Green Stormwater Infrastructure Fundamentals and Design

Allen P. Davis
William F. Hunt
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To our families and to creating a better earth for our children and grandchildren.

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Preface

The intention of the authors is to present the fundamentals of green urban stormwater infrastructure from an engineering design and performance analysis perspective. This book is intended to be used as a textbook in senior-undergraduate and first-year graduate courses in water resources/environmental engineering. It is also envisioned to be a reference for practicing engineers and other water/environment professionals. The book focuses on novel stormwater control measures (SCMs) and related technologies for the reductions of detrimental impacts from urban stormwater. Stormwater challenges have risen in importance as clean water focus has shifted from point to nonpoint source pollution as a source of water impairments. Stormwater also becomes part of the "one water" focus on long-term sustainable urban water. Many novel SCMs are nature-based and are considered as part of a "green infrastructure" approach that includes bioretention, vegetated swales, vegetated filter strips, green roofs, pervious pavements, water harvesting, and wetlands.

It is expected that users of this book would have had a course in engineering hydraulics/hydrology and some exposure to environmental engineering treatment processes and water quality. It is also complementary to graduate surface water hydrology and traditional water and wastewater treatment engineering. While written with an engineering focus, nonengineers such as landscape architects, planners, and environmental scientists should find the text useful. Specific attempts have been made to integrate both English (US customary) and metric units throughout the book.

The initial chapters provide background information on urban hydrology, water quality, and stormwater generation and characteristics. The preponderance of the book focuses on stormwater control and improvement via a suite of different green infrastructure technologies and techniques. Within this context, background information on engineering unit processes for affecting the water balance and improving water quality are presented. The evolving challenge of setting and meeting stormwater control metrics is discussed. The latter chapters provide specific details on categories of SCMs; topics such as selection, design, performance, and maintenance are presented in detail. SCM selection, treatment trains, and climate change are included as a final chapter. This text provides a baseline as this topic is a rapidly changing field.

About the Authors

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Robert G. Traver, Ph.D., P.E., D. WRE, F.EWRI, F.ASCE, is a Professor in the Department of Civil and Environmental Engineering at Villanova University, Villanova, PA, and former Edward A. Daylor Chair in Civil Engineering. He is the Director of the Villanova Center for Resilient Water Systems and the Villanova Stormwater Partnership.

Collectively, the authors have 90 years of research, education, and outreach experience encompassing the topics covered in this book. They have built, maintained, and monitored hundreds of SCM research practices and have authored over 300 refereed journal articles, including several together. They have presented research results all over the world, hosted international conferences, while also helping address state and local water challenges. The authors love each other, the field in which they work, and the people with whom they partner.

Acknowledgments

The authors are grateful for the contributions of many, many colleagues in the various research projects that have led to many subjects of this text. These include students, post-doctoral researchers, and faculty colleagues. We also thank the various agencies that supported, and continue to support and promote, green stormwater infrastructure research.

About the Companion Website

This book is accompanied by a companion website which includes a number of resources created by author for instructors that you will find helpful.

www.wiley.com/go/davis/greenstormwater

The Instructor website includes answers to the end-of-chapter problems

Please note that the resources in instructor website are password protected and can only be accessed by instructors who register with the site.

1

Introduction to Urban Stormwater and Green Stormwater Infrastructure

1.1 Population and Urban Infrastructure

Human population continues to increase in most areas of the world, including developed countries such as the United States. Two of the basic needs of humans are shelter and community. As we have progressed over the millennia, the ideas of shelter and community have evolved, first from simple villages to larger cities. More recently, these populations are shifting, generally from rural and inland areas to the coasts, while residents of inner cities are migrating to less dense suburban development. Frequently, the result is the consumption of pristine and agricultural land at rates disproportionately greater than population growth. As part of the development process, natural vegetation is replaced by lawn or pavement, soils are disrupted and compacted, pipes replace natural water courses, and the native topography is smoothed. Even in areas of urban redevelopment, frequently the impervious footprint increases as the living infrastructure becomes larger (Boorstein 2005; Hekl and Dymond 2016; MacGillis 2006).

Our past and current land development practices rely heavily on the use of impervious area infrastructure (materials that cover the ground and do not let water infiltrate down into the ground as it would in an undeveloped area) and piped systems. Large-area rooftops for homes and garages, highways, sidewalks, wide driveways, and generous patios are all desired attributes of increasingly affluent (sub)urban areas. Commercial and institutional properties provide for similar large impervious infrastructure and ample (if not excessive) parking. This urban network has replaced lands that were once undeveloped, such as forest, meadow, or open plains.

Rain that falls on developed areas is transported via impervious conveyance systems rapidly away from the original surface contact point, typically being discharged into the nearest waterway. This impervious area, coupled with a drainage system that accelerates the movement of runoff, vastly alters the water balance in the urban system. A variety of problems, including flooding, stream damage, loss of aquatic habitat, and significant downstream water body degradation, are the result. The amount of urbanization and related impervious area created has, and continues to, expand in many areas as demonstrated in Figure 1.1 for the greater Las Vegas area.

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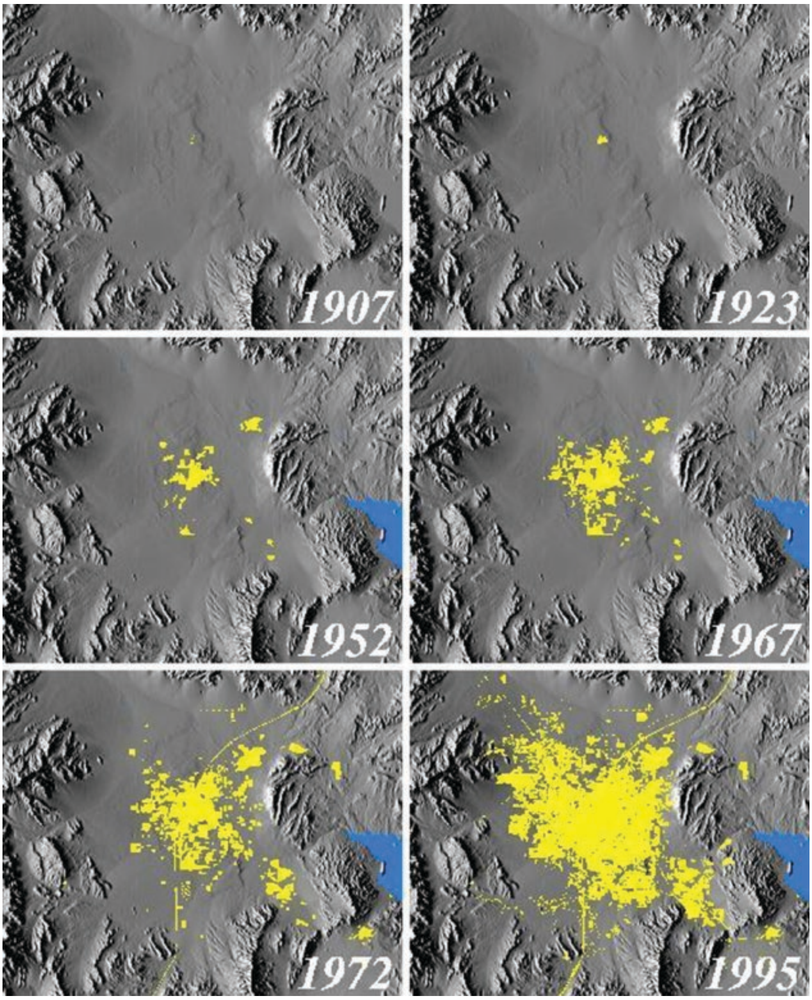

Figure 1.1 Spatial Patterns and Rates of Change Resulting from Urbanization of the Las Vegas Areas. (Credit: US Geological Survey).

