

Urban Stormwater Management: Evolution of Process and Technology

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Contents

1	Introduction	84
2	History of Stormwater Practice	85
2.1	The Pave and Drain Era	86
2.2	Stream Channel and Flood Protection	87
2.3	Natural Resource Protection	93
3	Stormwater, Site Planning, and Land Use	94
4	Reducing Stormwater Volume: A New Paradigm in Regulation and Design	97
4.1	Runoff Reduction Practices	98
4.2	Steps for the Runoff Reduction Method (RRM)	106
4.3	Accounting for Runoff Reduction Capabilities of Various Practices	109
5	Stormwater Management as an Interdisciplinary Field	110
6	Emerging Forms of Regulatory Integration	113
6.1	Runoff Volume	114
6.2	Stormwater Quality and Quantity	115
	Appendix A	116
	Appendix B	118
	References	119

Abstract The practice of urban stormwater management has evolved over the course of several decades. Initially, stormwater management concerned itself primarily with abating downstream flooding and was the sole domain of engineers. As the regulatory climate changed over time, so did design philosophy, along with the types of management practices, the computational methods, and the prominence of stormwater management as an integral part of the overall site planning process. The milestones of this evolution include the addition of stormwater quality treatment as a regulatory standard and, more recently, a focus on reducing the overall

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volume of runoff through the use of small-scale, distributed management practices (often under the banner of Low-Impact Development or Environmental Site Design). The volume reduction strategy, referred to as “runoff reduction,” has been adopted as a regulatory standard in some parts of the USA, along with new stormwater practice design specifications and computational methods. The approach demands that stormwater design reach beyond sole reliance on engineering, as the new best management practices (BMPs) include site design strategies that incorporate elements of soil science, horticulture, landscape architecture, and, importantly, site planning. These new strategies have certainly been elevated to prominence by virtue of the hydrologic benefits but also by the integration of stormwater management into Clean Water Act permits and Total Maximum Daily Loads (TMDLs) assigned to impaired urban streams and receiving waterbodies. This chapter will outline the evolution of stormwater management regulatory goals and the corresponding design strategies and include examples of how these approaches are changing the structural and nonstructural design of the urban landscape.

Keywords Channel protection • Impervious cover • Stormwater • Stormwater practice • Urban infrastructure

1 Introduction

Stormwater management has transcended many eras, beginning with an engineering focus on conveyance and shedding water rapidly from the developed landscape. Increasingly, the stormwater field has expanded its scope in terms of treatment objectives – treating the quantity and quality of runoff as well as reducing its volume (regulatory standards) – and in the range of professions and areas of expertise needed to implement successful stormwater projects in urban environments.

The earliest era was driven by urban infrastructure expansion during the industrial revolution, which gave rise to the need for drainage systems to safely remove stormwater to protect lives and infrastructure. Over many years, civil engineers developed hydrologic models and computational cost-benefit tools for predicting maximum rainfall and the scale of drainage infrastructure needed to protect the health, safety, and well-being of the public and infrastructure. The pave and drain design model was very effective at shedding stormwater from the urban environment and efficiently conveying it downstream to stream channels within and below the urban centers.

Over time, it became apparent that an important element of this strategy was being ignored – the receiving stream channel. The network of streams that previously meandered through the urban landscape were recognized as being more valuable and complex than simply a drainage conveyance for large pulses of

stormwater runoff. Peak flow attenuation in the form of stormwater detention basins was designed to minimize channel erosion and out-of-bank flooding.

Starting in the 1980s, a holistic view of the interconnected watershed gave rise to another set of performance goals – stormwater runoff quality. Provisions of the Clean Water Act were proving effective at improving the water quality of the nation’s rivers and streams by addressing pollution associated with industrial discharges and municipal wastewater treatment. However, continued decline of water quality soon cast a light on an almost invisible culprit – stormwater runoff tainted with a wide variety of pollutants flushed from the urban landscape [1]. The increased runoff was delivering more pollutants to the streams than could be assimilated. Acknowledgment of this problem effectively launched the modern multidisciplinary approach to stormwater management.

Though committed to the protection of the public’s health and well-being, civil engineers’ transition through these stormwater epochs has not been easy. Changes in design standards had to navigate through dizzying layers of federal, state, and local regulatory oversight and then be embraced by the land development industry.

This chapter will provide an overview of the history of stormwater practice in the USA as it evolved, with explanations of the engineering and watershed dynamics that informed various design eras. Next, the chapter will explore the relationship between stormwater management and the very fabric of how development sites, neighborhoods, and communities are designed in the first place. The key to this is improving the integration of stormwater and site design and community planning. It is only with this integration that communities can reduce stormwater impacts “by design.” A logical outgrowth of this exploration is an increased focus on stormwater volumes, and how combinations of site planning and various “runoff reduction” practices can help meet ever more stringent regulatory requirements.

An emerging trend in stormwater management is that many disciplines beyond engineering are becoming important pieces of the stormwater design puzzle. In an era where vegetation communities and stream dynamics are as important as engineered conveyance and storage systems, many areas of expertise are required to design, install, and maintain a well-functioning stormwater system. The chapter concludes with an examination of recent regulatory trends, as the regulatory approach becomes more holistic and ambitious in terms of meeting site and watershed objectives for clean water and better communities.

2 History of Stormwater Practice

The approach to managing stormwater runoff and the subsequent design of drainage infrastructure have evolved through three significant eras: (1) *pave and drain*, (2) *stream channel and flood protection*, and (3) *natural resource protection*. Each era is described briefly in this section.

2.1 The Pave and Drain Era

Historical drainage and infrastructure protection involved a philosophy of intercepting, collecting, and disposing of stormwater runoff as rapidly as possible. The early days of drainage design were largely focused on two systems – the *minor system* and the *major system* [2]. The *minor system*, sometimes referred to as the “conveyance system” consists of curbs, gutters, inlets, pipes, swales, channels, and appurtenant facilities all designed to minimize nuisance, inconvenience, and hazard to persons and property. The *major system* consists of the drainage system of natural channels, streams, floodplains, and, in some cases, large man-made systems (e.g., culverts) that carry excess flow over and above the hydraulic capacity of the various components of the *minor system*.

As this process evolved, the minor system was designed to efficiently capture, contain, and convey the maximum expected peak rate of runoff from larger storms. The adoption of a larger minimum design storm for the minor system is indicative of a failure to recognize the importance or even existence of the major system (natural stream network) and was a response to public safety and economic risks associated with increasing flood hazards in the built environment [3]. However, the preoccupation of engineering the minor system led to even greater cumulative impacts of increased flooding and channel degradation. In many cases, this required construction of large-scale engineered conveyance channels to protect adjacent properties from further damage (Fig. 1).



Fig. 1 An urban channelized and “hardened” stream (*left*). An eroded stream (with sewer manhole exposed) (*right*) (Source: US EPA)

2.1.1 The Rational Method

The primary design tool of the pave and drain era was the Rational Method for calculating the amount of runoff needed to be captured and conveyed. Once that number was calculated, hydraulics and fluid mechanics governed design of the drainage system. The most important feature of the Rational Method was its simplicity – having only three terms:

$$Q = CiA \quad (1)$$

Q = peak rate of runoff (m^3/s or cfs (cubic feet per second))

C = dimensionless runoff coefficient

i = rainfall intensity (measured in mm/hour or inches/hour)

A = contributing drainage area (m^2 or ft^2)

Simplicity is also a function of having a single runoff coefficient to characterize the hydrologic response of the contributing watershed, i.e., how much of the rainfall becomes runoff. This can be a problem if the designer is trying to determine the runoff from a complex watershed – different subareas consisting of different land covers – impervious cover, lawn, woods, and other surfaces, each having a different hydrologic response. Finally, the product of this simplicity is the calculation of peak discharge – not a runoff hydrograph, or runoff volume, or other time-based measures of the rainfall-runoff relationship. Rather, the Rational Method produces the maximum peak discharge that occurs when the entire drainage area is contributing flow. This was considered to be a perfectly acceptable methodology in the early twentieth century when highway designers popularized the Rational Method use on relatively homogenous watersheds for the design of culverts and drainage systems – a simple formula (no calculators or computers required) to calculate a peak discharge.

The drainage infrastructure of the pave and drain era and the majority of the drainage system infrastructures being designed today are still sized using the Rational Method. However, as the design parameters became more complex through time, hydrologists tried to improve the applicability of the Rational Method to large catchments with heterogeneous land cover, topography, soils, and rainfall characteristics (such as antecedent moisture conditions between storms). The resulting runoff unit hydrograph technique became the standard for the flow attenuation basin designs of the *stream channel and flood protection* era.

