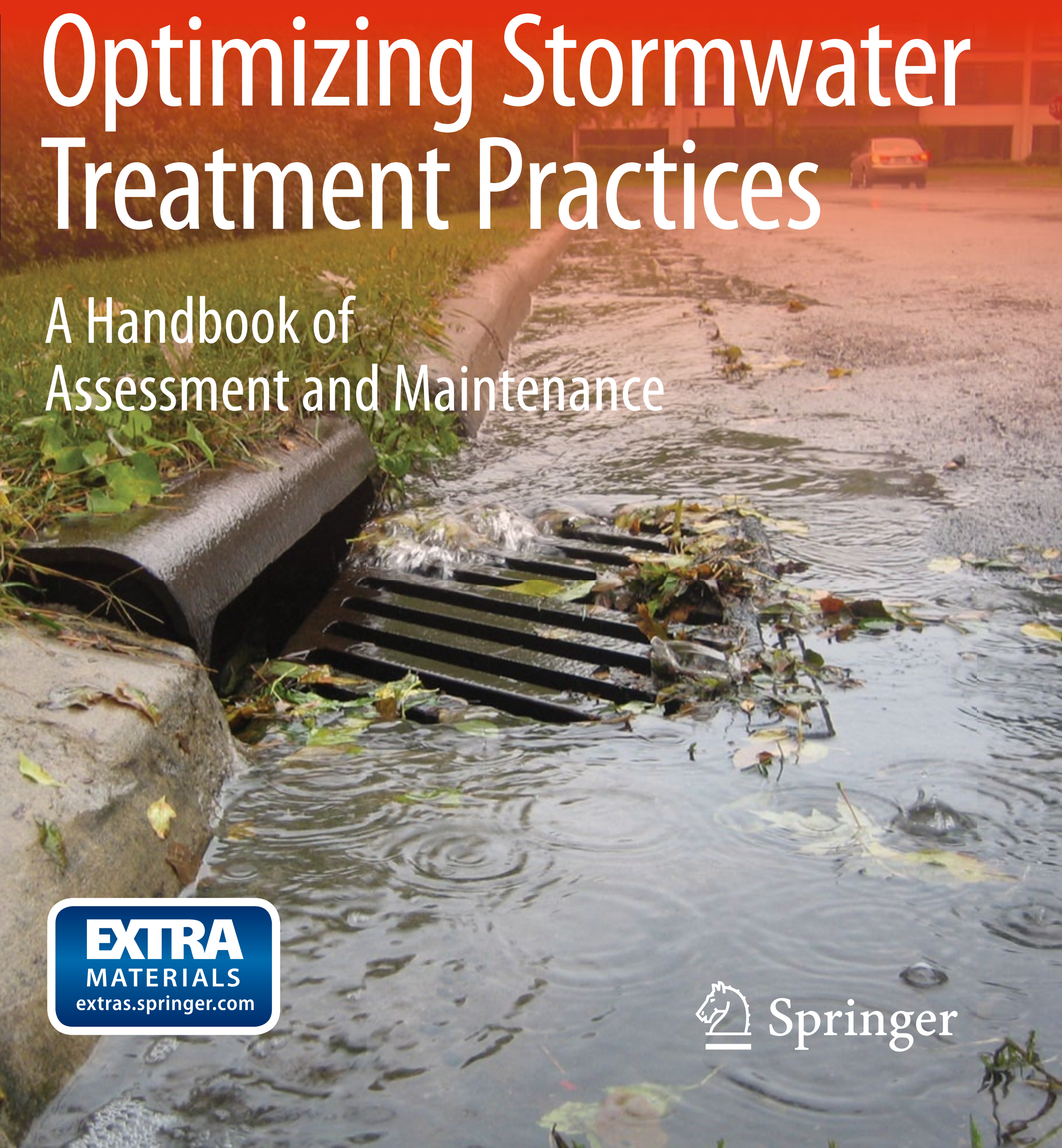
Optimizing Stormwater Treatment Practices

A Handbook of Assessment and Maintenance



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A Handbook of Assessment and Maintenance

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Preface

This book is intended to be a resource to cost-effectively assess the performance of, and schedule maintenance for, stormwater treatment practices. Maintenance should never occur without an accurate assessment of the operating condition of a stormwater treatment practice. Thus, this book first details how to assess the performance of a stormwater treatment practice. It provides distinct levels of standardized assessment methodology, in increasing cost and difficulty, from which the user can select only those methods that are necessary. It also provides instructions on how to successfully complete an assessment of a stormwater treatment practice, including all required tasks, sample and data analysis, and other items. Finally, the book provides detailed guidance on how to use the information gathered during assessment to select and schedule the most appropriate maintenance actions.

The methods presented in this book will:

- Help users select cost-efficient assessment methods
- Help users develop an assessment program
- Ensure that an assessment program yields meaningful results
- Provide guidelines for reporting results and scheduling maintenance
- Allow for more meaningful comparisons between assessment and maintenance results of different stormwater treatment practices

The intended audience for this book includes engineers, planners, consultants, watershed district personnel, municipal staff, and natural resource managers, among others. Thus, case studies have been included, when possible, to provide practical examples related to the concepts discussed.

The research project that preceded this book and led to the development of much of the material was funded by the Minnesota Pollution Control Agency with C. Bruce Wilson as project manager. The authors would like to thank Bruce and all the staff at the Minnesota Pollution Control Agency for their confidence in us to deliver a quality product. Several partner projects that provided material for the case studies were funded by the Local Road Research Board of Minnesota, Metropolitan Council Environmental Services, Minnehaha Creek Watershed District, Minnesota Department of Transportation, Mississippi Watershed Management Organization, and the US Environmental Protection Agency. The authors wish to thank many individuals and organizations for their contribution to the completion of these projects which led to the development of this book: Brooke C. Asleson, Lawrence A. Baker, William R. Herb, Raymond M. Hozalski, Omid Mohseni, John L. Nieber, Bruce N. Wilson, the University of Wisconsin Extension, Emmons and Olivier Resources, South Washington Watershed District, Ramsey-Washington Metro Watershed District, Sarah M. Stai, Westwood Professional Services, Three Rivers Park District, City of Blaine, and Wenck Associates, Inc. The authors especially thank Brooke C. Asleson, Lawrence A. Baker, William R. Herb and John L. Nieber for contributing material that led to the development of this book. The authors also thank Bob Newport at US EPA Region 5 for his continual support of this effort.