1.2 Impacts of Urbanization

Our cities, towns, and villages, and the transportation networks that connect them, all rely on impervious infrastructure. Rooftops, roadways, sidewalks, driveways, parking lots, basketball and tennis courts, and patios all direct rainfall rapidly to their periphery, eliminating the natural runoff reduction and filtration of the vegetated systems that have been replaced.

Figure 1.2 shows the water balance around areas with different levels of urban development. In the undeveloped lands (humid regions), about half of the annual incoming water via rainfall infiltrates, supplying both shallow and deep groundwater. Another large fraction of this volume is evaporated from the soil and vegetation and transpired through the leaves of the vegetation, the combined processes known as

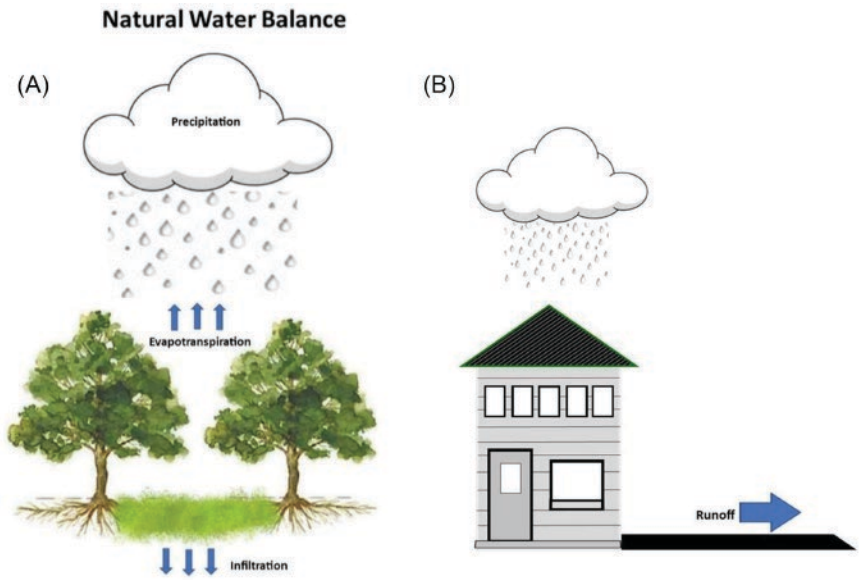

Figure 1.2 Water Balances for Different Land Use Conditions: (A) Natural Water Balance Showing Primary Water Pathways of Evapotranspiration and Infiltration and (B) Urban Water Balance Includes Runoff from Impervious Surfaces.

evapotranspiration (ET). This leaves only a small fraction of the incoming rainfall to become surface runoff.

As the amount of development increases within an area, so does the amount of impervious area. The vegetated land area available for the infiltration and ET of runoff becomes increasingly small. In highly urbanized areas, the water balance changes drastically, as shown in Figure 1.2B. Infiltration and ET are now greatly reduced. The bulk of the incoming rainfall now is converted to surface runoff, which must be responsibly managed so as to not to create public safety and health concerns, and to protect our waterways and water bodies from environmental problems.

Environmental impacts of land development are well known and additional details on these impacts continue to be forthcoming (Booth 2005). The increased volume and flows of stormwater runoff from urbanized areas, coupled with impaired water quality and increased temperature, amplify the magnitude and increase the probability of flooding, decrease stream baseflow, degrade downstream river channels, adversely affect the quality of receiving waters, and impact stream ecology (e.g., Walsh et al. 2005; Wang et al. 2003). High sustained flow rates (not just peaks) are associated with accelerated stream bank erosion and gully formation (Figure 1.3). Elimination of stream baseflow in headwater areas by eliminating rainfall infiltration can greatly impact downstream ecology and ecological processes (Sweeney et al. 2004). Loss of biological nutrient cycling processes in small streams will adversely impact water quality in downstream areas (Peterson et al. 2001).

While certainly flooding occurs with or without urbanization, the changes to the land increase the frequency and magnitude of such events, magnifying the impact to the local waterways. Figure 1.4 shows the great increase in amplitude in flow rate from

Figure 1.3 Stream Impacts from Uncontrolled Stormwater. (Photo by Authors).

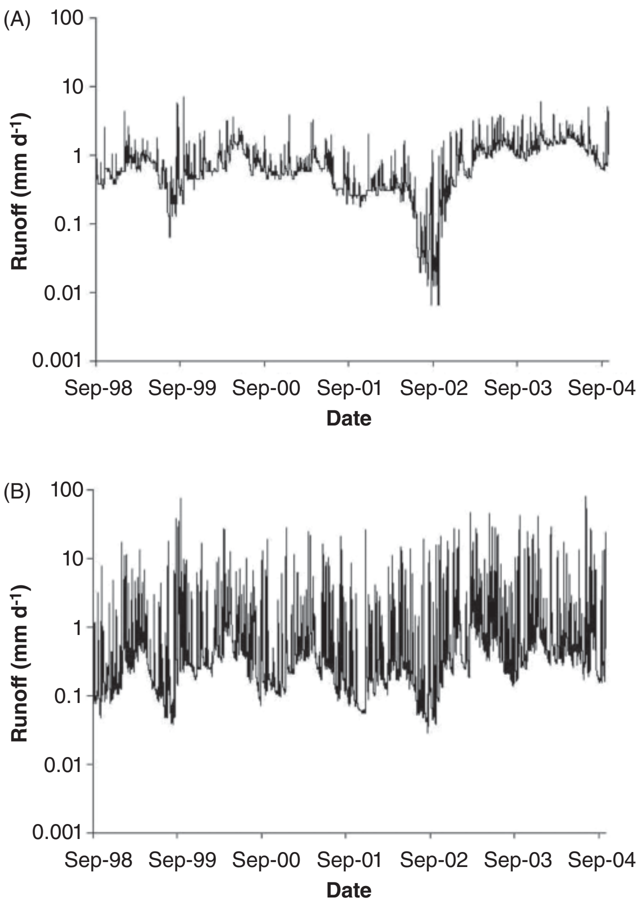

Figure 1.4 Continuous Flow Measured from Streams in Maryland (Normalized by Drainage Area): (A) Forested Stream and (B) Urban Stream. (Shields et al. 2008).

a highly impervious watershed as contrasted to that of a lower impervious watershed (note the log scale). In Figure 1.4A, the flow of a forested stream is given (in units of mm/day, which represents the stream flow divided by the stream catchment area). The flow averages about 1 mm/day, with limited excursions to about 10 mm/day during high flow events and as low as 0.01 mm/day during a very dry period.

