Chapter 8
LOW IMPACT DEVELOPMENT MONITORING

Low Impact Development (LID) is a stormwater management strategy that can be used to reduce runoff and pollutant loadings by managing runoff close to its source. The purpose of the LID monitoring guidance in this Manual is two-fold:

1) to provide monitoring guidance to evaluate hydrologic and water quality related performance of LID sites; and

2) to develop an initial standard protocol that compares the performance of LID studies to each other and to traditional stormwater Best Management Practice (BMP) monitoring studies.

The topics addressed in this chapter include an introduction to basic LID concepts, strategies for monitoring LID sites, and guidance on how to collect and report data. Information about how to interpret and evaluate LID monitoring data is included in Chapter 9. Selected LID monitoring case studies are included in Chapter 10.

Note: The term “green infrastructure” is commonly used to describe LID practices that are used in urban environments. For the purpose of this manual, the terms “green infrastructure” and “LID” are used interchangeably.

8.1 Introduction to LID

8.1.1 Basic LID Concepts

LID is an approach to stormwater management that seeks to minimize the potential adverse physical and chemical impacts of urban runoff by managing runoff close to its source. The Low Impact Development Center provides this description of LID:

> LID is an innovative stormwater management approach with a basic principle that is modeled after nature: manage rainfall at the source using uniformly distributed decentralized micro-scale controls. LID's goal is to mimic a site's predevelopment hydrology by using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source. Techniques are based on the premise that stormwater management should not be seen as stormwater disposal. Instead of conveying and managing/treating stormwater in large, costly end-of-pipe facilities located at the bottom of drainage areas, LID addresses stormwater through small, cost-effective landscape features located at the lot level. These landscape features, known as Integrated Management Practices (IMPs), are the building blocks of LID. Almost all components of the urban environment have the potential to serve as an IMP. This includes not only open space, but also rooftops, streetscapes, parking lots, sidewalks, and

medians. LID is a versatile approach that can be applied equally well to new development, urban retrofits, and redevelopment revitalization projects (http://www.lid-stormwater.net).

Exhibit 8-1. Other Resources for More Information on LID

U.S. Environmental Protection Agency Low Impact Development Web Page: http://www.epa.gov/owow/nps/lid/

Low Impact Development Center: http://www.lowimpactdevelopment.org/

University of New Hampshire Stormwater Center: http://www.unh.edu/erg/cstev/

National LID Clearinghouse: http://www.lid-stormwater.net/clearinghouse/index.html

North Carolina State University/North Carolina Cooperative Extension Stormwater Engineering Group: http://www.bae.ncsu.edu/stormwater/

Puget Sound Partnership Resource Center: http://www.psparchives.com/our_work/stormwater/lid.htm

Villanova Urban Stormwater Partnership: http://www.villanova.edu/vusp/

Prince George's County, Maryland: http://www.goprincegeorgescounty.com/government/agencyindex/der/lid/bioretention.asp

Jordan Cove Urban Watershed Project: http://www.jordancove.uconn.edu/jordan_cove/about.html

Street Edge Alternatives (SEA Streets) Project: http://www.seattle.gov/UTIL/About_SPU/Drainage_&_Sewer_System/Natural_Drainage_Systems/Street_Edge_Alternatives/index.asp

National Academy of Sciences, National Research Council Report: *Urban Stormwater Management in the United States*: http://www.nationalacademies.org/morenews/20081015.html

Exhibit 8-1 provides an overview of key websites that can be referenced for more information on LID concepts, design guidance, existing studies, and ongoing research.

While many of the individual LID techniques are comparable to some types of traditional stormwater BMPs, LID is an overall design philosophy based on the implementation of multiple, distributed small-scale controls throughout a development site. Exhibit 8-2 compares some LID practices to traditional stormwater BMPs. Guidance provided in Chapters 2 through 7 of this manual can generally be followed when monitoring individual LID BMPs. However, effectively monitoring overall LID sites can offer a unique challenge and is the focus of this chapter. To more clearly illustrate the differences between monitoring individual practices and monitoring at the site level, the following specific descriptions are provided:

1) Individual LID Practice Monitoring: In this case, an individual LID practice (e.g., a bioretention cell, a biofilter, infiltration basin, or permeable pavement parking lot) is isolated to monitor performance. This may also include monitoring a combination of practices in series such as a biofilter preceding a bioretention cell in a parking lot. These types of monitoring programs can generally follow the guidance previously provided in Chapters 2 through 7 of this manual, with particular attention to designing studies in a manner that incorporates a robust

hydrologic monitoring component and properly addresses the challenges that come with monitoring small watersheds with often poorly defined inflow and outflow monitoring stations. A number of studies exist that demonstrate individual LID practice monitoring approaches (e.g., Hunt et al. 2008, Davis 2008, Emerson and Traver 2008, Barrett et al. 2006, Roseen et al. 2006 and 2009, Li et al. 2009).