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Contents

Introduction 1

Abstract

Countries and organizations around the world are working to reduce stormwater runoff volumes and increase the quality of runoff before it enters receiving water bodies. These efforts have resulted in the development of stormwater treatment practices, designed to retain contaminants such as suspended solids, nutrients, bacteria, metals, and others. The stormwater treatment practices are designed to perform at a certain level of treatment, but, over time, the performance level will decline due to factors such as clogging with sediment, reaching some finite contaminant storage capacity, excessive vegetative growth, and a host of other factors.

Stormwater treatment practices must receive intentional and regular maintenance to perform at predetermined, desired levels of runoff volume reduction, contaminant load reduction, or other primary objective over an extended period of time. In order to perform cost-effective maintenance at optimal time intervals, the practice must be regularly assessed. Assessment, as defined in this book, is the determination of the level of performance of a stormwater treatment practice with regard to the treatment goals of the practice and/or the determination of the state of a stormwater practice. For example, the former may include determining the percent load reduction a practice obtains with regard to suspended solids, while the latter may involve inspecting inlet and outlet structures of a pond for structural integrity and potential blockage from trash and debris. Only after a practice is assessed can optimal maintenance actions be planned and performed.

This chapter presents three levels of assessment, including visual inspection, testing (including capacity and synthetic runoff testing), and monitoring. The levels increase in complexity as presented and should be used selectively in accordance with stormwater management goals.

As society has developed and population has increased, human impact on the Earth has increased substantially. Houses, office complexes, shopping malls, airports, road networks, and scores of other amenities that provide conveniences and increase quality of life also create environmental challenges that cannot be ignored.

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These challenges include changes in stormwater runoff quantity and quality as a result of anthropogenic activities.

Rain falling on an open field or prairie may be intercepted by vegetation, infiltrated into the soil, and stored in low-lying areas. Over time this water can be transferred to the atmosphere through evaporation and transpiration (i.e., evapotranspiration). Together, these mechanisms, called abstractions, can significantly reduce the fraction of rain that becomes runoff as it travels across the watershed and into a receiving water body.

If an open field is developed for human occupation, however, heavy construction equipment can compact the soil and reduce its infiltration capacity, vegetation will likely be removed, which will reduce interception and evapotranspiration, and pervious soil will be covered by impervious surfaces such as asphalt, concrete, and buildings. These changes significantly increase the volume of stormwater runoff and the velocity at which it travels across the surface. Furthermore, the composition of stormwater is affected. Rainwater that runs off metal roofs and buildings can acquire dissolved metals such as copper, lead, and zinc (Davis et al. 2001). The application of fertilizers, herbicides, and pesticides can contribute excess nutrients (i.e., phosphorus and nitrogen) and toxic chemicals to the runoff (APHA 1998a, US EPA 1999a). Through tire wear, brake pad erosion, and other mechanisms, vehicular traffic generates metals and solid particles that build up on the road and nearby ground surface and are washed off during a rain event. These changes have a significant negative impact on the quality of surface waters that receive urban stormwater runoff.

1.1 Need for Treatment

Formal action to reduce stormwater pollution in the USA was taken in 1987 with the passage of amendments to the Clean Water Act that required the United States Environmental Protection Agency (US EPA) to address this issue. The US EPA did so with the passage of the National Pollution Discharge Elimination Systems (NPDES) Phase I (1990) and Phase II (2003) requirements. Under this program, most stormwater discharges are considered point sources and require an NPDES permit. Also, under section 303(d) of the Clean Water Act, states are required to develop a list of impaired waters, which are water bodies that do not meet water quality standards. States must also develop Total Maximum Daily Loads (TMDLs) for these impaired waters, which are the maximum daily pollutant load a water body can receive and still meet water quality standards. In order to meet the goals of a TMDL, the pollutant loading to a water body, of which stormwater runoff often contributes a large fraction, will have to be reduced. Thus, to meet this need, technologies (herein called stormwater treatment practices) have been developed for reducing stormwater runoff volume and improving its quality.

The United Nations Millennium Project, which was commissioned in 2002, seeks to develop an action plan to reduce world hunger, poverty, and disease

(UNMP 2005). Millennium Goal 7 seeks to ensure sustainability and has driven countries to address stormwater pollution and reduce stormwater runoff contamination. For example, in order to help achieve Goal 7, China is addressing stormwater pollution in the city of Wuhan as part of a plan to improve living conditions in this highly urban area (ADB 2006).

In the European Union, the Water Framework Directive (WFD), which established regulations to protect and restore surface and ground waters across Europe, was passed in 2000 (European Commission 2008). With regard to surface waters, the WFD lists 33 priority pollutants and sets limits on the concentration of these contaminants in sources discharging to water bodies and in the water bodies themselves. Contaminants addressed by the WFD include phosphorus, suspended solids, and metals, among others. The regulation also calls for all surface waters to meet good ecological status, which means if the water body becomes impaired or threatened, relevant regulations can be made stricter. To meet WFD requirements, member countries must address point and nonpoint source pollution in their river basin management plans and adopt control measures to limit contamination of surface waters.