2.2 Stream Channel and Flood Protection

The next phase of stormwater management expanded the scope of the engineered system by recognizing the interrelated functions of collection and storage of stormwater runoff. As the urbanized landscape was engineered to shed stormwater

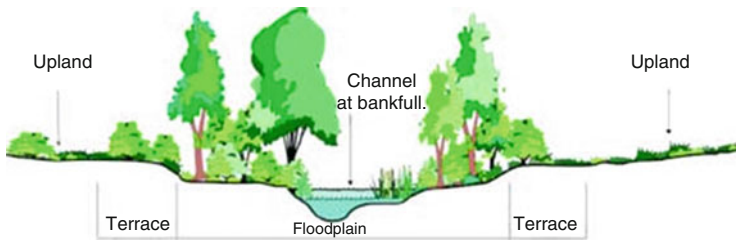


Fig. 2 Typical natural stream cross section with riparian ecosystem [4]

runoff as quickly as possible, small streams became raging rivers within a matter of hours or even minutes of the rainfall as the drainage system quickly and efficiently sent torrents of stormwater into the stream. Stream channels underwent often dramatic changes – widening of the channel banks and down-cutting of the stream bed in order to evolve and accommodate the new watershed conditions.

Stream channels were formed over geologic time by runoff from an undeveloped watershed. Periodic rain events and the runoff characteristics of the watershed – such as land cover, soil types, topography, and other factors – generate runoff, measured in terms of total volume of runoff and the peak rate of runoff (m^3/s or cfs). The stream channel evolves over time until it reaches its hydraulic equilibrium – a flow area (depth and width), floodplain, and supporting riparian zone necessary to carry the base flow, the runoff from frequently occurring storms (bank-full), and the runoff from the large infrequent storms (floodplain) (Fig. 2). Continued variations in the velocity of the natural flow and the transport of sediment balance create a stable “hydraulic geometry.” The natural system achieves a delicate balance based on the hydrologic response of the contributing watershed.

Less than a 10 % increase in impervious cover can change the hydrologic response characteristics of a watershed and impact stream equilibrium, causing erosion and a decline in aquatic health [5]. The symptoms of the changes in hydrologic response include (1) an increase in flow volume, (2) a decrease in lag time (time for runoff from the drainage area to reach a downstream point), and (3) an increase in peak discharge.

The increase in flow volume primarily reflects changes in land use and land cover as the construction of impervious surfaces, e.g., shopping centers, roads and highways, subdivisions, and other developed areas, reduces the infiltration capacity of the landscape and increases total runoff volume. Decrease in lag time is a product of the increase in impervious surfaces and the installation of the efficient drainage network. Impervious surfaces shed runoff more quickly than undeveloped landscape, and the drainage network carries it quickly through the watershed to the receiving stream, resulting in larger and sudden peak surges of runoff. The increase in peak discharge is the result of the combination of increased volume and decreased lag time.

Using Fig. 3 to help visualize the impact of impervious cover, imagine 3 inch (76.2 mm) of rainfall on an undeveloped watershed, generating 0.5 cfs ($0.014 \text{ m}^3/\text{s}$)

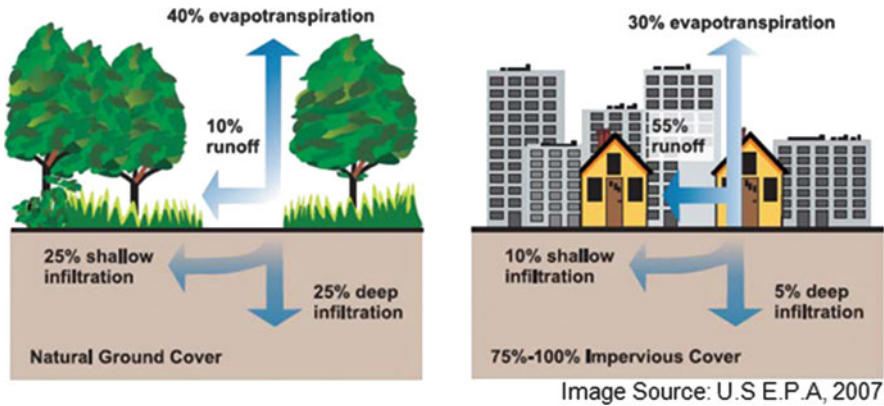


Fig. 3 Developed watersheds generate 7–10 times the amount of runoff compared to undeveloped watershed from the same amount of rainfall [6]

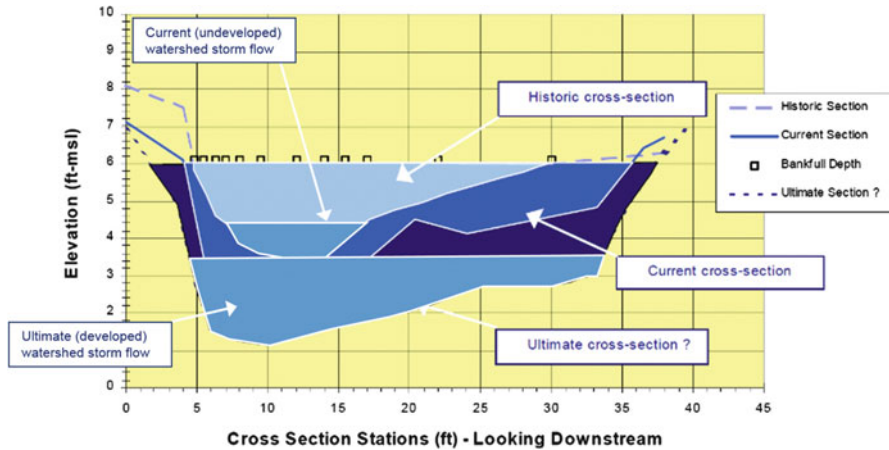


Fig. 4 Representative stream channel cross-section enlargement [7]

per acre of watershed. Now imagine the same watershed covered with a typical urban infrastructure, associated decrease in infiltration and evapotranspiration, and increase in runoff. That same 3 inch (76.2 mm) rainfall generates close to 4.5 cfs (0.13 m³/s) per acre of watershed.¹ This generates, on average, an increase of 7–10 times in the volume and peak rate of runoff.

Stream channels are overwhelmed by this new flow regime and begin to rapidly change to establish a new hydraulic geometry and equilibrium. The low-flow portion of the channel must get larger (wider and deeper) to carry the larger and more frequent “bank-full” flow (Fig. 4). Furthermore, as is often the case in

¹Typical scenario of undeveloped condition consisting of woods and hydrologic soil group B and developed condition consisting of urban/commercial land on the same soil types

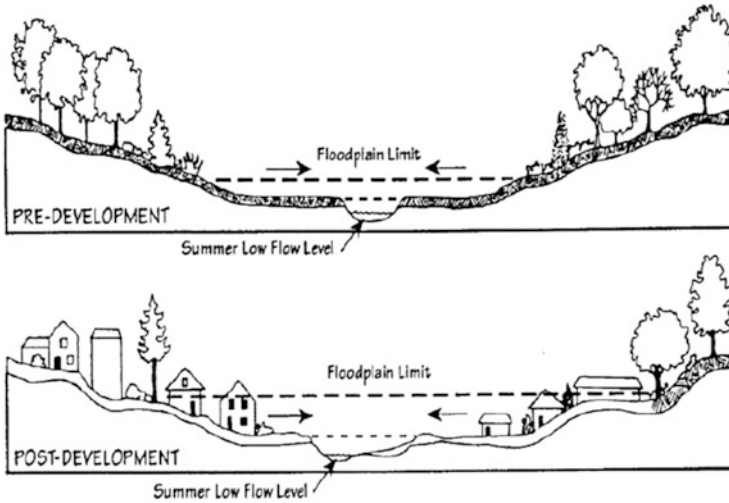


Fig. 5 Changes in floodplain limits and encroaching development lead to property damage during “bank-full” flow conditions [8]

developed areas, the adjacent floodplain has likely been squeezed by development, adding a secondary impact of property damage (Fig. 5). Unfortunately, the hydraulic geometry of this new flow regime is a larger and deeper channel that does not support the aquatic biology of a healthy stream.

Working backward from this new flow regime, it is estimated that the new out-of-bank rainfall-runoff storm event is likely to occur 8–10 times per year rather than the once per year, or once per 2 years, characteristic of an undeveloped watershed. The increased frequency of the channel erosion and out-of-bank flows accelerates channel erosion, stream degradation, and loss of critical stream health functions (Fig. 6).

In developed watersheds, instances of increased channel erosion and flooding are not isolated incidents. These affected areas include stream corridors that wind through new suburban and commercial developments, readily visible to the watershed’s inhabitants (often from their own backyards). This phenomenon compelled a wave of new state and local stormwater management programs focused on detention basins designed to attenuate the peak flow and increase the lag time. Designers would now calculate the detention basin storage volume needed to detain the runoff volume while releasing it at a slower rate.

2.2.1 Natural Resource Conservation Service (NRCS) Hydrologic Methods

New stormwater management ordinances expanded on the pave and drain strategy by adding the design element of runoff detention. Designers would now calculate



Fig. 6 Enlarged stream cross section in response to watershed development (*Source*: second author)

the storage volume needed within a detention basin to capture and detain the runoff volume while releasing it at a slower rate. Therefore, designers needed to know, in addition to the peak rate of runoff, the rate of runoff entering the basin for each time increment and the total volume of runoff for the target design storm. With this revised storage objective, the Natural Resource Conservation Service (NRCS) methods were considered to be more applicable to stormwater management design goals.