Contrast these data to Figure 1.4B, which shows the same data for a highly developed catchment area. The flows are much more erratic and vary significantly throughout the study. Both high and low flows are frequent as the stream responds rapidly to rainfall that falls on the catchment areas.

In the watershed, impervious surface without adequate drainage leads to pooled water during large rain events. This pooled water is dangerous to vehicle travel and pedestrians and can cause flooding of buildings in the urban area. Figure 1.5 shows nuisance flooding in a residential area of New Bern N.C. Note the depth of water as the vehicles pass each other.

Figure 1.5 Nuisance Flooding New Bern NC. (Photo by Authors).

Figures 1.6 and 1.7 show other effects of excess water related to high impervious area. Figure 1.6 clearly shows the accelerated erosion of a drainage swale threatening the stability of the adjacent house. Figure 1.7 shows a flood on the larger Perkiomen Creek in Pennsylvania. While not visible on the photo, cars on the bridge could not move because the bridge approaches were under water. In addition to obvious flood hazards, standing water can lead to other health concerns.

Increased imperviousness from urbanization leads to high flows that also change the river channels through erosion and deposition. Figure 1.8 shows incisions and bank erosion from high flows in streams in Maryland. Over time, soil is washed from tree root structures, the trees become unstable and will fall into the stream.

The relationship between impervious cover and stream biotic health has been documented by many researchers. Figure 1.9 shows declines of macroinvertebrate indicator

Figure 1.6 Severely Eroded Neighborhood Swale. (Photo by Authors).

Figure 1.7 Significant Flooding of the Perkiomen Creek, PA. Note Heavy Sediment Load Carried by the River. (Photo by Authors).

taxa in streams in Maryland as a function of the impervious cover in the watershed (King et al. 2011). The dramatic increase in the decline of the taxa demonstrates changes in the physical and chemical conditions of the stream ecosystems. As the fraction of impervious area increases, various alterations to the stream characteristics result, making it a less-favorable habitat for many diverse aquatic species, and indicating poor stream health. This change occurs dramatically, from only about 0.5% to 2% impervious cover.

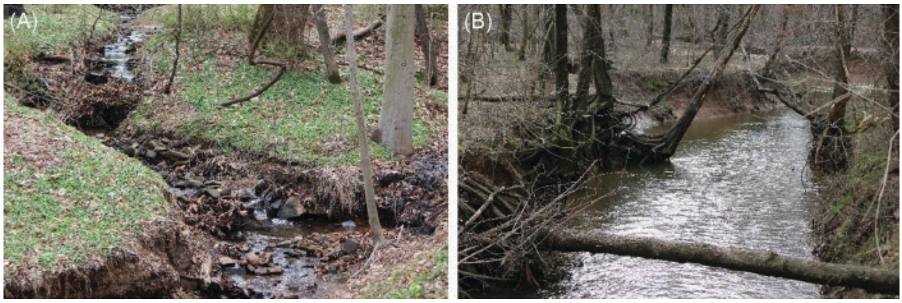

Figure 1.8 Incised Streams in Maryland, Resulting from Erosive Flows: (A) Small Stream and (B) Large Stream. (Photos by Authors).

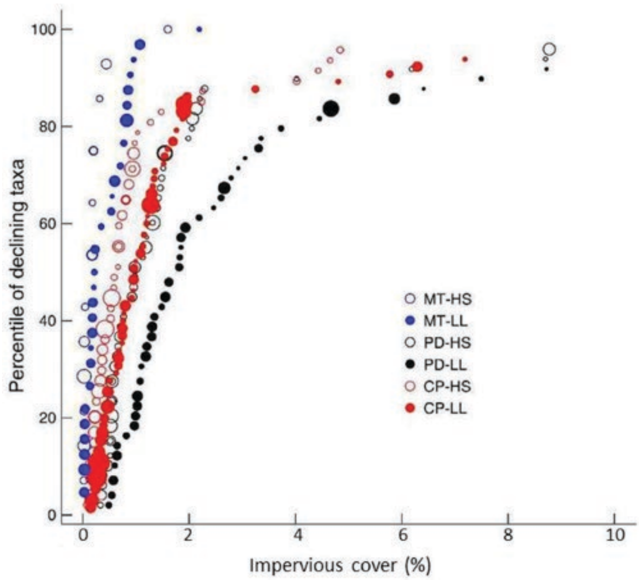

Figure 1.9 Data Indicating the Reduction of Various Organism Populations with Increasing Watershed Urbanization (Impervious Coverage) (King et al. 2011). MT, PD, and CP Represent Mountain, Piedmont, and Coastal Plain Geology, Respectively. HS Represents High Slope Small Watersheds; LL Represents Low Slope Large Watersheds.

1.3 The US Regulatory Environment

The governing legislation driving urban stormwater management in the United States is the Clean Water Act (CWA). The CWA was promulgated in the early 1970s to address water pollution in waters of the United States, with a goal to "restore and maintain the chemical, physical, and biological integrity of the nation's waters." Initially enforcement of the CWA focused on discharges of wastewater (sometimes untreated) from municipal wastewater treatment plants and from various industries. This enforcement led to the development of the National Pollutant Discharge Elimination System (NPDES) program. NPDES programs are managed by the states and establish a permitting process for any entity that discharges to the nation's waters. NPDES permits for industry and wastewater treatment plants commonly specify limits for several water-quality parameters. The limits will depend on the industry and the water body into which the discharge occurs.

In 1987, the Water Quality Act, a modification to the CWA, required stormwater discharges to operate under the NPDES system. This includes municipal, construction, and industrial stormwater; agricultural runoff was removed so that it is not regulated under the CWA.

Regulation of municipal separate storm sewer systems (MS4s) was implemented in two phases. In the first, implemented in 1990, large jurisdictions (cities and counties), defined as those with population of 100,000 or more, were issued NPDES permits for their stormwater. Phase I covers about 750 municipalities in the United States (www.epa.gov). Figure 1.10 displays a timeline of stormwater regulatory actions and milestones.