2) Overall Site Level LID Monitoring: In this case, the composite site level performance, which includes multiple distributed controls, is monitored. An example of a monitoring study of this type is the approximately 12-acre Somerset Development in Maryland (Cheng et al. 2003). Due to the varying types, number, and spatial distribution of the LID practices, and more importantly the lack of specific discharge locations, these types of monitoring study designs can present significant challenges to the researcher. In some cases, modifications to the drainage system must be made, either in the design phase or as a post-construction retrofit, to facilitate effective monitoring. Historically, reference or "parallel" watershed study designs have often been used to assess performance at the site level. Alternatively, "before and after" studies can provide very useful insight into how well a LID site is performing relative to pre-development hydrology, which is the fundamental stated goal for LID development and retrofit projects.

3) Hybrid LID-Traditional Site Level Monitoring: In this case, a site to be monitored may include multiple distributed controls and LID principles, but it may also incorporate some traditional larger-scale stormwater management components at the downstream end of the study site, particularly for flood control. For example, a study by Selbig and Bannerman (2008) involves a Cross Plains, Wisconsin LID site with multiple distributed controls and a larger-scale infiltration basin located at the downstream end of the drainage. Retrofits of existing subdivisions would often fall into this category. Historic approaches to monitoring these types of sites are similar to those for the overall LID-based site development described above. These types of sites may be more straightforward to monitor relative to the overall LID-based sites because there is often a centralized discharge point to facilitate sample collection.

Exhibit 8-2. Relationship between LID and Traditional Stormwater BMP Terminology

LID Practice	**Traditional Stormwater Practices** *(included in 1999 Release of BMP Database)*
Bioswale	Grass Filter Strip and Swale
Bioretention Cell[1]/Rain Garden	Vegetated Media Filter/Vegetated Infiltration Basin
Infiltration Basin	Infiltration Basin
Infiltration Trench, Seepage Pit	Percolation Trench and Dry Well

[1]Bioretention is used to refer to systems with and without underdrains. Systems with underdrains discharge predominantly to the downstream stormwater conveyance system, but may promote incidental volume reduction through infiltration below underdrains and soil soaking and drying. Systems without underdrains discharge primarily to groundwater or evapotranspiration, not to the downstream conveyance system. These systems may fill up and bypass, but have no other surface discharges.

LID Practice	**Traditional Stormwater Practices** *(included in 1999 Release of BMP Database)*
Wet swale	Wetland Channel and Swale
Stormwater Wetland Pocket Wetland	Wetland Basin
Porous Pavement (multiple types)	Porous Pavement (multiple types)
Tree Planter Downspout Planter Box	Vegetated Media Filter
Green Roof	
Rain Barrel/Cistern	Detention/Retention (Tank)
Manufactured Devices (not typically classified as LID, but can provide pre-treatment as part of an LID treatment train)	Manufactured Device: media filtration units
	Other Manufactured Devices: oil/grease separator, hydrodynamic separator, swirl concentrator
Non-structural Practices (e.g., education, source controls)	Non-structural Practices (e.g., education, source controls)
Site Design Practices (e.g., narrow streets, reduced imperviousness, minimal curb and gutter, open drainage, preserving natural areas)	Some Site Design Concept (e.g., "Minimizing Directly Connected Impervious Area," "Disconnecting Hydraulically Connected Impervious Area")

8.1.2 What Distinguishes a LID Site?

LID sites can be characterized based on overall approach to site design and typical design features, with several common features described below.

Site Planning

Site planning is a key element of the LID sites and is often what fundamentally distinguishes new LID developments from their traditional counterparts. Site planning for LID sites will typically include one or more of the following elements:

- Conservation and Minimizing Disturbance: Preserve natural infiltrative characteristics of the soils by minimizing disturbance and avoiding compaction throughout project phasing and construction sequences.

- Minimizing Building and Travelway Coverage: When constructing buildings on site, minimize impervious rooftops and building footprints. For travelways, this includes constructing streets, driveways, sidewalks, and parking lot aisles to the minimum widths necessary, provided that fire protection access, adequate parking, public safety and a walkable environment for pedestrians are not compromised.