NRCS has been developing runoff models for agricultural watersheds since the 1930s with the first fully published methodologies in the 1950s [9]. The NRCS method utilizes a range of watershed hydrologic parameters such as soil types, land cover, land treatment, initial abstraction, time of concentration, and antecedent moisture conditions that allow for modeling of complex watersheds and generating both a peak rate of discharge and a runoff hydrograph.

A runoff hydrograph is a plot of the rate of runoff with respect to time, with the maximum discharge occurring at the peak of the curve (Fig. 7). For stormwater management purposes, another important feature of the hydrograph is that total runoff volume is represented by the area under the curve.

The data required for designing a detention basin is a straightforward task of hydrology and hydraulics. The NRCS methodology for the hydrologic analysis of a watershed was updated and repackaged in 1975 as *Technical Release 55 (TR-55): Urban Hydrology for Small Watersheds*. Updated in 1986, TR-55 presents simplified procedures to calculate storm runoff volume, peak rate of discharge,

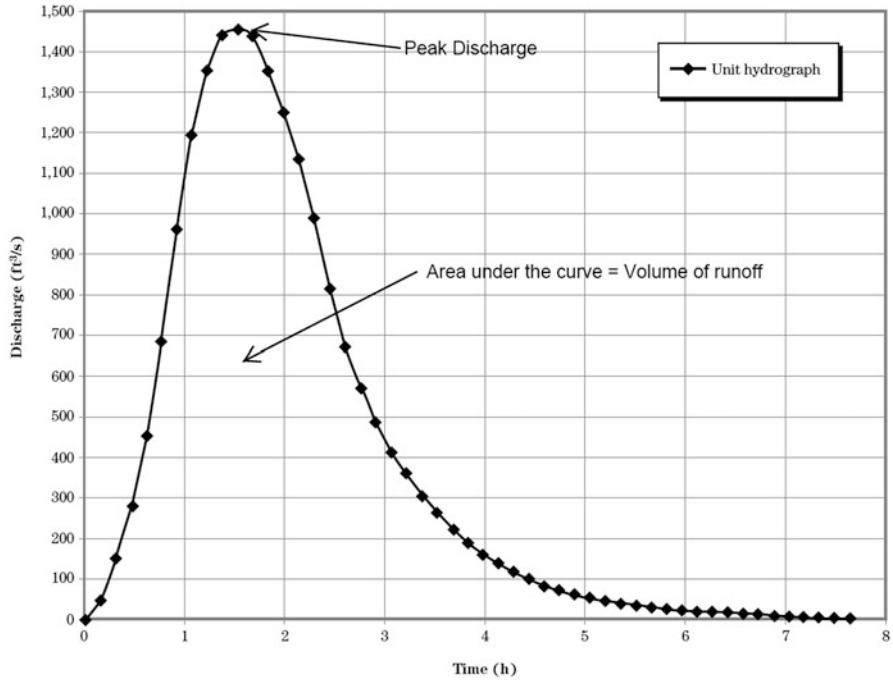


Fig. 7 Example of a unit hydrograph [10]

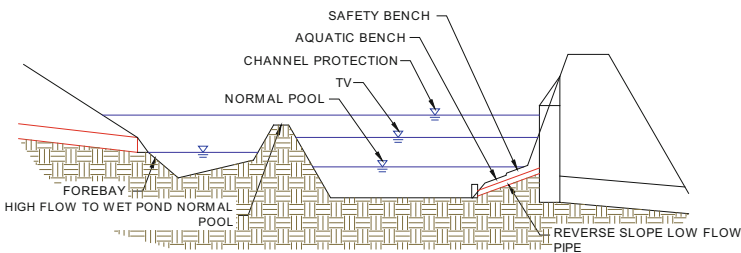


Fig. 8 Image of typical multi-criterion detention basin: storage volume for water quality volume, 2-year and 10-year design storms, and an outlet riser structure [12]

hydrographs, and storage volumes required for the design of detention basins in small urbanizing watersheds [11].

The design of detention basins to reduce the post-developed 2-year peak rate of runoff to the pre-developed peak rate has been applied on most development projects, large and small, for many years. Most local stormwater management programs include detention requirements for channel protection, i.e., detention of the 2-year return interval design storm, and additional requirements for localized flooding control, i.e., detention of the 10-year (or other targeted large) return interval design storm (Fig. 8).

Many jurisdictions, especially those experiencing rapid growth, sought benefits through an economy of scale and preferred a single large detention facility designed to manage the peak runoff from multiple developments, rather than stormwater basins on every development site. This strategy, referred to as a regional stormwater program, often sacrificed the intermediate channels between the developed land and the regional basin as an acceptable trade-off for the reduced total construction costs, long-term maintenance costs, and land costs. Over time, the regulatory agencies responsible for preserving the natural stream channels would begin to deny permits due to the impacts of in-stream construction of embankments and temporary impoundments.

Over a period of years, evidence of channel erosion downstream of these detention basins has given credence to what stream geomorphologists had known all along – the changes in the contributing watershed could not be mitigated by simply attenuating the peak discharge. The hydrologic response characteristics of impervious cover and an improved drainage system generate 7–10 times increase in runoff volume which translates to an increase in the frequency of occurrence of the peak discharge. Furthermore, the flow attenuation provided by multiple detention ponds scattered throughout a watershed can add to the problem by increasing the duration of the peak discharge, thereby also increasing the damaging erosive energy exerting forces on downstream stream networks.

A new approach was needed that recognized the fuller dimensions of the hydrograph – peak rate and volume – and how changes in watershed land use affect the natural stream network (previously identified as the *major system*).

2.3 Natural Resource Protection

In 1983, US Environmental Protection Agency (US EPA) released the results of the Nationwide Urban Runoff Program (NURP). The program's goal was to compile a database and develop analytical methodologies that would allow the examination of the quality characteristics of urban runoff, the extent to which urban runoff is a significant contributor to water quality problems across the nation, and the performance characteristics and the overall effectiveness and utility of management practices for the control of pollutant loads from urban runoff [1].

The report noted that water *quantity* problems are relatively easy to identify and describe, e.g., channel erosion resulting from a tenfold increase in flow and out-of-channel flooding is easy to notice. On the other hand, water *quality* problems often go unnoticed and don't manifest themselves immediately, but rather over a long period of time in which the causes have been embedded into the landscape. Water quality management was becoming a new and important design objective for stormwater management.

A related trend emerged in the late 1990s. Low-Impact Development (LID) gained traction as a design and computational approach to addressing the obvious impacts of urbanization on aquatic systems – a design strategy with the goal of

maintaining or replicating the predevelopment hydrologic regime through the use of a variety of design techniques [13]. LID expanded on the hydrologic functions of storage, infiltration and ground water recharge, as well as the reduction in volume and frequency of discharges through the use of integrated and distributed micro-scale stormwater retention and detention areas.

LID also built on minimization and avoidance strategies of preserving and protecting environmentally sensitive site features such as riparian buffers, wetlands, steep slopes, valuable (mature) trees, flood plains, woodlands, and highly permeable soils, all of which have been incorporated into the EPA stormwater permit lexicon. The LID lexicon became a guiding theoretical principle in many state stormwater programs. Where LID was envisioned as a strategy to influence the fundamental process of urbanization, the *pave and drain* development infrastructure was still being implemented, with a sprinkling of LID on the side.

This critical step in the evolution of stormwater compelled the search for a practical methodology for assessing the applicability and implementation of site design strategies. The first step was an impressive array of new and equally inviting development acronyms: Environmental Site Design (ESD), Green Infrastructure (GI), and Better Site Design (BSD). The next step was to develop the scientific basis and a regulatory framework for codifying the implementation of site design strategies and distributed runoff retention practices for achieving volume reduction goals as a compliance tool. The concept is certainly not new; however, the evolving multidisciplinary design team concept is new, and with a regulatory framework supporting it, progress is being made.

The following sections describe how these new approaches led to a movement to integrate stormwater management with fundamental site design principles and to utilize stormwater (runoff) volume as a unifying theme for computations and design.

3 Stormwater, Site Planning, and Land Use

LID and its companion movements illustrated that the best and most direct way to reduce stormwater runoff impacts and volumes is to reduce the amount of stormwater generated in the first place. This process begins with site planning and design, both at the site and community scales. Development projects can be designed to reduce their impact on watersheds when careful efforts are made to conserve natural areas, reduce impervious cover, and better integrate stormwater treatment. By implementing a combination of these approaches, it is possible to reduce the amount of runoff and pollutants generated by a site, a neighborhood, or entire watershed.