Early CWA regulatory actions primarily focused on point source impacts and have been successful at reducing their impact significantly. Point sources are direct (treated) wastewater discharges from municipal wastewater treatment plants and from industries. As a result of this regulatory structure, the majority of the US water body impairment sources shifted from point to non-point sources (Figure 1.11). Non-point sources

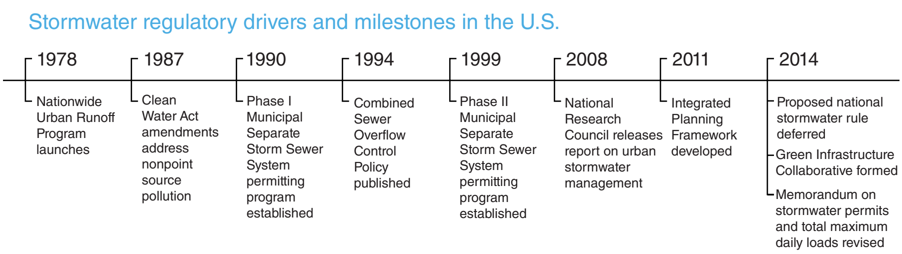

Figure 1.10 Stormwater Regulatory Drivers and Milestones in the United States (with Permission, Water Environment Federation, WEF 2015).

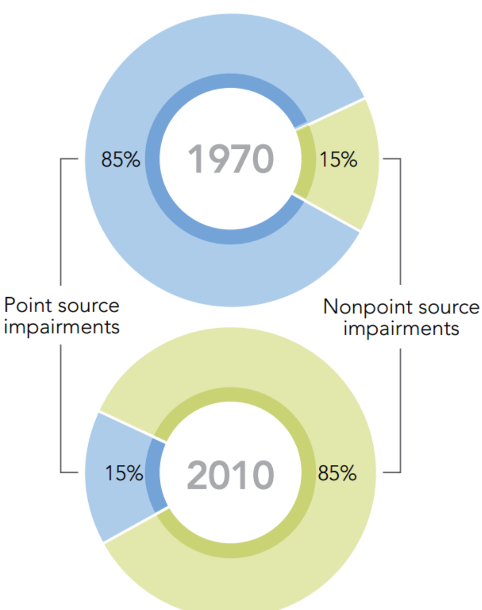

Figure 1.11 Shift of Balance of Impairment Sources from Point to Non-Point after Initial Enforcement of the Clean Water Act (with Permission, Water Environment Federation, WEF 2015).

are primarily stormwater from urban, highway, industrial, construction, and agricultural land uses.

Recognizing the need to address non-point sources, NPDES Phase II was implemented in 1999 targeting smaller urbanizing areas. Phase II covers approximately 6700 jurisdictions (www.epa.gov) and requires programs to reduce pollutant discharge to the "maximum extent practicable" (MEP), protect water quality, and meet the water-quality requirements of the CWA.

In all but five cases, the authority for NPDES permitting and enforcement for Phases I and II has been delegated to each respective state. MS4 NPDES permits are generally issued in 5-year cycles. Stormwater NPDES permits have focused on implementing "Best Management Practices" and public education for stormwater control, targeting runoff from diffuse surfaces. These best management practices (BMPs) can be structural stormwater control measures (SCMs) or nonstructural practices, such as street sweeping, both of which are discussed in later chapters. Recently, especially in areas in which surface water quality has remained poor, NPDES permits are becoming increasingly stringent for both Phases I and II communities.

Twenty-seven industrial sectors are included under the industrial stormwater program. The US EPA has created a multi-sector general permit (MSGP) that specifies benchmark monitoring for most of these sectors. The benchmark monitoring is used as a measure of the effectiveness of stormwater management at the site. Construction permits cover construction activities and focus on land disturbances. The general permits have identical provisions for all facilities under the same sector. For large facilities with unique challenges, an individual NPDES permit can be issued. Frequently, an individual permit would cover all water discharges at a facility: stormwater and process wastewater.

Late in 2000, the CWA was amended to address combined sewer overflows (CSOs). Many older cities combined street drainage and sewage collection and conveyance in the same piping system; originally these networks discharged directly to local water bodies (Figure 1.12). Over time these pipe networks were redirected to wastewater treatment plants. However, with these combined systems, larger stormwater events (0.5 in. (1.2 cm) and up) can overload the pipe and treatment systems, causing

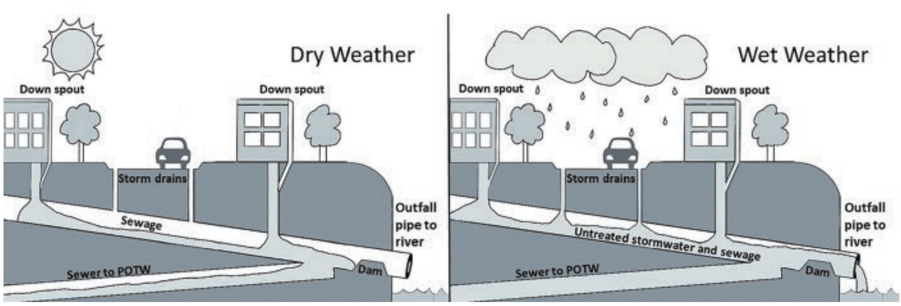

Figure 1.12 A Combined Sewer System. During Dry Weather (and Small Storms), All Wastewater and Stormwater Flows are Handled by the Publicly Owned Treatment Works (POTW). During Large Storms, the Relief Structure Allows Some of the Combined Stormwater and Wastewater to Be Discharged Untreated to an Adjacent Water Body.

discharge of untreated stormwater and sewage, an event known as a CSO. The new legislation requires cities with combined sewers to develop long-term control plans to reduce the impacts of CSOs, to bring them into compliance with the CWA. Figure 1.13 shows CSO locations in the New York City area.

Another section of the CWA that impacts stormwater is the *Total Maximum Daily Load* (TMDL). Water bodies of the United States are designated for specific uses, usually by the respective states. These uses can include drinking, swimming, fishing, and so on. Under Section 303(d) of the CWA, water bodies that cannot meet their designated use, because of poor water quality, are labeled as *impaired*. The impairment is attributed to a specific water-quality parameter, such as bacteria, nutrients, or sediment.

When a water body is classified as impaired, the CWA requires the establishment of a TMDL. A TMDL is set for a water body based on estimates of the pollutant load (mass) that the water body can adequately manage yet still meet its designated uses. In

Figure 1.13 Combined Sewer Overflow Locations in the New York City Metro Area. (Credit: U.S. EPA 2011a).

an impaired water body, the overall pollutant load to a water body exceeds the TMDL. In this case, specific reductions to the various water discharge sectors will be required, a so-called pollution diet plan to eliminate the water body state of impairment and return the water quality to the designated use condition. These sectors include municipal and industrial wastewater discharges, agricultural runoff, and urban runoff. Increasingly, TMDL concerns are being written into MS4 NPDES permits. The result can be very stringent requirements for the management and control of urban stormwater.