Australia has also focused efforts on managing urban stormwater runoff, as evidenced by its National Water Quality Management Strategy (ARMC-ANZ-ECC 2000), Urban Stormwater Initiative, Clean Seas programs (Commonwealth of Australia 2002), and other programs. Overall, 12% of rainfall in Australia reaches surface waters as runoff, but in urban areas the amount jumps to 90%. Polluted urban runoff has been recognized as a significant source of water pollution. As a result, Australia is focusing efforts to reduce pollution in urban stormwater runoff and develop water management policies that result in ecological sustainable development.

Because of increased attention to stormwater quality, municipalities, watershed districts, and other organizations around the globe have spent countless resources on the installation, operation, and maintenance of stormwater treatment practices. Maintenance for a stormwater treatment practice ensures the practice is performing as designed and extends the useable life of the practice. Because maintenance is an ongoing task, resources, that are often limited, must be allocated to the maintenance of stormwater treatment practices each year. In order to optimally allocate resources and plan maintenance, the performance of stormwater treatment practices must be assessed. Historically, however, there has been little guidance on assessment and/or maintenance strategies. Therefore, assessment and maintenance are rarely performed in the most cost-effective manner. In order to optimize maintenance, stormwater treatment practices must be regularly assessed.

1.2 Need for Maintenance

In order to keep performing as designed, stormwater treatment practices require regular maintenance. For example, as a detention pond fills with sediment over time, it will approach its storage capacity, and previously settled solids may be resuspended and washed out of the pond. Also, if there is no remaining capacity to store newly settled solids, total suspended solids removal by the pond may decrease or not occur at all. In this case, removal of accumulated sediment will help restore the pond and improve its performance. As another example, Lindsey et al. (1991) found that 53% of the infiltration trenches investigated were not operating as designed, 36% were partially or totally clogged, and 22% exhibited slow infiltration. Detention ponds and infiltration trenches are not unique; any stormwater treatment practice will experience a drop in performance over time and, at some point, will require maintenance if it is to perform at desired levels. This fact generates two important questions that form the foundation of this book: (1) How can one most cost-effectively assess the performance of a stormwater treatment practice and, (2) Based on the assessment results, what kind of maintenance action is warranted, if any?

1.3 Maintenance Challenges and Limitations

Stormwater treatment practice maintenance is the purposeful management of a stormwater treatment practice so as to ensure proper function and extend the useable life by maintaining a desired level of performance and efficiency. Maintenance activities can be broken down into three different categories: routine (regular and relatively frequent), nonroutine (irregular and less frequent), and major (irregular and rare) actions, as shown in Fig. 1.1. The purpose of routine and nonroutine maintenance activities is to prevent or limit the need for major maintenance, and therefore the combination of these activities is called preventative maintenance.

Stormwater treatment practices have a life cycle from their creation (design and construction) through operative stages (functional or not) that is largely dictated by operation and maintenance actions. As maintenance involves a significant amount of resources (personnel, equipment, materials, sediment disposal expense, etc.), a major challenge is how to most cost-effectively budget these resources so that nonroutine and major maintenance activities occur as infrequently as possible without underutilizing resources on excessive and unnecessary routine maintenance. In order to successfully balance limited resources and meet this challenge, assessment must occur on a regular basis.

Accurate assessment results will indicate if maintenance is needed, what level of maintenance activity is warranted, and can be used to help estimate when future maintenance will be required. By identifying the level and timing of maintenance required, assessment prevents unnecessary maintenance activity, which helps to conserve valuable limited resources. Regular assessment also identifies the need for maintenance, so that problems with a stormwater treatment practice can be identified and resolved as soon as possible, before the state of the practice deteriorates further. In this way, assessment can minimize the frequency of nonroutine and major maintenance actions.

The impact of regular assessment resulting in optimal maintenance does have limits, however. The best maintenance action performed at the best possible time will not always restore the practice to previous performance levels. At some time over the

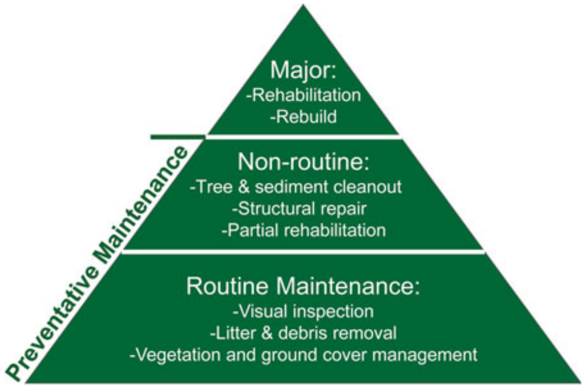

Fig. 1.1 Stormwater treatment practice operation and maintenance pyramid

life of any practice, rehabilitation, replacement, or rebuilding of the practice will be required. For example, a sand filter accumulates relatively large solid particles on its surface, while some smaller particles travel into the filter media before being strained and retained by the filter media. Because the top solid layer tends to more quickly reduce filtration capacity than the solids trapped below the media surface, removing the surface layer of solids from the top of a filter is a maintenance action that is often recommended when the flow rate through the filter drops to unacceptable levels. Although this action can significantly increase the flow rate through the filter, the filtration capacity is also somewhat reduced because of the finer solid particles that have accumulated within the media. Eventually, as the smaller particles trapped within the filter become more and more numerous, the filter media will clog throughout a significant portion of the media depth and removing the top layer of solids will have little effect on the overall capacity of the filter. When this occurs, major maintenance, such as replacing the entire media bed, will be necessary. In this example, no routine or even nonroutine maintenance could have prevented the need for major maintenance.