The goals of this site and community planning approach include (1) preventing stormwater impacts rather than mitigating them; (2) managing stormwater (quantity and quality) as close to the point of origin as possible and minimizing collection and conveyance; (3) utilizing simple, nonstructural methods for stormwater

management that are lower cost and lower maintenance than structural controls; (4) creating a multifunctional landscape; (5) using hydrology as a framework for site design; and (6) conducting community planning to avoid the proliferation of impervious cover and disturbed land across wide swaths of the community.

Terminology can be confusing with stormwater management concepts: “Low-Impact Development” (LID), “Green Infrastructure,” “Environmental Site Design,” and “Better Site Design” (BSD) have similar and overlapping goals. All of these terms refer to goals of replicating a more natural hydrology at development sites, preserving key natural resources, and treating stormwater close to its source with distributed (and often vegetated) practices. In this chapter, BSD is used to describe these approaches collectively, referring to a group of generally nonstructural and policy-related practices that achieve the aforementioned objectives [14]. This is not to imply that all of these terms have identical meanings and objectives. BSD is simply used here to refer to the general approach of linking stormwater with site planning and design.

BSD is also related to the concept of “Smart Growth.” While BSD refers to *how* development is conducted at the scale of an individual site or neighborhood, smart growth is a concept that operates at a broader, community-wide scale and is more concerned with *where* development takes place. Smart Growth directs a community’s development to designed areas with existing infrastructure (e.g., infill and redevelopment) while avoiding new growth (or sprawl) in the countryside. Smart Growth can be the backbone of a community’s land use strategy and is an important tenet of community planning [15]. Table 1 outlines some of the benefits of using BSD for various stakeholders involved in the land development process.

Table 1 Benefits of BSD for various stakeholders, as compared to conventional development

Stakeholder	Benefits
Developers	Provides flexibility in design options Allows for more sensible locations for stormwater facilities Facilitates compliance with wetland and other regulations Allows for reduced development costs, especially for stormwater infrastructure
Local government	Improves quality of life for residents Facilitates compliance with wetland and other regulations Assists with compliance of Municipal Separate Stormwater System (MS4) permits and Total Maximum Daily Loads (TMDLs) Increases local property tax revenues due to higher home values
Homeowners	Increases property values Creates more pedestrian-friendly neighborhoods Provides open space for recreation Results in a more attractive landscape Reduces car speed on residential streets Promotes neighborhood designs that provide a sense of community
Environment	Protects sensitive forests, wetlands, and wildlife habitats Protects the quality of local streams and lakes Generates reduced loads of stormwater pollutants Allows more recharge of groundwater supply Helps reduce soil erosion during construction

BSD aims to protect and conserve natural areas, reduce impervious cover, and integrate stormwater management with site design. These principles can provide notable reductions in stormwater runoff rates, volumes, and pollutant loads. Also, they can reduce development costs and increase property values [16–18].

When applied to development design, BSD must be considered very early in the development process, and this has become one of the primary challenges to implementation, as most common land development projects tend to address stormwater and runoff very late in the process – once road and lot footprints have been established. The Smart Growth context is even more challenging, as existing (and often very old and decaying) drainage systems need to be reworked and retrofitted to become more functional for water quality protection.

Furthermore, many communities across the country have found that their own local “development rules” (e.g., subdivision ordinances, zoning ordinances, parking lot and street design standards) have prevented BSD techniques from being applied during the site planning and design process [14]. These communities have found that their codes and ordinances are responsible for the wide streets, expansive parking lots, and large lot subdivisions that are crowding out the very natural resources they are trying to protect. Examples include the minimum parking ratios that many communities require for retail or commercial development and zoning restrictions that limit conservation development designs. Common land use development regulations, codes, and policies influencing the creation of impervious cover (and that should be reviewed for consistency with BSD and Smart Growth goals) include [19]:

- *Zoning ordinance* specifies the type of land uses and intensity of those uses allowed on any given parcel. A zoning ordinance can dictate single-use, low-density zoning, which spreads development out throughout the watershed, creating excess impervious cover.
- *Subdivision codes* or ordinances specify specific development elements for a parcel, e.g., housing footprint minimums, distance from the house to the road, the width of the road, street configuration, open space requirements, and lot size, all of which can lead to excess impervious cover.
- *Street standards or road design guidelines* dictate the width of the road for expected traffic, turning radius, the distance for other roads to connect to each other, and intersection design requirements. Road widths, particularly in new neighborhood developments, tend to be too wide, creating considerable impervious cover.
- *Parking requirements* generally set the minimum, not maximum, number of parking spaces required for retail and office parking. Setting minimums leads to parking lots designed for peak demand periods, which can create acres of unused pavement during the rest of the year.
- *Minimum setback requirements* can spread development out by leading to longer driveways and larger lots. Establishing maximum setback lines for both residential and retail developments brings buildings closer to the street, reducing the impervious cover associated with long driveways, walkways, and parking lots.

- *Site coverage limits* can disperse the development footprint and make each parcel farther from its neighbor, leading to more streets and roads and thereby increasing total impervious cover throughout the watershed.
- *Height limitations* limit the number of floors for any building. Limiting height can spread development out if square footage cannot be met by vertical density.

To aid in the process of evaluating local codes and regulations, Appendix A provides a sample of questions that can be used with the goal of streamlining implementation of BSD. The questions are organized by general BSD categories of community planning, site planning and design, and reducing impervious cover. A more comprehensive analysis of local development regulations, with more concrete, in-depth questions should be conducted with the Codes and Ordinance Worksheet available in the *Better Site Design* manual [14] or a similar “green codes” tool.

Fortunately, communities have tools at their disposal to better integrate BSD and Smart Growth into local codes and policies. Appendix B provides a partial list of regulatory and site design and policy tools and strategies to consider when developing successful and robust local programs to achieve the goals of better growth patterns and fewer stormwater impacts by design.

This section addressed how BSD and other tools can help reduce stormwater impacts by design. However, this is only one step in a multistep process of stormwater design that also includes using a variety of structural and nonstructural practices in combination with site design and planning. The following section integrates the BSD approach with a more comprehensive design strategy with an acute focus on reducing stormwater volume – the issue of runoff reduction.

4 Reducing Stormwater Volume: A New Paradigm in Regulation and Design

Previous sections addressed the concepts of Better Site Design (BSD) and community land use and development strategies that can be used to reduce stormwater impacts by design, as well as the interrelated concept of Low-Impact Development (LID). LID addresses site design issues but provides a more holistic framework for understanding the hydrologic impacts of land development and replicating a more natural hydrologic response. This and the concept of “Green Infrastructure” stormwater practices are defining a new paradigm for stormwater management. A unifying concept of these approaches is using stormwater practices, integrated throughout a site, that help reduce the overall volume of stormwater generated by and leaving the site, along with the attendant pollutant loads and erosive forces for downstream channels.

In 2008, the Center for Watershed Protection (CWP) and the Chesapeake Stormwater Network (CSN) developed a site planning and computational approach, known as the runoff reduction method (RRM), that quantifies runoff (or volume)

reduction from development or redevelopment sites [20]. The practices employed in such a scenario are referred to as runoff reduction practices.

4.1 *Runoff Reduction Practices*

This section briefly describes and illustrates a list of practices represented in various stormwater design manuals and specifications [e.g., 21–25].

4.1.1 **Vegetated Filter Strips**

Vegetated filter strips are areas that manage runoff from adjacent developed areas by slowing the runoff and allowing sediment and pollutants to settle out, filtering runoff through the vegetation, and infiltrating into the existing or amended soils (Fig. 9). Applicable to small commercial and residential impervious areas, its critical design elements include maximum allowable contributing impervious area, slope, and minimum dimensions.

4.1.2 **Sheet Flow to Conservation Area**

Conservation areas are the “natural” alternatives to vegetated filter strips and consist of natural vegetation (e.g., forest, meadow) receiving runoff as sheet flow



Fig. 9 Vegetated filter strip (*Source*: first author)

from adjacent developed areas (Fig. 10). Often adjacent to streams or natural features, conservation areas should be protected with easements or other legal instruments to ensure that they function as a natural buffer system. As opposed to vegetated filter strips, conservation areas are outside the limits of disturbance and are not graded. Applicable in residential and commercial drainage areas, its critical design elements include maximum allowable contributing drainage area, slope, minimum dimensions, and long-term management of vegetation.

4.1.3 Simple Impervious Surface Disconnection

Simple impervious disconnection is a landscape practice that directs runoff from rooftops and other small areas of impervious surface to adjacent pervious areas as sheet flow (Fig. 11). Such areas are small scale (as compared to filter strips) and intended for residential or small commercial areas. Critical design elements include maximum allowable drainage area, slope, and minimum dimensions.

4.1.4 Impervious Disconnection with Alternative Practices

Impervious disconnection with alternative practices is utilized when there is insufficient room to establish sheet flow or meet other *simple impervious disconnection* criteria (Fig. 12). Alternative practices include soil amendments, residential rain gardens, rainwater harvesting, stormwater planters, and infiltration (covered separately in more detail below). Its effectiveness is based on the same performance



Fig. 10 Sheet flow to conservation area (Source: first author)



Fig. 11 Simple impervious surface disconnection (*Source: first author*)



Fig. 12 Impervious disconnection with alternative practice (*Source: second author*)

mechanisms as the individual practices. Critical design elements include the volume and depth of incorporation of soil amendments and design elements of the alternative practice.