In addition, many states have developed their own regulations to address stormwater impacts. Most of these state requirements started as flood control criteria and focused on peak runoff flow rates from the site during extreme events. Pennsylvania, for example, passed its stormwater management act in 1978 in response to Hurricane Agnes. While the language of the act addressed increase of runoff from developing areas, the act was interpreted as requiring that the peak flow leaving the project site be maintained at preconstruction levels for extreme events. Later this requirement evolved into reducing peak flow after construction to less than preconstruction in an effort to consider the downstream watershed (Traver and Chadderton 1983).

As the focus of stormwater management has shifted over the past decade to addressing smaller storms, many states and municipalities added volume control to their stormwater regulations. While it is argued that volume or peak rates are not addressed under the CWA, it is not possible to address environmental quality without it (NRC 2009). Table 1.1 compares stormwater volumetric requirements for a few states for comparison.

Table 1.1 Volumetric Retention Standards for Discharges from New Development (Compiled from U.S. EPA 2011b).

State or locality (date enacted)	Size threshold	Standard
Vermont (2003, draft 2010)	1 acre	Capture 90% of the annual storm events
New Hampshire (2009)	1 acre/100,000 ft^2 outside MS4	Infiltrate, evapotranspire or capture first 1.0 in. from 24-h storm
Wisconsin (2010)	1 acre	Infiltrate runoff to achieve 60–90% of predevelopment volume based on impervious cover level
West Virginia (2009)	1 acre	Keep and manage on site 1 in. rainfall from 24-h storm preceded by 48 h of no rain
Montana (2009)	1 acre	Infiltrate, evapotranspire, or capture for reuse runoff from first 0.5 in. of rain
Portland, OR (1990)	500 ft^2 of impervious cover	Infiltrate 10-year, 24-h storm
Anchorage, AK (2009)	10,000 ft^2	Keep and manage the runoff generated from the first 0.52 in. of rainfall from a 24-h event preceded by 48 h of no measurable precipitation

1.4 Urban Stormwater Management

As stated earlier, without the ability to infiltrate, rain that falls on impervious surfaces will collect and travel quickly over these surfaces, moving polluted waters to our stream systems and causing erosion and sediment deposition. In a highly developed area, without a place to go, this water will pool, creating a flooding hazard, and increase flooding in area streams.

1.4.1 Flood Control

The first generation of stormwater management was developed to reduce flooding hazards. Storm drains and storm sewer networks were installed to collect runoff from impervious areas. These drains were directed into the nearest stream or river so that rainfall that fell on the impervious area could be conveyed away as quickly as possible. In many older cities, the sanitary sewer system (for conveyance of wastewater to treatment plants) was already in place. In some situations, the urban flooding challenge was addressed by piping the stormwater into the sanitary sewer networks, creating combined sewers. These engineering projects addressed the urban flooding problem but created others.

During heavy rainfall events, these drainage systems put a tremendous water burden on the repository of the flow, either the stream outfall or the sanitary conveyance and treatment network. This increased flow comes quickly, with high volumes and velocities. The streamflows are increased dramatically, resulting in erosion of the streambed, scour, and stream flooding. Loss of aquatic habitat occurs, including beneficial stream processes, such as nitrogen processing. These problems associated with stormwater discharges have been termed *urban stream syndrome* (Barco et al. 2008; Walsh et al. 2005). In many cases, due to the perceived need for space and to prevent erosion, entire streams were replaced with concrete channels and ditches (Figure 1.14).

Figure 1.14 Hardened Urban Stream, Crow Branch in Laurel, MD. (Photo by Authors).

During heavy rains in combined sewer areas, very large volumes of water are dumped to the sanitary sewer system. This runoff volume can be too much for the sewer network and wastewater treatment plant to handle. As a result, relief areas are constructed into the sewer system so that if the flows become too large, they will overflow into the nearby streams and rivers. The result of this relief is that during large rainfall events, runoff, mixed with raw sewage, is directly discharged, untreated into the environment. This condition, obviously, creates major public health and environmental problems and is a violation of the CWA. CSOs can occur many times per year in some cities.

1.4.2 Peak Flow Control

Recognizing that direct connections to the nearby streams were causing environmental damage to the streams and surroundings, efforts were subsequently made to incorporate some degree of runoff storage to reduce extreme event peak flows into the newer stormwater systems that were being installed. Generally, this consisted of some type of dry or wet pond that was placed between the new impervious infrastructure and the receiving stream. This pond would fill during the rain event and was managed with weirs so that it would restrict the outflow to preconstruction levels. Figure 1.15 shows an early 1980s Pennsylvania wet pond, designed to hold peak flows at preconstruction levels for the 24 hour 2–100-year design storms (Chapter 6). The ponds were designed to be deep to prevent growth of vegetation.

The ponds addressed the peak flow problem directly at the point of design, but still the challenge of high erosive flows remained, which was commonly exacerbated by the combination effect of multiple individually designed storage facilities

Figure 1.15 Stormwater Management Retention Pond Circa 1980s. (Photo by Authors).

within a watershed (Emerson et al. 2005; Traver and Chadderton 1983). While arguably effective at the property line for extreme events, the increased volume and extended increased velocities exacerbated the erosive discharge for the stream. McCuen and Moglen (1988) stated, "Both theory and experience indicate that, while detention basins designed to control peak discharge are effective in controlling the peak rates, the basins are ineffective in controlling the degradation of erodible channels downstream of the basin."

1.4.3 Watershed Approach to Peak Flow

Recognizing that timing of release from detention basins could actually increase flood peaks (Emerson et al. 2005; McCuen and Moglen 1988), many regions in the 1980s started to require downstream analysis for extreme events to ensure that the cumulative increased peak flow effects from detention basins did not increase river flows downstream of the developed properties. Termed *Release Rates*, this analysis was codified based on watershed modeling of extreme design storms, often requiring that outflows from individual extreme events be reduced below preconstruction levels to avoid unintentional downstream peak flow increases due to the extended outflow of runoff. For example, it is common to require that the 2-, 10-, and 100-year storm to be reduced to a fraction of the preconstruction peak level, often as much as 50%, resulting in much larger regulatory structures.

A few areas, early on moved away from individual storm analysis, instead using a continuous simulation approach to look at the annual impact. As the mechanisms for stream erosion and sedimentation are related to both flow rate and duration of these flows, Western Washington requires a continuous simulation analysis that demonstrates that the postconstruction flow durations are held for selected extreme events ranging from 50% of the 2-year storm to that of the 50-year storm (Ecology 2005).

1.4.4 Water-Quality Control

In the 1990s, it was recognized that more and more, urban runoff was a significant contributor to quality problems in receiving waters. Regulations promulgated in the 1970s and 1980s placed severe restrictions on discharges from point sources, that is, industrial and municipal wastewater treatment plants. As the water quality from industrial discharges improved, and more urban infrastructure was installed, pollutant loads from non-point sources, such as urban runoff, were becoming a significant contributor of the overall pollutant burden of many water bodies (Amandes and Bedient 1980).