1.4 Assessment Strategies

For reasons discussed above, before maintenance of any stormwater treatment practice is performed, the practice must be assessed to determine its level of performance with regard to stormwater management goals (e.g., volume reduction, suspended solids removal). The assessment results should be accurate and within an acceptable level of uncertainty. Only after the current level of performance is determined and compared to the original or desired level of performance can a wise decision regarding maintenance be made. If maintenance is not immediately warranted, assessment results can help estimate when maintenance may be required in the future. Thus, assessment must not only be an integral part of any stormwater treatment practice maintenance plan, but it must also be the first requirement and must take place prior to any maintenance activity. Also, because assessment is a part of maintenance, if the implementation of a maintenance plan is to be cost-effective, all assessment activity must be cost-effective. In order to help users perform cost-effective assessment, three levels of assessment strategies, in order of increasing time, cost, and complexity, are presented and described in this book. To best use resources, should choose the lowest level of assessment, or combination of levels, that will achieve the storm water management goals.

1.4.1 Visual Inspection, Testing, and Monitoring

Implementing cost-effective assessment and maintenance is specific to each stormwater treatment practice and each assessment goal. Thus, only a brief overview of the three assessment techniques, is presented in this chapter. More detailed information on assessment techniques, including specifics for practices that utilize sedimentation, filtration, infiltration, and biological processes for stormwater treatment, is presented in subsequent chapters. The three levels of assessment, visual inspection, testing (capacity and synthetic runoff), and monitoring, are presented and briefly discussed below.

1. *Visual inspection*: A rapid assessment procedure that qualitatively evaluates and documents the functionality of a stormwater treatment practice by sight only. The primary purpose of visual inspection is to identify, diagnose, and schedule maintenance for stormwater treatment practices. The results can be used to select and schedule maintenance.
2. *Testing*: Testing of stormwater treatment practices consists of making a series of measurements under conditions *other than* a natural runoff event. Testing is further subdivided into two kinds of testing, capacity testing and synthetic runoff testing.
   (a) *Capacity testing*: An assessment method that uses a series of spatially distributed, relatively rapid, and simple point measurements. Specifically, capacity testing can be used to estimate the surface saturated hydraulic conductivity at specific locations within a practice or the depth of accumulated sediment, which can be related to the sediment removal capacity (remaining sediment storage volume) of an entire stormwater treatment practice. The results can be used to select and schedule maintenance.
   (b) *Synthetic runoff testing*: An assessment method in which a prescribed amount of synthetic stormwater is applied to a stormwater treatment practice under controlled conditions to assess its effectiveness. With measurements such as drain time and mass of pollutant capture, synthetic runoff testing can be used to assess the performance of a stormwater treatment practice for runoff volume reduction (e.g., through infiltration) and pollutant removal efficiency. Results from synthetic runoff testing can also be used to calibrate watershed models for simulation of performance during natural rainfall events.

3. *Monitoring*: An assessment method which measures performance of a practice during natural rainfall or snowmelt events by measuring influent and effluent flow rates, collecting influent and effluent stormwater samples for analysis, and comparing influent and effluent volume, pollutant concentration, or pollutant load. Monitoring is the most comprehensive form of assessment and can assess multiple aspects of stormwater treatment practice performance (e.g., peak flow reduction and pollutant removal). It also requires a significant amount of data to calculate reliable results because the number and range of variables are large. The results from monitoring can be used to describe the runoff and pollutant load characteristics of a watershed and the associated response of stormwater treatment practices.

Developers of an assessment program should consider each of the three levels of assessment based on effort and uncertainty aspects. The lowest assessment level should be considered first, and the next highest level should only be considered when warranted by the goals of the assessment program. By this process, assessment may include any combination of the three assessment levels, but inclusion of all three levels is not mandatory (and often not recommended). Each level of assessment will vary in application based on the stormwater treatment practice and the assessment goals. A summary of the three levels of assessment, including the relative effort, typical elapsed time, advantages, and disadvantages, is given in Table 1.1.

Visual inspection (level 1) and capacity testing (level 2a) do not depend on the size of the stormwater treatment practice and therefore can be applied to any practice. The applicability of synthetic runoff testing (level 2b), however, is dependent on the size of the practice and the available water supply. Monitoring is only limited by the site design and accessibility of the practice.

1.5 Need for This Book

Other stormwater management books and manuals discuss the design of stormwater treatment practices and may sometimes include hypothetical or assumed maintenance schedules. In contrast, this book provides instructions on how to directly measure the level of performance of stormwater treatment practices and bases proposed maintenance schedules on actual performance and historical maintenance efforts and costs. The inspection methods, which are proven in the field and have been implemented successfully, are necessary as regulatory agencies begin requiring measured performance of such devices.

In order to determine the effectiveness of stormwater treatment practices, it is common to monitor the practice during actual rainfall or snowmelt events. This process is time consuming, expensive, and uncertain. It involves waiting for a rainfall event, hoping the depth of rain and duration are adequate for measurement and sampling equipment, and collecting water samples for an unknown duration of time. It is not uncommon to monitor many (~20) rainfall events over 2 years before obtaining sufficient information to minimize uncertainty. The continuous change in discharge, concentrations, and performance means that uncertainties are still great.

Table 1.1 Comparison of the three levels of assessment

	1. Visual inspection	2a. Capacity testing	2b. Synthetic runoff testing	3. Monitoring
Objectives	Determine if stormwater treatment practice is malfunctioning	Determine infiltration or sedimentation capacity and rates	Determine infiltration rates, capacity, and pollutant removal performance	Determine infiltration rates, capacity, and pollutant removal performance
Relative effort	1	10	10–100	400
Typical elapsed time	1 day	1 week	1 week–1 month	14+ months
Advantages	Quick, inexpensive	Less expensive, no equipment left in field	Controlled experiments, more accurate with fewer tests required for statistical significance as compared to monitoring, no equipment left in field	Most comprehensive, assesses stormwater treatment practice within watershed without modeling
Disadvantages	Limited knowledge gained	Limited to infiltration and sedimentation capacity/rates, uncertainties can be substantial	Cannot be used without sufficient water supply, limited scope	Uncertainty in results due to lack of control, equipment left in field

We have developed a three-tiered assessment technique in which each tier increases in complexity and cost. In this technique, monitoring is the highest tier; thus, significant amounts of time and money can be saved if one of the two lower tiers can be used to assess the stormwater treatment practice. This book describes how to determine which tier is appropriate and provides detailed information on how to perform each tier of assessment. The assessment can then be used to schedule maintenance, document performance for regulatory agencies, and perform construction due diligence. This book also documents the maintenance actions and frequency needed to maintain performance once the appropriate assessment techniques have been chosen and implemented, and the cost of maintenance. This book also contains a substantial number of examples and case studies to illustrate the use of the material.