4.1.5 Bioretention

Bioretention is a landscaped practice that uses plants, mulch, and soil to treat runoff (Fig. 13). The practice is commonly used in parking lot islands and edges and as part of commercial site plans. It can be designed as an infiltration practice or an extended filtration practice (with an underdrain). Critical design elements include surface ponding volume, soil media depth, and underdrain and several design variations.

4.1.6 Permeable Pavement

Permeable paving materials include concrete, asphalt, and interlocking pavers that allow runoff to filter through voids into a gravel storage reservoir (Fig. 14). It can be designed as an infiltration practice, an extended filtration practice (with an underdrain and stone sump), or a filtering practice (underdrain without sump). Critical design elements include structural load capacity for traffic, surface slope, and limiting the size of the “external” drainage area (adjacent impervious that “runs onto” the permeable pavement).

4.1.7 Grass Swale

Grass swales are designed as conveyance systems with enhanced design features to also provide a level of stormwater treatment and retention (Fig. 15). Designs can be



Fig. 13 Bioretention (Source: first author)



Fig. 14 Permeable pavement (*Source:* second author)



Fig. 15 Grass swale (*Source:* second author)

cost effective when used in place of curb and gutter, pipes, and other conveyance systems. Design features include maximum allowable longitudinal slope (or the use of check dams), maximum velocity and depth of flow, large storm conveyance, and trapezoidal cross-section geometry.

4.1.8 Infiltration

Infiltration practices utilize temporary surface or underground storage to allow incoming stormwater runoff to infiltrate into underlying soils (Fig. 16). Runoff first passes through multiple pretreatment mechanisms to trap sediment and organic matter before it reaches the practice. It can be designed as basin, trench, or small-scale practice. Key design features include runoff pretreatment, soil permeability testing, and subsoil conditions – such as groundwater. There are generally strict limitations on use at hot spots or brownfields.

4.1.9 Regenerative Stormwater Conveyance (RSC) System

The RSC system is an open-channel conveyance structure that encourages surface flow to transition to shallow groundwater flow through a series of step-pools and riffles and an underlying sand/mulch bed. It can be adapted for moderately steep slopes and used to retrofit existing degraded outfalls or for new development in some cases (Fig. 17). Critical design features include storage volume and peak flow design of riffles and pools, adequate energy dissipation and anchoring system, hydraulic design for large storms, and tying into existing stream channels.

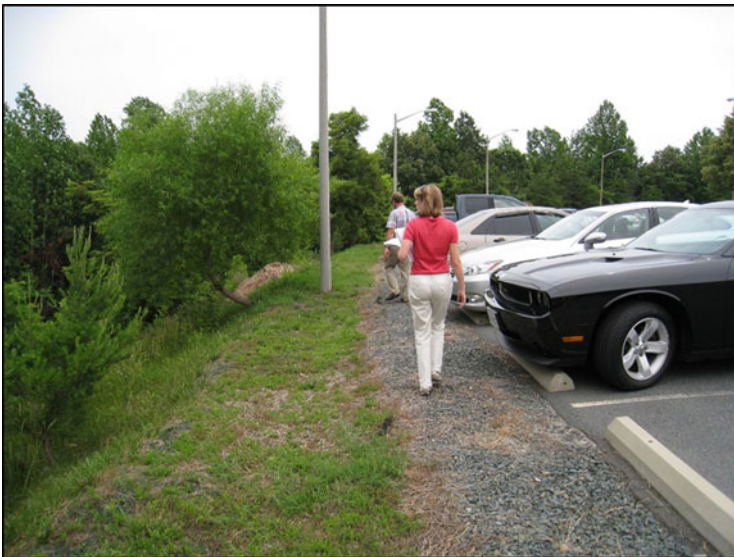


Fig. 16 Infiltration trench (*Source: first author*)



Fig. 17 Regenerative stormwater conveyance (Source: Center for Watershed Protection)

4.1.10 Rainwater Harvesting

Rainwater harvesting systems (RWH) provide for the capture, storage, and release of rainwater for future beneficial use, either inside or outside the building (Fig. 18). Systems usually capture rooftop runoff. Storage tanks can be a variety of materials and either above ground or underground. RWH is ideal for sites with a beneficial use of the water, such as irrigation, toilet flushing, cooling towers, vehicle washing, etc. Benefits include reducing the use of potable water for irrigation and other outdoor uses, flushing, etc. Design elements include establishing a reliable water budget and pretreatment. Rainwater harvesting is discussed more extensively in chapter “[Modern Rainwater Harvesting Systems: Design, Case Studies, Impacts](#)” of this volume.

4.1.11 Vegetated Roofs

Vegetated roofs are an alternative roof surface that typically consists of waterproofing and drainage materials and an engineered growing media that is designed to support plant growth (Fig. 19). Captures and temporarily stores stormwater within the growing media. Vegetated roofs provide significant life-cycle cost benefits to the building and the environment beyond the stormwater reduction. Vegetated roofs are discussed in more detail in chapter “[Sustainable Water Management in Green Roofs](#)” of this volume.

Ultimately, the choice of practices that a stormwater design professional may use for a particular application depends on meeting local and state standards and requirements to reduce peak flows, pollutant loads, and/or stormwater volumes.



Fig. 18 Rainwater harvesting (*Source: Center for Watershed Protection*)



Fig. 19 Vegetated roof (*Source: West Virginia (USA) Department of Environmental Protection*)

There are many different contexts for compliance, and, as states and local governments update their codes and design standards, the compliance goals change (see discussion in Sect. 2).

4.2 Steps for the Runoff Reduction Method (RRM)

The runoff reduction method (RRM) was originally developed for the Commonwealth of Virginia as a compliance framework for the state’s updated stormwater regulations that “encourage” the use of LID [20]. As a compliance tool, the RRM has also been adopted by a number of other states and local governments updating their stormwater design standards and practice specifications, all with variations in methodology and computation procedures [21–25]. This appears to be a growing trend in the USA and some other countries, as stormwater volume (and not just peak rate control) becomes an important metric for a more evolved approach to stormwater management. Figure 20 illustrates the RRM’s conceptual three-step compliance procedure that prioritizes BSD and runoff reduction practices, as described in more detail below.

Step 1: Apply BSD Practices to Minimize Impervious Cover, Grading, and Loss of Forest Cover The conceptual three-step RRM process starts with the intended LID goals of minimization and avoidance – avoid impacting the natural features that will continue to provide a hydrologic benefit in the developed landscape and minimize impervious cover and other site features that increase the runoff volume and peak discharge. This step focuses on implementing BSD practices during the early phases of site layout. The goal is to minimize impervious cover and mass grading and maximize retention of forest cover, natural areas, and undisturbed soils (especially those most conducive to landscape-scale infiltration). These strategies reduce stormwater volumes and impacts by design and thus are the most economical and require the least maintenance over time.

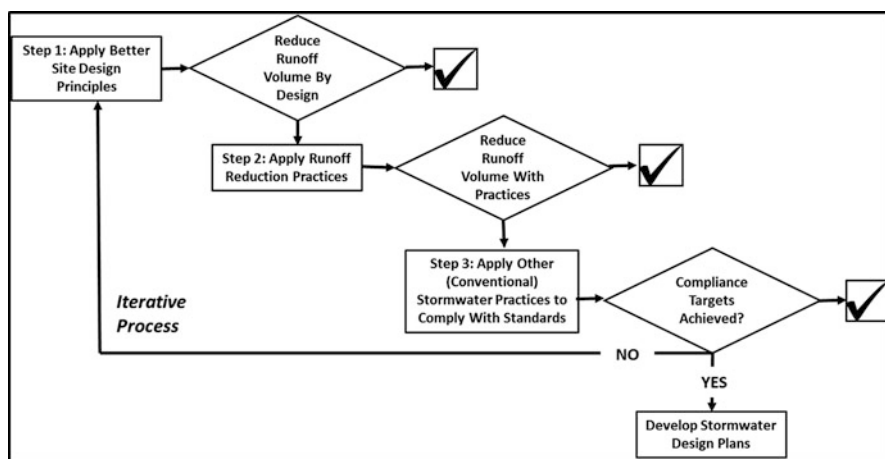


Fig. 20 Conceptual compliance flow path prioritizing Better Site Design and runoff reduction practices (Adapted from Hirschman et al. [20])

Step 2: Apply Runoff Reduction (RR) Practices The second step of RRM includes selecting runoff reduction practices that reduce runoff volume through canopy interception, soil infiltration, evaporation, transpiration, rainfall harvesting, engineered infiltration, or extended filtration. In this step, the designer experiments with combinations of the runoff reduction practices (described in previous sections above). In each case, the designer estimates the area to be treated by each practice to incrementally reduce the volume of runoff generated by the site. The designer is encouraged to use practices in series within individual drainage areas (such as rooftop disconnection to a grass swale to a bioretention area) in order to achieve a higher level of runoff reduction. A series of practices strung together in this manner is often referred to as a “treatment train.”