In response, water-quality requirements were added to stormwater regulations. In many jurisdictions, this led to the definition of a *water quality volume*. The water-quality volume is a runoff volume defined by the regulatory agency that must be captured and treated. This volume is found as a rainfall or runoff depth, over the drainage area (or some fraction of the drainage area). It is assumed that the majority of the pollutant load is present in this initial runoff volume (Chapter 3), and that it is a significant fraction of the annual runoff.

1.5 Climate Change and Stationarity

Most hydrologic design is based on the concept of stationarity. Stationarity assumes that events of the future can be predicted by understanding events from the past; that is the population distribution of events does not change. Standard hydrologic design has always assumed that rainfall frequencies are constant over the long term. This allows us to design infrastructure based on probabilities for rainfall, floods, and so on. Return periods used for design are based on historical data sets that are assumed to match future events.

Nonetheless, global climate is changing now. Overall global temperatures are increasing (Melillo et al. 2014). This impacts the hydrologic cycle, and accordingly, stormwater, in many ways. Additionally, changes at the regional and local level can be very different from global trends. The most recent data and predictions indicate that generally areas will become wetter and exposed to more intense rainfall during wet seasons and dryer during dry seasons. As precipitation is a key driver of SCM performance, changes to precipitation volume, intensity, and frequencies will drive our stormwater management approaches. Much of the United States is expecting more frequent and higher intensity events, with periods of increased drought. Regulatory goals and design concepts will need to be rethought as precipitation patterns change. As will be discussed in future chapters, green stormwater infrastructure (GSI) can be more flexible and resilient than traditional curb, gutter, and piping systems ("gray infrastructure"), as there may be some dampening of the effect due its functional dependence on natural processes.

1.6 Green Stormwater Infrastructure

As stormwater management criteria expanded, better ways to address the urban runoff challenge were developed and, a number of topics began to emerge and coalesce. Philosophies were introduced, such as implementing ways to manage stormwater directly at the source, rather than downstream after it has been combined with flow from large areas. New performance metrics were discussed, focusing on having the land behave hydrologically similar to that when it was undeveloped, a goal of restoring the watershed to "pre-development hydrology." These ideas led to interest in incorporating green space into the urban areas and making these green spaces functional with respect to hydrology and water-quality management. This philosophy has gradually matured under several different concept titles. An example of this concept is shown in Figure 1.16, with a water balance diagrammed in Figure 1.17. These titles include low-impact development, sustainable urban drainage, and GSI.

The ideals of GSI are to mitigate the deleterious effects of urban stormwater using natural processes such as vegetation and soils at or near where the rain falls. The water balance in urban areas is modified so that less surface runoff is created and more rainfall is allowed to infiltrate and evapotranspire. Water quality is improved by various natural processes, including sedimentation, filtration, adsorption, and biological processes. Overall, the water balance more closely mimics the preconstruction conditions.

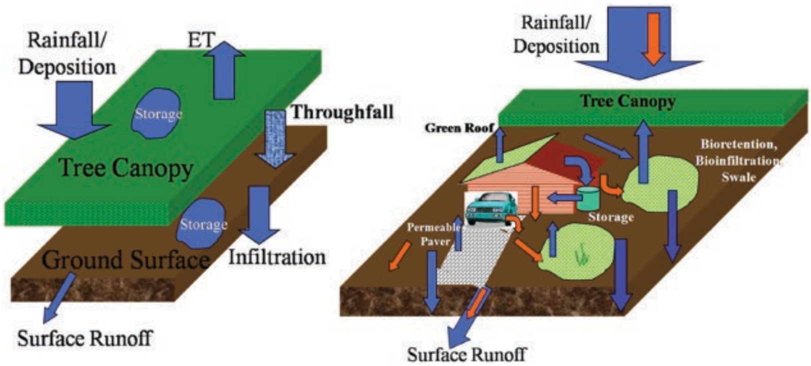

Figure 1.16 Land Development Using the Various Concepts of Green Stormwater Infrastructure to Mimic Pre-Development Hydrologic and Water Quality Conditions.

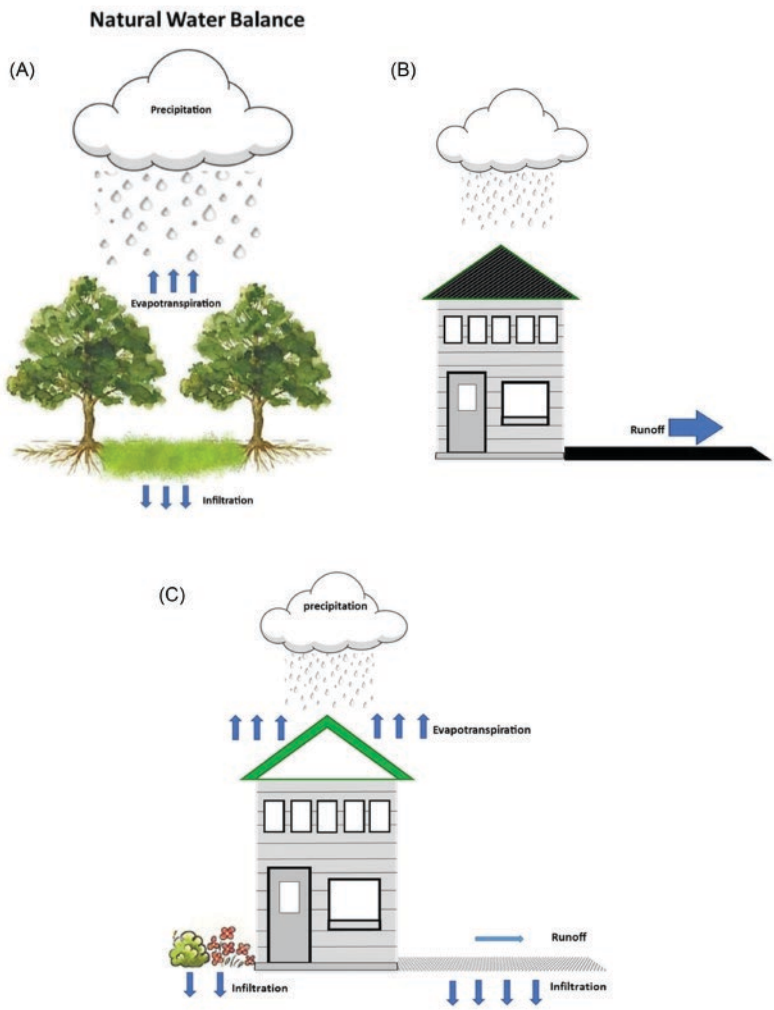

Figure 1.17 Water Balances for Different Land Use Conditions: (A) Natural Water Balance Showing Primary Water Pathways of Evapotranspiration and Infiltration; (B) Urban Water Balance Includes Runoff from Impervious Surfaces; and (C) Green Infrastructure Water Balance Promotes Evapotranspiration and Infiltration in the Built Environment from Green Roofs, Permeable Pavements, and Other Stormwater Control Measures.