1.6 About This Book

This book, "*Optimizing Stormwater Treatment Practice: A Handbook of Assessment and Maintenance*," is organized into 13 chapters, References, and one appendix. Each chapter is intended to provide guidance and information on stormwater (e.g., stormwater processes), assessment (e.g., water budget measurement), or maintenance. To help the reader find specific information within this book, each chapter and the Appendix are briefly described below.

Chapter 1: Introduction. Chapter 1 describes the need for stormwater treatment and maintenance of stormwater treatment practices; assessment strategies including inspection, testing, and monitoring; and the need for and organization of this book.

Chapter 2: Impacts and Composition of Urban Stormwater. Urban development results in impacts by stormwater on water resources. Chapter 2 describes these impacts, including flow and channel alteration as well as pollutants such as nutrients and metals. Chapter 2 also provides numerical values for typical concentrations of some pollutants of concern in urban stormwater.

Chapter 3: Stormwater Treatment Processes. Urban stormwater runoff can be treated to reduce runoff volume, peak flow, and pollutants. Chapter 3 discusses processes relevant to stormwater treatment, including physical, biological, and chemical processes. Understanding these processes is critical to developing a successful assessment and maintenance program.

Chapter 4: Stormwater Treatment Practices. Chapter 4 provides a detailed description of the most common stormwater treatment practices, including dry and wet ponds, filtration practices, infiltration basins and trenches, biofiltration/bioinfiltration practices (rain gardens), constructed wetlands, and swales.

Chapter 5: Visual Inspection of Stormwater Treatment Practices. The first step in understanding the performance of a stormwater treatment practice is visual inspection. Chapter 5 provides detailed information for visual inspection of stormwater treatment practices including the most common inspection criteria and inspection considerations specific to each stormwater treatment practice.

Chapter 6: Capacity Testing of Stormwater Treatment Practices. Capacity testing is a testing methodology comprising a series of spatially distributed point measurements. Chapter 6 provides details about applying capacity testing to stormwater treatment practices with details specific to each treatment practice and a case study of capacity testing to measure infiltration rate in a bioinfiltration (rain garden) practice.

Chapter 7: Synthetic Runoff Testing of Stormwater Treatment Practices. Synthetic runoff testing is a testing methodology in which synthetic stormwater is applied to a stormwater treatment practice and the response by the practice is measured. Chapter 7 provides details about applying synthetic runoff testing to stormwater treatment practices with details specific to each treatment practice.

Chapter 8: Monitoring of Stormwater Treatment Practices. Monitoring stormwater treatment involves setting up equipment that will measure flow and collect samples during natural rainfall events. Through monitoring, the performance of a stormwater treatment practice can be determined for actual runoff events from the contributing watershed. Chapter 8 provides details about applying monitoring to stormwater treatment practices with details specific to each treatment practice and a case study of monitoring a dry pond.

Chapter 9: Water Budget Measurement. Assessment of stormwater treatment practices requires an understanding and accurate measurement of the water budget. Chapter 9 describes several methods for measuring water budget inflows and outflows, such as open channel flow, conduit flow, infiltration, and rainfall, and provides recommendations for simple, accurate water budget measurement.

Chapter 10: Water Sampling Methods. One possible goal of an assessment program is to determine the pollutant removal efficiency of a stormwater treatment practice. To determine pollutant removal efficiency, pollutant amounts (e.g., mass, concentration) in stormwater runoff must be measured. Chapter 10 discusses methods for measuring pollutant(s) in stormwater runoff, including the number of storm events and samples, sampling methodology (e.g., flow-weighted), and handling, as well as special considerations such as winter sampling in cold climates and automatic sampling of suspended solids.

Chapter 11: Analysis of Water and Soils. Stormwater often contains several pollutants at various concentrations. Determining target pollutants and accurate analytical methods is important in developing a simple and cost-effective assessment and maintenance program. Chapter 11 describes common stormwater analyses and quality assurance/quality control considerations such as bias, precision, and inspection.

Chapter 12: Data Analysis. Once assessment data have been collected, the data must be analyzed to determine the performance of the practice. Chapter 12 describes methods for analyzing assessment data, such as summation of loads and the Event Mean Concentration (EMC) and calculating the corresponding uncertainty.

Chapter 13: Maintenance of Stormwater Treatment Practices. Performance will determine whether a stormwater treatment practice is functioning adequately. For practices that are functioning below desired levels, appropriate maintenance should be performed. Chapter 13 provides guidance for determining what maintenance is required, describes maintenance activities specific to each stormwater treatment practice, and presents actual maintenance frequency, effort, and costs for various kinds of stormwater treatment practices.

Appendix A: Visual Inspection Checklists. Appendix A contains all the checklists for visual inspection of stormwater treatment practices.

References: A complete list of references cited throughout the book is provided.

Impacts and Composition of Urban Stormwater

2

Abstract

If construction or development occurs in a watershed, the area of impervious surfaces such as roads, parking lots, and buildings typically increases, with a corresponding decrease in the area of natural pervious surfaces. The result is an increase in stormwater runoff volumes, peak flow rates, and a degradation of runoff quality. The degradation of runoff quality can be observed in increased concentrations and total mass loads of nutrients and other organics, metals, chlorides, bacteria, viruses, hydrocarbons, and other substances, as well as increases in runoff temperature. The increased loading of these substances to receiving water bodies can be quite detrimental. This chapter discusses the most common contaminants found in urban stormwater runoff, their impacts, and typical concentrations.