Step 3: Use Conventional Stormwater Practices as Needed Ideally, the compliance volume reduction target can be met using only steps 1 and 2. However, situations exist where volumes, detention, or storage targets cannot achieve full compliance. Step 3 involves selecting stormwater practices that, if needed, reduce the pollutant load further via pollutant removal process of settling, filtering, adsorption, and biological uptake. In these situations, the designer can select additional, conventional BMPs – such as sand or organic filters, wet and dry ponds, and stormwater wetlands – to meet the remaining load requirement.

In reality, the process is iterative for most sites. When compliance cannot be achieved on the first attempt, designers can return to prior steps to explore alternative combinations of BSD, runoff reduction practices, and conventional practices to achieve compliance. The runoff reduction performance of the stormwater management practices can also provide credit toward the channel protection requirements by reducing the volume of runoff and in some cases reducing the peak discharge of the targeted design storm as well.

As illustrated in the three-step process, a comprehensive or holistic approach to stormwater design will take advantage of all the multiple tools offered by site design and structural BMPs. Often, the best results can be achieved by using a variety of practices that each work to reduce volumes and pollutant loads using different processes [26]. A designer could choose to put three sand filters in series, one draining to the next. However, since all three practices rely on filtration as the treatment mechanism, the effectiveness of this “treatment train” will diminish with each subsequent practice in the chain.

A better approach would be to use a treatment train consisting of a vegetated swale (relying on biological uptake and infiltration), followed by a filter and then a pond or basin that uses settling as the main treatment mechanism. In this way, a variety of treatment mechanisms are at work to reduce pollutant loads and volumes. Table 2 provides a general overview of the various treatment mechanisms, in addition to runoff reduction, employed by commonly used stormwater practices.

Table 2 Stormwater pollutant removal processes (Adapted from [23, Table 3.3])

Removal process	Description and pollutants affected	BMPs
Gravitational separation (also settling or sedimentation)	Downward removal of solids denser than water and floatation removal of those lighter than water. Pollutants: sediment, solids (particulates associated with other pollutants such as nutrients and metals), oil (hydrocarbons), BOD, particulate COD	Cisterns, permeable pavement, grass swale, BMPs with ponding component, bioretention, regenerative stormwater conveyance system, filtration, stormwater wetlands, and wet and dry extended detention ponds
Filtering	Straining of pollutants by passing stormwater through a media finer than the target pollutants. Pollutants: solids, pathogens, particulate nutrients, particulate metals, BOD, particulate COD	Filtration, vegetated filter strips, bioretention, permeable pavement, grass swale, regenerative stormwater conveyance system, vegetated roof, stormwater wetlands
Infiltration	Passing stormwater downward through existing soils below the surface grade. Pollutants: volume, solids, pathogens, nutrients, metals, organics, BOD, particulate COD	Infiltration, vegetated filter strips, bioretention, permeable pavement, grass swale, regenerative stormwater conveyance system
Sorption	Includes adsorption and absorption – the physical molecular level attraction of a pollutant to media or soil particles. No chemical change (such as ion exchange) occurs. Pollutants: dissolved phosphorus, metals, and organics	Filtration, vegetated filter strips, bioretention, permeable pavement, grass swale, regenerative stormwater conveyance system, vegetated roof, stormwater wetlands
Biological uptake	Broadly termed transfer of substances from runoff to plants can include evapotranspiration. Pollutants: volume, hydrocarbons, nutrients, metals, organics, BOD, particulate COD	Vegetated filter strips, bioretention, grass swale, vegetated roof, stormwater wetlands
Ion exchange	Molecular exchange of one ion from the soil or filter media with an ion in the stormwater to remove pollutants; the ion from the media passes harmlessly through with the stormwater, while the pollutant remains sequestered in the media. Pollutants: metals	Filtration (depending on the media)
Chemical transformation	Process by which pollutants react with other compounds to change structure and are either harmlessly removed or sequestered. Pollutants: nitrogen (ammonia, nitrate, nitrite), organics, hydrocarbons	Filtration, vegetated filter strips, bioretention, permeable pavement, grass swale, regenerative stormwater conveyance system, vegetated roof, stormwater wetlands

4.3 Accounting for Runoff Reduction Capabilities of Various Practices

In order for the RRM to serve as a compliance tool, the runoff volume reduction capabilities for the range of stormwater practices had to be identified and quantified. During the development of the method, a literature search was performed to compile data on the runoff reduction capabilities for different stormwater practices [20]. Runoff reduction data were limited for most practices. However, many recent studies have started documenting runoff reduction performance. Based on the research findings, runoff reduction rates were assigned to various BMPs, as shown in Table 3.

In this context, runoff reduction is defined as the average annual runoff volume reduced through canopy interception, soil infiltration, evaporation, transpiration, rainfall harvesting, engineered infiltration, or extended filtration. This is important because many stormwater metrics are based on a design storm, so the average annual measurement is a bit different, and moderates the variability that would be witnessed seasonally or between different rainfall depths and intensities.

The range of values shown in Table 3 represents the median and 75th percentile runoff reduction rates based on the literature search. Several practices reflected moderate to high capabilities for reducing annual runoff volume. Others – including

Table 3 Average annual runoff reduction values for various stormwater practices (Adapted from [20])

Best management practice	Average annual runoff reduction ^a (%)
Vegetated filter strip	25–50 %, depending on soils, with A/B soils performing at the upper end
Sheet flow to conservation area	50–75 %, depending on soils, with A/B soils performing at the upper end
Simple impervious surface disconnection	25–50 %, depending on soils, with A/B soils performing at the upper end
Impervious surface disconnection with alternative practices	Variable, based on practice used
Bioretention	40–80 %; practices with underdrains at lower end; those that infiltrate into native soils at upper end
Permeable pavement	45–75 %; practices with underdrains at lower end, infiltrates into native soils at upper end
Grass swale	10–20 %
Infiltration	50–90 %
Regenerative stormwater conveyance	40–80 %, depending on soils, with A/B soils performing at the upper end ^b
Rainwater harvesting	Variable, depends on roof capture area, tank size, and beneficial use of water
Vegetated roof	45–60 %, depends on depth and storage of roof media
Dry extended detention pond	0–15 %

^aRunoff Reduction expressed as a percent reduction in the annual volume of runoff from rain events up to 1 inch (2.54 cm) [20] based on the practice design meeting up-to-date specifications, such as for Virginia and Washington, DC. Ranges indicate median and 75th percentile values

^bRunoff reduction assumed to be comparable to bioretention/amended media filter practices

Table 4 Design variations based on geographic and site conditions

Conditions and challenges	Design considerations
Ultra-urban, redevelopment, disturbed sites (e.g., brownfields): Sites where space for stormwater management is extremely limited and/or where previous contamination may limit excavation or use of soils for infiltration	Infiltration into the existing (disturbed or contaminated) soils is likely restricted. Practices may have to use impermeable liners, be shallow in profile, and tie into a storm drainage system. Permeable pavement, green roofs, bioretention planter boxes, and rainwater harvesting may be good options
Karst: Limestone or dolomite landforms characterized by potentially rapid movement of surface water down through solution channels; higher potential for contamination of wells, springs, and surface water	Large infiltration practices can create sinkholes or possibly contaminate down-gradient water supplies. It is advisable to conduct a predesign geophysical investigation to locate karst features and use small-scale, distributed practices to not concentrate too much water. Similar practices as listed above may be applicable
Coastal: Flat terrain, potentially high groundwater table, previously ditched and drained for agriculture	Excavation depths may be limited, such as for bioretention with an underdrain system. Shallow, vegetated practices are preferable. Permeable pavement, green roofs, and rainwater harvesting may be good choices, as well as retrofit of drainage ditches into meandering wetlands. Design should consider sea level rise and future conditions
Soils: Clay or tight soils that have inherently low infiltration rates	Many practices – such as bioretention and permeable pavement – can be outfitted with underdrain pipes that will allow the practices to function in marginal soils. Some infiltration is still likely to occur, even with clay or hydrologic soil group C soils

filtering, wet swales, wet ponds, and stormwater wetlands – were found to have a negligible effect on runoff volumes and were not assigned runoff reduction rates.

As the concepts of runoff reduction, LID, and Green Infrastructure began to take hold, many concerns were raised about feasibility, achievability, and affordability in different settings. Many locations were questioning whether these types of practices could be used in places with high groundwater table or depth to bedrock, karst topography, ultra-urban settings, and steep terrain. These legitimate concerns led to some innovations that allowed practice designs to be adapted to various land use and geographic settings, as outlined in Table 4. The table is not exhaustive as to the various challenging settings that one may confront when implementing these types of practices but is meant to be representative.