1.7 Stormwater Control Measures

A number of techniques and processes are employed to reduce the impacts of urban stormwater runoff. Collectively, these are known as SCMs. These processes have been historically designated as stormwater BMPs. This designation is still prevalent but is not as precise and specific as SCM (NRC-National Research Council 2009).

Common green infrastructure SCMs include vegetated technologies such as vegetated swales and filter strips, rain gardens and bioretention, green roofs, and wetlands. Other SCMs that reduce runoff and are also considered part of green stormwater infrastructure include water-harvesting technologies, infiltration basins, and permeable pavements. Green infrastructure SCMs attempt to beneficially affect the urban water balance, and to reduce the pollutant load, to counteract the problems created by urban development, as noted in Figure 1.17. These SCMs provide storage and promote infiltration and ET of rain and runoff, reducing volumes, flows, and velocities. In most SCMs, specific design and operational characteristics will promote the inclusion of environmental unit processes that will improve (or in some cases of poor design, worsen) water quality in the runoff. (Water-quality improvement may be less of an issue in CSO watersheds.) Selection and sizing of SCMs depend on many parameters, including catchment area size and land use, hydrologic and water-quality goals, soil and geologic conditions, and available land space for the SCM. More and more, knowledge is available to tailor specific SCM selection and designs to area needs, and even reversing development impacts through retrofitted older paved areas. SCMs are engineered technologies and techniques that will follow specific hydrologic and water-quality improvement process rules. This selection process and design parameters are covered in the later chapters of this book.

1.8 Stormwater Infrastructure and Equity

It is recognized that stormwater infrastructure historically has not been equitably distributed throughout the built landscape. It is well documented that people of color and other minorities, through various policies and initiatives, have been forced to live in areas that are more prone to negative environmental factors, including flooding, poor infrastructure, and air pollution.

Incorporation and selection of green stormwater infrastructure in any neighborhood, but specifically in underserved areas, must be carefully done, with consideration of the past, present, and future. This is necessary to balance equity and to address previous poor and racist decisions and policies. GSI implementation must balance the needs and recognize the history of the neighborhood. Sudden large investments in infrastructure, including GSI, will alter, maybe drastically, the characteristics and personality of the neighbor. While hopefully being beneficial, a large infrastructure investment can impact housing prices and related cost of living issues in the neighborhood. This can lead to gentrification in established neighborhoods that have developed over many years. Engineers and other stormwater professions should work with the communities throughout the entire project to understand the needs and constraints of the community as the GSI projects are implemented.

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Problems

1.1 Does your state or local jurisdiction have a stormwater manual? Try to find it on the web. What year was it created? What stormwater control measures does it promote and describe?

1.2 How many 303(d) impaired waters are listed in your state? What is the greatest cause of the impairment?

1.3 Find the river, lake, or reservoir closest to your home or school. Is it listed as 303(d) impaired? If so, describe the impairment. If not, find the nearest river with an impairment. Does it have an approved TMDL?

2

Precipitation: The Stormwater Driver

2.1 Introduction

Effective implementation of green stormwater infrastructure (GSI) requires an understanding of the hydrological processes that occur within landscapes that have been altered by human activities and the resulting impact to the water cycle. To mitigate these impacts, the GSI professional must be able to evaluate the hydrologic processes for both the preconstruction and postconstruction conditions, select a strategy and level of green infrastructure mitigation, and track the precipitation hydraulically from the impervious surface to, and through, the green infrastructure stormwater control measure (GI SCM). This chapter introduces the reader to urban hydrology concepts and rainfall characterization. Chapter 6 further develops this topic, where hydrologic and hydraulic processes are discussed in detail. It is presumed that the reader has a fundamental understanding of fluid mechanics and hydrology.

2.2 The Urban Hydrologic Cycle

The hydrologic cycle comprises the movement of water from the clouds, to rainfall, to runoff and infiltration into the soil, entering our streams and groundwater sources, frequently to the ocean, where evaporation and/or transpiration transfer the water back to the clouds again. As the system is powered by energy from the sun, it is continuous. Figure 2.1 describes the "natural" hydrologic cycle of many temperate regions, which demonstrates that on an annual basis, the majority of the rainfall returns to the atmosphere through evapotranspiration (ET), with a fraction becoming surface runoff. The remaining water soaks into the ground, either replenishing the groundwater storage or becoming the baseflow of our streams and rivers.

As described in Chapter 1, urban development interrupts and short-circuits the natural hydrologic cycle. Ubiquitous impervious area in developed regions prevents the rainfall from entering the ground and accelerates the speed that the runoff enters our streams and rivers. Note that as shown in Figure 2.2, the urbanized watershed transfers water that previously was destined for groundwater, baseflow, or ET to surface runoff. Thus, the urban hydrology focus then is on these transport pathways and their effects.

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Companion Website: www.wiley.com/go/davis/greenstormwater

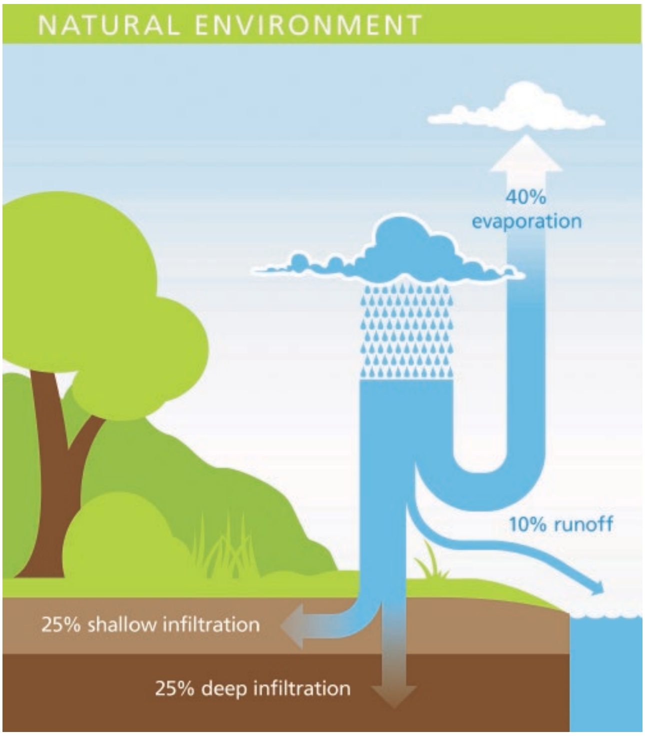

Figure 2.1 The Natural Hydrologic Cycle. (Credit: Philadelphia Water Department).