2.1 Impacts of Urban Stormwater

The impact of the increase in urban stormwater runoff volumes and pollutant loads is substantial. Urban stormwater is responsible for about 15% of impaired river miles in the USA (US EPA 2000b) and urban stormwater is the leading cause of pollution to fresh and brackish receiving waters (Mallin et al. 2009). Stormwater impacts can be hydrologic, chemical, biological, or physical, but the impacts of greatest concern are biological integrity and habitat alteration due to the loading of sediment, nutrients, metals, chloride, bacteria, high temperature water, oxygen-demanding substances, and hydrocarbons (US EPA 1992). Although the impacts tend to increase as the urbanization within the watershed increases, negative impacts can be significant in watersheds that are less than 10% urbanized (Pitt 2002).

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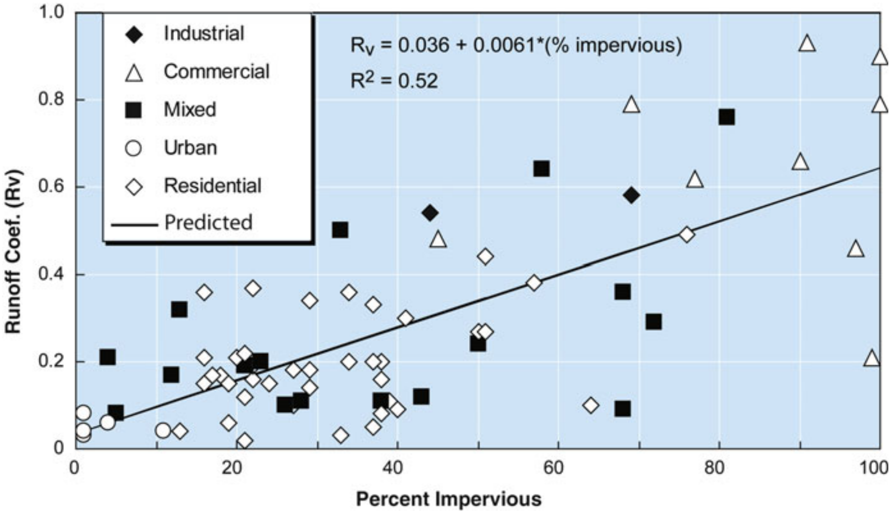

Fig. 2.1 Percent impervious surface versus runoff coefficient for watersheds included in the National Urban Runoff Program (NURP) study (US EPA 1983)

2.1.1 Flow and Channel Alteration

Urbanization, as reflected by increased impervious surface, alters watershed hydrology in several ways. As shown in Fig. 2.1, for sites studied in the US EPA's National Urban Runoff Program (US EPA 1983), one way is an increase in the runoff coefficient (ratio of inches of runoff to inches of rainfall) as the percentage of impervious surface in the watershed increases. Increasing imperviousness also leads to hydrographs with shorter durations and greater peak flows, larger flood flows, and smaller base flows (Paul and Meyer 2001). Some of the effects of altered flow on biota are due to larger peak temperatures, altered sediment discharge, unstable channels, fewer pools, and degraded habitat due to channelization. Evaluations of stream habitats indicate that flow and channel alteration are major contributors to the observed decline in biological integrity often associated with increased imperviousness (Paul and Meyer 2001; Pitt 2002; Booth et al. 2002; and Schueler 2000a).

2.1.2 Nutrients

Nutrients, primarily phosphorus and nitrogen, increase plant growth in streams, reservoirs, and lakes in a process called eutrophication. In many parts of the country, stormwater containing a large concentration of nutrients enters lakes, causing nutrient enrichment, reduced water clarity, and increased presence of undesirable blue-green algae and other plants. Upon decomposition and oxidation of the plant matter, dissolved oxygen in the water body is consumed, and can be reduced to zero or near zero levels.

Because of urban sprawl, residential land is now the dominant land use in 64% of the nation's water supply reservoirs (Robbins et al. 1991). Eutrophication caused by nutrients in stormwater often impairs municipal drinking water supplies. One example is the New Croton Reservoir, which provides daily drinking water to about 900,000 New York City residents. Due to excessive phosphorus loading, the reservoir suffers from algae blooms, low dissolved oxygen, and poor taste. As a result, it is common for the use of this reservoir to be reduced or temporarily suspended in the summer (NYSAGO 2011).

Excessive nutrient loading can also stimulate the growth of undesirable rooted aquatic plants in streams. The US EPA reports that approximately 11% of the nation's assessed stream miles are threatened or impaired due to excess nutrients (US EPA 2000b). With only 26% of the total stream miles assessed, the total number of stream miles that are threatened or impaired is likely significantly higher.

2.1.3 Metals

A large number of potentially toxic substances, including metals, occur in stormwater. Metals of primary concern (based on toxicity and occurrence) are cadmium, copper, zinc, and lead (Jang et al. 2005; Rangsivek and Jekel 2005), with roughly 50% of the metal load in dissolved form (Morrison et al. 1983). Lead concentration in the environment has declined since the 1970s, when lead in gasoline and paint was banned, but there is still substantial degrading lead paint present in the urban environment, making this a continuing concern. Note the smaller lead concentration in the three more recent stormwater studies in Table 2.4, as compared with that in the NURP study (US EPA 1983).

Large concentrations of metals can be lethal, and moderate concentrations can reduce growth, reproduction, and survival in aquatic organisms. Small concentrations of metals also have been documented to alter the behavior and competitive advantage of invertebrates, a result that could change the balance of ecosystems (Clements and Kiffney 2002). Kayhanian et al. (2008) investigated the toxicity of stormwater runoff from urban highway sites near Los Angeles, USA. Results indicated that the toxicity to water fleas and flathead minnows of the most toxic samples was mostly, but not entirely, due to copper and zinc.