5 Stormwater Management as an Interdisciplinary Field

With the advent of a new set of strategies and design approaches (Better Site Design, Low-Impact Development) and a new suite of runoff reduction practices, the field of stormwater management is in a very dynamic period. Stormwater

management has emerged as a true multidisciplinary profession and is no longer the sole domain of engineers. Numerous university-based stormwater centers are training professionals in a variety of disciplines, including engineering, hydrology, landscape architecture, horticulture, soil science, geomorphology, land use planning, and ecosystem science.

Using bioretention as a typical example, Fig. 21 illustrates the typical construction sequence involved with installation of a bioretention practice. As demonstrated in this figure, many elements to this practice make it more complicated than the basins and ponds of the past. Layout must be fairly precise with regard to excavation depths and how the different layers are assembled. The specification, fabrication, and placement of the special engineered soil media require a high level of quality control. The practice is also characterized by installing a plant community that is not only pleasing aesthetically but that can survive in the unique wet and dry cycles of a bioretention and develop over time as a plant ecosystem. These, and other steps, are necessary for truly successful implementation of the practice.

The interdisciplinary element of modern stormwater management is what makes it both exciting and challenging, as various fields of knowledge must be leveraged



Fig. 21 Typical installation sequence for bioretention (Source: first author)

Table 5 Disciplines needed for successful design and installation of bioretention

Site assessment to inform design process	<p><i>Site planner or landscape architect</i> determines how the practice will fit into the site plan and avoid ecologically sensitive areas, such as mature tree stands, wetlands, streams and springs, existing vegetation</p> <p><i>Soil scientist</i> determines permeability and infiltration rate of on-site soils at proposed practice location</p> <p><i>Surveyor</i> produces base map and locates utilities, property boundaries, and other features</p>
Design	<p><i>Engineer</i> designs grading, materials, erosion and sediment control, and connection with existing storm sewer system</p> <p><i>Landscape architect, horticulturalist, or landscape designer</i> determines plant communities and species that best replicate local ecosystems and that will blend with the overall site</p> <p><i>Local government stormwater specialist</i> reviews and approves plan</p>
Supply materials	<p><i>Qualified materials' vendor</i> supplies stone, underdrain pipe, specialized bioretention soil media, mulch, erosion control matting, and other materials</p> <p><i>Plant nursery</i> supplies appropriate plant stock, preferably consisting of native species</p> <p><i>Certified laboratory</i> tests bioretention soil media to verify that it meets specifications for particle size and composition, performed as needed</p>
Installation of practice	<p><i>Qualified contractor</i> installs as per the design plans and specifications, as well as avoid compaction and handle materials properly</p> <p><i>Trained (and certified) inspector</i> represents the local government and/or owner to ensure that the practice is built according to the specifications</p> <p><i>Engineer of record and surveyor</i> certifies the practice is constructed according to the plan and to produce a record drawing or as-built plan</p>
Maintenance of the practice	<p><i>Trained (and certified) inspector</i> represents the local government and/or owner to conduct annual or periodic inspections and produce punch list of required actions to maintain practice performance and longevity</p> <p><i>Landscape contractor</i> maintains the plant community, removes invasive plants, and adds mulch, according to a preestablished maintenance plan</p> <p><i>Construction contractor</i> makes periodic more significant repairs involving grading, repairing components, or rebuilding the practice</p>

for projects, often with limited budgets and schedules. The multiple disciplines, identified above, will work on a collaborative basis, integrating ideas, practices, and implementation of BMPs. Many professions and professional societies are rising to the challenge by creating continuing education trainings and special subdisciplines with a stormwater focus.

Continuing with the bioretention example, Table 5 outlines the various facets of practice design, construction, and maintenance and the various disciplines that can

or should bring expertise to the project. Stormwater management has transcended its historical focus, and future success depends on continuing to build this interdisciplinary approach.

6 Emerging Forms of Regulatory Integration

The earliest incarnation of US EPA regulation of municipal stormwater management was the Phase I Municipal Separate Stormwater System (MS4) permit program finalized in 1990 [27]. The Phase II program was promulgated in 1999 and was more prescriptive in requiring programmatic goals to address impacts of stormwater, referred to as the six minimum control measures. Table 6 outlines the chief elements and differences between the Phase I and Phase II programs.

As US EPA’s experience in implementing the Clean Water Act evolved, there were opportunities to evaluate the various programs. The Phase I and Phase II MS4 permit programs combined with the industrial activity permits, including construction, were successful in identifying more discharges than US EPA and the state permit programs could handle. And while acknowledging that much progress had been made, US EPA also acknowledged that significant challenges to protecting waterbodies from the impacts of stormwater remained, noting that urban stormwater was the primary source of water quality impairment in 13 % of all rivers and streams, 18 % of all lakes, and 32 % of all estuaries.

To help identify solutions to this challenge, the US EPA requested that the US National Research Council (NRC) review its permitting program and offer suggestions for improvement. The following provides a very brief review of select

Table 6 US EPA National Pollutant Discharge Elimination System (NPDES) municipal stormwater program [27]

Phase I (finalized in 1990)	Phase II (finalized in 1999)
Regulates medium and large MS4s (defined as areas that serve 100,000 or more people) Ten categories of industrial operations Active construction sites of five acres or more	Regulates small MS4s located in an “urbanized area” as defined by the Bureau of Census Additional MS4s outside of UAs designated by the NPDES permitting authority Active construction activities disturbing between 1 and 5 acres
Requires: MS4s to develop and implement a stormwater management plan (SWMP) to: Find and eliminate illicit discharges Control discharges from its system by addressing runoff from active construction sites, new development and redevelopment, industrial program Construction and industrial stormwater dischargers to develop and implement stormwater pollution prevention plans (SWPPP)	Requires: MS4 SWMP must include six minimum control measures: Public education and outreach Public participation/involvement Illicit discharge detection and elimination Construction site runoff control Post-construction runoff control Pollution prevention/good housekeeping

recommendations from the report: *Urban Stormwater Management in the United States* [28]. The items covered here are those that could or already have influenced the delivery of local stormwater management programs. The report is over 600 pages, and this is in no way a review or summary of the entire report.

6.1 *Runoff Volume*

As described previously, the 15–20 years of stormwater management evolution had drifted through several stages before finally settling on the concept of runoff (volume) reduction through site design strategies and site-based stormwater management practices. One of the recommendations (among many) in the NRC report was to focus on targeting runoff volume as part of site development compliance requirements [28].

Emphasis on site design (nonstructural) BMPs that avoid or at least minimize the creation of runoff volume and the introduction of pollutants will reduce the mass pollutant load from developing lands. Emphasis on the runoff reduction BMPs that decrease surface runoff peak flow rates, volumes, and elevated flow durations caused by urbanization will likewise reduce pollutant loads. Expanding on that concept, the report identified benefits in using volume (or flow or impervious cover) as a surrogate measure of stormwater loading. Efforts to reduce the surrogate will automatically achieve reductions in pollutant loading, as well as stream channel erosion and sedimentation that adversely impacts surface water quality.

Establishing these more readily measured surrogate parameters as the regulatory target will help eliminate the technical and expensive challenges of regulating highly variable pollutant loading inputs from complex urban watersheds and individual dischargers. The report noted that these challenges have led to unreliable and ineffective monitoring and self-reporting.

However, the technical and regulatory climate of stormwater management has proven to be a more complicated arena. In January of 2013, a Federal Court in Virginia ruled that the US EPA exceeded its authority in establishing a flow-based total maximum daily load (TMDL) for Accotink Creek in Fairfax, Virginia [29]. The ruling stated that runoff and other “nonpollutants” could not be used as surrogates for pollutants to meet total maximum daily loads. In this case, flow was the surrogate for sediment loading in the stream. The ruling raised several questions since the flow was based on sediment rating curves, which ascertained the flow that could be generated within the watershed while still meeting the creek’s water quality standard.

The technical connection between the flow and the sediment loading may have been secondary to the extreme flow reductions that would have been required by the TMDL. The issues of reducing runoff volume and flows in a highly urbanized watershed are no more challenging than if the TMDL had targeted the sediment directly. Targeting volume or flow or even impervious cover would have provided

more readily available sources to retrofit and established a more direct path toward compliance.

6.2 Stormwater Quality and Quantity

In 2012, a review of state stormwater programs around the country was conducted for US EPA to identify the impact to states of adopting a volume retention standard as part of a potential national rulemaking process. The review revealed that 18 states had adopted a form of volume reduction or retention [30]. The review also revealed that, since the NPDES stormwater program does not include a quantity or channel protection standard, these strategies were largely absent from the state regulatory programs. In some cases, local watershed initiatives established local requirements that were not captured in the review.

In recognition of the demonstrated negative effects of watershed hydrologic modification on the attainment of beneficial uses, the NRC report recommended that the stormwater program embraces water quantity as a concern along with water quality [28].