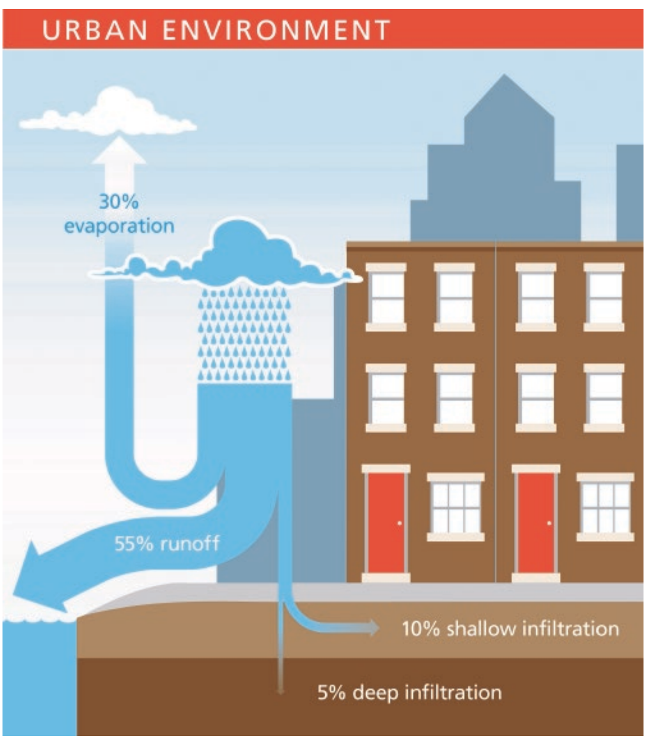

Figure 2.2 The Urban Hydrologic Cycle. (Credit: Philadelphia Water Department).

Stormwater runoff from urbanized areas is characterized by rapidly changing and widely fluctuating flows and pollutant concentrations, which are heavily tied to the contributing impervious area and flow conveyance pathways. Runoff from pavement and compacted soils can be extremely flashy due to the lack of soil retention and speed of the runoff traveling over various impervious surfaces or in shallow concentrated flow. Drainage area characterization must take into account not only the land form but the stormwater conveyance and collection systems, which often may behave differently depending on the size of the storm event being considered and the season. As the magnitude and pattern of the hydrologic cycle is different across the United States and throughout the world, so are the design goals and the regulatory structures. Design goals may be related to nuisance flooding, water quality and stream geomorphology, combined sewer overflows, or more extreme flooding events. Some regions deal with extreme precipitation events separately from the more frequent storms both from a regulatory and design approach perspective. The differences are further complicated due to the historic development of the regulatory structure, but in all scenarios the fundamental hydrologic processes remain.

Urban stormwater hydrologic goals are normally related to an occurrence probability, a specific time duration, and the regulatory process. These goals can include extreme event peak flow rates from a specified return period or historic storm, an annual view of velocity changes of rate and duration based on geomorphic impacts, and daily or seasonal volumes. Other goals can include a hybrid time-related volume focus, for example, capturing the first flush of rainfall (commonly somewhere between 1 and 3 cm; also known as the water quality volume), or a combination of volume and annual duration of flow rates. These principles are discussed in Chapter 6. In any event, to meet the design intent, the GSI professional must be able to evaluate the hydrologic characteristics for both the preconstruction and postconstruction conditions in order to determine what mitigation approach is required and to predict the performance of the GSI and GI SCMs.

Depending on the approach, the specific time focus for GI evaluation may extenuate or negate individual components of the design. For example, when considering a peak flow during a storm event, ET may be considered insignificant. However, if that focus is lengthened, then ET becomes a key component when determining the rate of recovery of storage capability prior to the next storm, or when looking at the annual performance of a SCM designed for smaller individual storms. In any event, the intent of GSI is to reverse the effects of urbanization, inserting “green” processes within the gray infrastructure to approach the natural hydrologic cycle as a goal.

2.3 Precipitation

Understanding GSI starts with a fundamental characterization of rainfall. For every region and climate throughout the world, the rainfall volumes and patterns influence the GSI strategy approach to be used. For example, the weather in Seattle, Washington, is dominated by frequent smaller storm events for most of the year. Therefore, a small runoff volume can be an effective target, which is ideal for green infrastructure mitigation. However, the challenge for Seattle and other municipalities with similar climates is how to implement GSI that can endure the annual multi-month dry season. A very different challenge occurs in Austin, Texas, where the majority of rainfall falls during relatively few infrequent, but large storm events.

Conversely the rainfall on the east coast of the United States is more uniformly distributed, but with higher precipitation influenced by occasional tropical storms leading to large erosive channel forming events. Higher temperatures in the lower latitudes (which impact plant selection and water needs) and snow and ice (and snow removal) in the northern regions are factors that must be part of GI design considerations. An effective GI strategy requires understanding the climate seasonality and future-predicted climate change trends.

2.4 Precipitation Depths

Precipitation depth is characterized based on a specified time frame of interest, such as a year, season, individual storm event, or peak rate within that storm event. Statistical analysis is used to relate the rainfall depth to a time interval and frequency of occurrence, to develop target storm characteristics commonly known as *design storms*. A more sophisticated approach would be to use an annual or multiyear climate record as further discussed in Chapter 6. A statistical comparison of precipitation data, based on historical records of precipitation, is presented in Table 2.1 for four US cities. Differences in rainfall characteristics become clear when comparing the number of rainy days (≥0.1 in.; ≥0.25 cm) to the number of days with large rain events (≥1.0 in.; ≥2.54 cm).

From the GSI perspective, of interest is how many times per year a set rainfall event occurs. From this information must come the storage volume a SCM must contain to hold the runoff from these events. For example, in Washington, DC, the great majority of rainfall events are less than 1 in. (2.54 cm). Therefore, most runoff volumes will be produced from storms 1 in. or less, and the 1-in. runoff volume is exceeded on average less than 10 times a year (Table 2.1).

The long-term rain gage data available from the US National Oceanographic and Atmospheric Administration (NOAA) is a valuable resource for these types of analyses. Consider the 53-year rainfall record from the Philadelphia (PA) Airport rain gage (www.ncdc.noaa.gov/cdo-web). Figure 2.3 shows the rainfall daily volumes (depths) sorted from smallest to largest in a cumulative distribution curve (Figure 2.3, percent storm). This curve gives the percentage of total rainfall depth represented by the corresponding depth, and smaller depths.

Table 2.1 Comparison of Annual Precipitation Data for Four Locations within the United States 1980–2010 (Data from NOAA National Center for Environmental Information)

	Washington DC	Houston TX	Minneapolis MN	Seattle WA
Average precipitation (in.) (cm)	39.7 (100)	49.8 (126)	30.6 (78)	37.5 (95)
Average snowfall (in.) (cm)	15.4 (39)	0.1 (0.25)	54.4 (138)	6.8 (17)
Average number of precip. events ≥ 0.1 in. (≥0.25 cm)	70.1	64.2	61.8	91.0
Average number of precip. days ≥ 1.0 in. (≥2.54 cm)	9.4	15.1	6.0	4.6