Once in an aquatic environment, metals can accumulate in freshwater biofilms to such an extent that the biofilm concentrations are larger than sediment metal concentrations. Fish and invertebrates feed on biofilms, as a result, the metals can be transferred through the food chain (Ancion et al. 2010), and bioaccumulation will continue to occur.

Of the stream miles assessed in the USA as of 2011, approximately 7% have been categorized as threatened or impaired due to metals other than mercury. Mercury, which is a metal more common to runoff from industrial land uses and

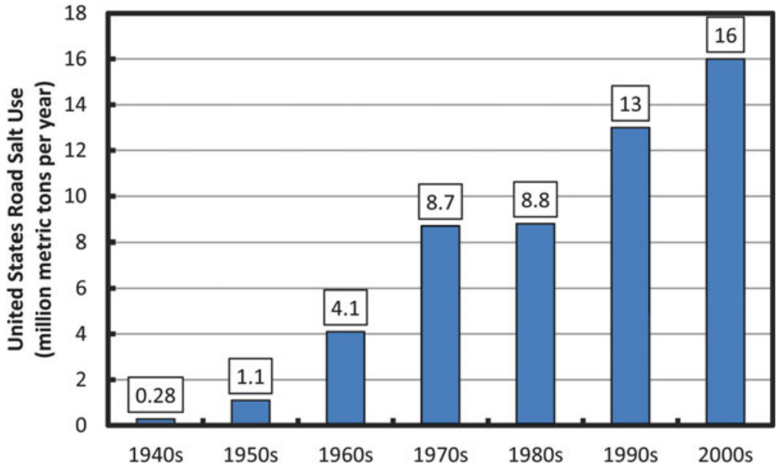

Fig. 2.2 Increase in annual road salt use in the USA (NURP) study (US EPA 1983)

atmospheric deposition, has threatened or impaired approximately 5% of assessed stream miles (US EPA 2011). As more stream miles are assessed, these numbers are likely to increase.

2.1.4 Chloride

Chloride is an emerging urban pollutant as a result of road deicing (Novotny et al. 2009). The chloride concentration in streams has been directly correlated with the percent of impervious surface area (Kaushal et al. 2005) and the quantity of rock salt purchases (Novotny et al. 2008). Furthermore, annual road salt use in the USA has continually increased since the 1940s (Fig. 2.2).

After application on a road surface, salt will typically travel to receiving waters, where it can increase the salt concentration of the water body. Peak chloride concentration in winter runoff has been observed close to sea water (35,000 mg/L) at 11,000 mg/L (Corsi et al. 2010), and peak chloride concentration in urban streams during winter can be several thousand mg/L. At these concentrations, chloride can negatively impact the water body. For example, salt increases the density of water, and highly saline waters can settle to the bottom of lakes and alter lake mixing patterns. This process can extend periods of low oxygen in or near the sediment which, in turn, can cause the release of dissolved phosphorus and metals (Wetzel 1975; p. 224). Increased salt concentration can also negatively impact aquatic life by decreasing biodiversity, increasing mortality rates of tadpoles, and decreasing the overall health of organisms (Novotny and Stefan 2010).

The US EPA's acute and chronic water quality limits for chloride in fresh water are 860 mg/L and 230 mg/L, respectively. Studies have found that these limits are often exceeded in northern metropolitan areas during the winter, and less often

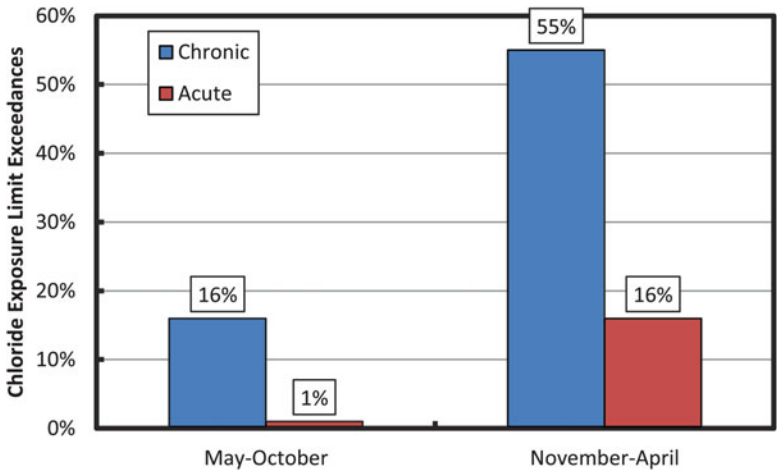

Fig. 2.3 Chloride exposure limit exceedances in summer (May–October) and winter (November–April) for 168 monitoring stations in 13 northern metropolitan areas (Corsi et al. 2010)

during the summer. Exceedance was negligible in all southern monitoring sites (Fig. 2.3).

In the Minneapolis-St. Paul metropolitan region of Minnesota, background chloride concentration in urban lakes was 3–10 mg/L before development, but in 2005, after development, averaged 87 mg/L. Detailed modeling (Novotny and Stefan 2010) has shown that at current road salt application rates, the salt concentration will continue to rise such that some urban lakes will exceed the established chronic standard of 230 mg/L (four-day average) (MPCA 2003) for impairment to aquatic habitat. Clearly, salt concentration in road runoff and surface waters cannot be ignored.

2.1.5 Bacteria and Viruses

The potential for bacterial contamination of water is generally measured by the concentration of fecal coliforms, *Escherichia coli*, or enterococci. Although most fecal coliforms are not pathogenic, they are currently the best established representative surrogate, or indicator, of human pathogens.