6.2.1 Receiving Stream Health

The current local stormwater program regulatory framework includes a presumptive compliance associated with implementing site-specific practices in conjunction with development, along with other strategies of stormwater retrofitting and addressing discharges from municipal and industrial sources. The NRC report recommends that the programmatic implementation goals shift to a broader perspective of achieving a targeted condition in a biological indicator associated with aquatic ecosystem beneficial uses or no net increase in elevated flow duration [28].

6.2.2 Watershed-Based Permitting

The current NPDES permit program consists of a series of independent permits targeted toward different dischargers within the same watershed. Permits for municipal, construction, and industrial permits are implemented in “silos” that are independent of each other. The issuance and expiration dates are often on different schedules, and not all discharges are covered.

The NRC report recommends that a watershed-based approach be adopted to integrate all discharge permitting under the municipal authority. The lead and co-permittees would be responsible for collaborating on identifying the watershed goals and implementation plans for achieving compliance. Most importantly, the watershed approach would incorporate the full range of sources, including municipal storm sewer systems, municipal wastewater collection and treatment systems,

public streets and highways, industrial stormwater wastewater discharges, private residential and commercial property, and construction sites.

Appendix A

Typical questions for reviewing local regulations for compatibility with Better Site Design (BSD) and planning principles

Community planning	
Community planning, infill and redevelopment, smart growth	Does the community have incentives or other regulatory or non-regulatory means to promote infill and redevelopment in areas already served by infrastructure? In general, is it more or less difficult for developers to build in already developed areas versus greenfields?
Site planning and design	
Natural resources inventory	Is a natural resources inventory required or incentivized as part of the preliminary design? Does the community have a land conservation, open space, or green space plan with which individual development sites can integrate? Are there any incentives to developers or landowners to preserve land in a natural state (density bonuses, conservation easements, or lower property tax rates)?
Conservation of natural features	Is there a stream buffer ordinance in the community that provides for greater buffer requirements than the state minimums? Do the buffer requirements include lakes, freshwater and tidal wetlands, or steep slopes? Do the buffer requirements specify that at least part of the buffer be maintained with undisturbed vegetation? Does the community restrict or discourage development in the full build-out 100-year floodplain? Does the community restrict or discourage building on steep slopes?
Development design	Does the local permitting agency provide pre-application meetings, joint site visits, or technical assistance with site plans to help developers best fit their design concepts to the topography of the site and protect key site resources? Are there development requirements that limit the amount of land that can be cleared in a multiphase project? Does the community allow and/or promote planned unit developments (PUDs) which give the developer or site designer additional flexibility in site design? Are open space or cluster development designs allowed? Are the submittal or review requirements for open space designs greater than those for conventional development?

(continued)

	<p>Are flexible site design criteria (e.g., setbacks, road widths, lot sizes) available for developers who utilize open space or cluster design approaches?</p> <p>Does a minimum percentage of the open space have to be managed in an undisturbed natural condition?</p>
Tree conservation and tree canopy	<p>Does the community have a tree protection ordinance?</p> <p>Is a minimum percentage of a parking lot required to be landscaped and/or planted with trees?</p>
Management of open space, sustainable landscaping	<p>Does the community have enforceable requirements to establish associations that can effectively manage open space?</p> <p>Is there adequate guidance for the managers of open space (e.g., homeowners' associations) on how to select and manage vegetation in a sustainable manner?</p>
Community planning: reducing impervious cover	
Reducing roadway and right-of-way width and length	<p>Do road and street standards promote the most efficient site and street layouts that reduce overall street length?</p> <p>What is the minimum pavement width allowed for streets in low-density residential developments?</p>
Alternative roadway components	<p>What is the minimum radius allowed for cul-de-sacs?</p> <p>Can a landscaped island be created within a cul-de-sac?</p> <p>Are alternative turnarounds such as "hammerheads" allowed on short streets in low-density residential neighborhoods?</p> <p>Can "open-section" roads be utilized under certain conditions as an alternative to curb and gutter?</p>
Reducing paved parking and walking areas	<p>What are the minimum parking ratios for various development types?</p> <p>If mass transit is provided nearby, are parking ratios reduced?</p> <p>What is the minimum parking space size?</p> <p>What percentage of parking spaces are required to have smaller dimensions for compact cars?</p> <p>Is the use of shared parking arrangements promoted?</p> <p>Are there any incentives to developers to provide parking within structured decks or ramps rather than surface parking lots?</p> <p>Are there provisions or incentives for shared driveways, reduced setbacks to allow for shorter driveways, and/or use of permeable materials for driveways?</p> <p>Are sidewalk layouts (both sides vs. one side), widths, and materials gaged by the expected use of the sidewalk?</p>
Reducing building footprints	<p>Does the community provide options for taller buildings and structures which can reduce the overall impervious footprint of a development?</p>

Appendix B

Regulatory and site design/policy strategies to implement Better Site Design, Smart Growth, and better integration of land use with stormwater management

Adapted from Hirschman and Kosco [19]

Regulatory tools

Overlay zoning – a technique to “overlay” more protective standards over land with existing zoning. This procedure can be helpful to stormwater managers who need special protection in a discrete area within the watershed. Examples are drinking water supply watersheds, wellhead protection areas, areas subject to flooding, and watersheds for critical resources, such as wetlands and special recreational areas. The overlay zone typically designates allowable land uses and performance standards (see below)

Special use permits. In zoning codes, there are often two lists – allowable uses and uses allowed by special use permit. Stormwater managers might want to explore the use of special use permits to apply BMPs for certain uses (e.g., stormwater hot spots, direct discharges to wetlands)

Performance standards – usually associated with particular land use categories and can also be tied to special use permits, overlay zoning, and/or rezoning applications. Examples include minimization of clearing and grading, minimization of creation of new impervious surfaces, tree preservation or canopy targets, protection of riparian buffers, and septic system location and design

Special stormwater criteria are specifically tailored to discharges to sensitive receiving waters and likely reside in the stormwater ordinance and/or design manual. Examples include temperature control for trout streams, more aggressive nutrient management for drinking water supplies and wetlands, groundwater protection criteria for wellhead protection areas, special detention criteria for flood-prone areas, and pollution prevention measures for stormwater hot spots. (See Chap. 4 [19] for more detail on special stormwater criteria.)

Site design and policy tools

Compact development – seeks to meet a certain level of development intensity on a small footprint. Communities might seek this type of design to support walkability, transit station access, reduced infrastructure costs, or for water resource protection. Compact designs can be used in any development setting from ultra-urban retrofits to rural village centers

Street design. Many state departments of transportation are issuing “context-sensitive” alternatives for street design, including narrow streets and multiple transportation modes. For transportation planners, the narrow streets are aimed at slower speeds and neighborhood design models. Stormwater managers thus have overlapping interests in better street design

Utility planning. The rational and planned expansion of public water, sewer, and other utilities is critical for both land use planning and stormwater management. Utility extensions will likely encourage future growth at higher densities. Utility extensions should be planned for areas designated for infill, redevelopment, and future growth. On the other hand, utility restrictions should be considered for sensitive watersheds

Mixed-use development. Highly separated uses (e.g., retail, schools, housing, and employment centers) are implicated in highly dispersed development. A high degree of automobile-supporting infrastructure, which can be over 50 % of development-related imperviousness, is “built in” because walking and other modes of travel cannot be effectively supported. Bringing the uses closer together can lower the number and length of auto trips or support trip substitution. Less roadway and parking can translate into a lowered overall development footprint

Infill. Communities are increasingly interested in targeting development to areas where the surrounding land is already developed and served by public utilities. An example is developing housing surrounding a mall or office park. This “infilling” can satisfy a high degree of development demand in an efficient manner

(continued)

Redevelopment. One of the strongest watershed strategies is reusing (and improving) vacant or underused sites that are already under impervious cover. This can also work for abandoned sites in rural areas as well. Programs such as downtown revitalization, Main Street programs, and brownfield redevelopment programs support these efforts

Conservation development is a strategy that can work in various development contexts (e.g., urban, suburban) to coordinate and conserve open space. For stormwater, a particular emphasis may be placed on riparian buffers, forest protection, and open space areas that capture and disperse runoff

Purchase and transfer of development rights (PDR, TDR). PDR programs purchase development rights from landowners and are particularly targeted to areas or watersheds where rural character and natural resources should be protected. TDR programs set up development rights markets whereby some landowners (in rural or sensitive watersheds) can sell their development rights to landowners in areas where growth, infill, and redevelopment are encouraged

Fee-in-lieu programs for stormwater. In certain areas, stormwater management goals cannot be met solely with on-site stormwater BMPs. Watershed-based approaches are needed to address issues that extend beyond the site boundary. Examples would be areas with existing flooding or drainage problems, impaired watersheds, and watersheds with streambank erosion problems. In these cases, a fee-in-lieu payment or offset fee can be collected from developers to partially offset full on-site compliance. The local stormwater program then uses the accumulated fees to conduct needed watershed repairs and improvements (See Chap. 4 [19] for more information on watershed-based stormwater management approaches and criteria).

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