Rain and increased runoff increase the presence of microbial pathogens in marine and estuarine waters, an effect that can be a direct health threat to humans and can contaminate shellfish. In fact, urban stormwater is the cause of 40% of shellfish closures in US waters (Mallin et al. 2009). In one study, the number of gastrointestinal diseases per 1,000 swimmers was shown to increase linearly with coliform counts (Durfour 1984). One outcome of elevated coliform levels is beach closings. From 2006 to 2009, 32–43% of beaches nationwide were affected by closings each year (US EPA 2011).

Fecal coliform concentrations are generally largest immediately after rainstorms. A study of Minnehaha Creek in Minnesota (Wenck 2003) reported that fecal coliforms in excess of 2000 CFU/100 mL were found only within 3 days of a rainstorm. Fecal streptococci and *E. coli* were found in 94% and 95.5%, respectively, of municipal separate storm sewer system (MS4) outfalls monitored (Clark and Pitt 2007). This indicates that a large percentage of fecal coliforms are a result of stormwater runoff.

Fecal coliforms are excreted from the bodies of warm-blooded animals. For urban stormwater, sources may include humans (via illicit sewage connections to stormwater conveyances), dogs, cats, geese, raccoons, and other wildlife. Although generation rates (number of coliforms excreted per day) for various organisms (dogs, geese, humans) are well known (Schueler 2000b), there is little information regarding "delivery ratios" (the fraction of excreted coliforms that enters runoff) for urban stormwater.

Potential for groundwater contamination by bacteria and pathogens depends on the soil chemical properties, adsorption capability, the ability of the soil to physically strain the pathogens, and pathogen survival. Bacteria survive longer in low pH (acidic) soils and in soils with large organic content. Bacteria and viruses can move through soil media and may be transported to aquifers by infiltrating stormwater. The transport distance of bacteria seems to be a function of bacteria density and water velocity through the soil (Camesano and Logan 1998; Unice and Logan 2000). Pitt et al. (1996) rate enteroviruses as having high groundwater contamination potential for all surface and subsurface infiltration/injection systems and a variety of other pathogens as having high groundwater contamination potential for subsurface infiltration/injection systems.

Although documented cases of groundwater contamination do exist, bacteria are generally removed by straining at the soil surface and sorption to solid particles. Once removed from the water, the ability of bacteria to survive is a function of factors such as temperature, pH, and presence of metals, among others. Bacteria survival may be between two and three months, but survival for up to 5 years has been documented (Pitt et al. 1999). Although not readily modeled in natural environments, fecal coliforms can also regrow in the environment under warm conditions with a supply of organic matter for food, conditions commonly found in wetlands or stormwater ponds.

As part of the National Urban Runoff Program, fecal coliforms were evaluated at 17 sites for 156 storm events, and based on the results, it was concluded that coliform bacteria in urban runoff may exceed US EPA water quality criteria during and after storm events (US EPA 1999a). There existed a high degree of variability within the data, but land use did not appear to correlate with coliform concentration. During warmer months, concentrations were approximately 20 times larger than cold months.

A study by the National Academy of Sciences (NAS 2000) noted that very large removal rates—on the order of 99% would be needed to reduce coliforms from the levels observed in urban stormwater (15,000–20,000/100 mL) to the EPA's 200/100 mL criterion for recreational water. Their review indicated that bacterial

Table 2.1 Comparison of mean bacterial removal rates achieved by different stormwater treatment practices

	Bacterial removal rate%		
Bacterial indicator	Ponds	Sand filters	Swales
Fecal Coliform	65% ($n = 9$)	51% ($n = 9$)	–58% ($n = 5$)
Fecal Streptococci	73% ($n = 4$)	58% ($n = 7$)	N/A
E. coli	51% ($n = 2$)	N/A	N/A

The number (n) of practices analyzed indicated in parenthesis (data from NAS 2000)
N/A = Information not reported in the source

removal rates in several types of stormwater treatment practices were significantly less than 99% (Table 2.1). Studies of coliform regrowth in stormwater ponds have apparently not been reported in the peer-reviewed literature.

2.1.6 Temperature

Urbanization generally requires removing crops, trees, and native plants from parcels of land and replacing them with roads, parking lots, lawns, and buildings. Along with the impacts previously mentioned, these changes in land use affect riparian shading and heating of runoff in these areas, which results in increases in summertime temperatures of nearby streams. This can significantly impact relatively cool waters, such as trout streams that are fed by groundwater, because increases in the volume and temperature of runoff from impervious surfaces will dilute the colder groundwater, lower the volume of groundwater entering the water body, and reduce coldwater fish habitat.

In most temperate climates, the risk to salmon and trout populations due to increased temperature is of concern. Water temperature affects many areas of fish health, such as migration, disease resistance, growth, and mortality (Sullivan et al. 2000).

The US EPA reports that, of the 935,393 stream miles assessed nationwide, approximately 5% (46,786 miles) are threatened or impaired due to thermal pollution (US EPA 2011). With only 26% of the nation's stream miles assessed, the total length of impaired streams is certain to increase. In a study of 39 trout streams in Wisconsin and Minnesota, stream temperatures increased 0.25°C (0.5°F) per 1% increase in watershed imperviousness (Wang et al. 2003). In Minnesota, no temperature increase is allowed in cold water streams (Class 2A) while warm water streams (Class 2B) are allowed a temperature increase of 3°C (5°F) (MPCA 2003).

The temperature of stormwater runoff is controlled by the initial rainfall temperature and by the heating/cooling processes with the land and other surfaces during runoff. The temperature of land surfaces is controlled by several processes including solar radiation during the daytime, atmospheric long wave radiation, long wave back radiation from the surface, evaporative heat flux, and sensible heat flux. Land surfaces are heated above ambient air temperature primarily by solar radiation. Asphalt and roof surfaces in Minnesota reach daily maximum temperatures that