- Maintaining Natural Drainage Patterns and Designing Drainage Paths to Increase Time of Concentration: Key elements include: maintaining depressions and natural swales; emphasizing sheet flow instead of concentrated flow; increasing the number and lengths of flow paths; maximizing non-hardened drainage conveyances; and

maximizing vegetation in areas that generate and convey runoff. This group of practices often includes eliminating curbs and gutters or including curb cuts to allow runoff to enter LID practices, such as roadside swales, bioretention areas, or infiltration trenches.

- Source Controls: These practices include: minimizing pollutants; isolating pollutants from contact with rainfall or runoff by segregating, covering, containing, and/or enclosing pollutant-generating materials, wastes, and activities; and conserving water to reduce non-stormwater discharges.

- Specific LID Techniques: Common techniques used at LID sites include permeable pavements, natural drainage system elements, stormwater harvesting, and green roofs. (These are discussed separately below.)

For example, a LID site may be a several acre mixed urban community that includes high density cluster development with green roofs on multifamily homes, downspout planter boxes or rain gardens in commercial landscaped areas, permeable pavement on driveways and sidewalks, and residential roads having no curbs or gutters with vegetated swales.

Given the distributed nature of these controls and practices, LID monitoring approaches must be carefully developed in order to provide meaningful data within a reasonable budget. In many cases it is not realistic to monitor the performance of each individual practice. This is one of the key reasons that overall LID site monitoring often compares LID site hydrology and water quality to that of one or more reference watersheds. Exhibit 8-3 shows a side-by-side comparison of a traditional development and an LID-based development. As can be seen in the exhibit, the LID site is fundamentally different from a planning perspective and incorporates conservation of open space and preservation of native vegetation, and minimizes the disturbed area of the development.

Exhibit 8-3. Traditional versus LID Development Comparison (PSAT, 2005)

The LID site shown in Exhibit 8-3 also illustrates the integration of traditional BMPs in an overall LID scheme. A vegetated pond is provided near the outlet of the catchment, complementing LID site design principles and on-site stormwater controls by capturing and treating water that cannot be captured and eliminated at the lot level.

Typical Design Features

Inherently the design of low impact developments and retrofit projects is a creative process and is quite site specific; however, a number of typical features are consistently incorporated into many designs including:

- Natural Drainage System Elements/Vegetated Infiltration/Filtration Features: Infiltration practices are used to directly route runoff to the subsurface where it is temporarily held in pore spaces before evaporating from surface soils, transpiring from vegetation, percolating down to the groundwater table, or discharging via interflow. One way to do this is through bioretention cells or rain gardens that are designed to capture sheet flow and hold it in the pores of amended soil and shallow surface storage before the captured water percolates to groundwater or evapotranspirates. These systems provide significant protection of groundwater quality by facilitating contact with amended soils before percolation to groundwater. Vegetated practices can also be used; these focus more on evapotranspiration processes by incorporating absorptive soils (e.g., peat) and dense vegetation. Vegetation can also keep the top layer of soil stable and open for infiltration. Bioswales and vegetated filter strips can also treat stormwater in a similar way, but they do not typically have appreciable surface storage and often receive runoff along their entire length. Another way is through planter boxes which are structural units that intercept runoff along a curb or from a roof downspout. While these devices can be easier to implement in ultra-urban retrofit situations and effectively delay the hydrograph response, the volume reductions may not be significant if the device includes an underdrain connected to the storm drain system.

- Green Roofs and Green Facades: Green roofs and green facades are increasingly common. These design features contain a specially engineered, light-weight media that supports vegetative growth—typically short, drought- and temperature-resistant grasses in a variety of forms. The green roof media and vegetation have the potential to store and evapotranspire precipitation, as well as reduce peak flows through temporary storage. Green roofs and facades have many additional benefits including significant reductions in urban heat island effects.

- Cisterns/Rain Barrels/Rainwater Harvesting: These features can be used to alter runoff timing and reduce peak flows and decrease runoff volumes where reuse is effectively incorporated into the design. Typically, runoff from traditional roofs can be diverted and collected in rain barrels or cisterns, where legally permissible. (In some parts of the country, water rights constraints limit this practice.) This practice reduces runoff volume while storing water for future non-potable uses such as irrigation. When using this technique, barrels should be screened to intercept debris and control mosquitoes, or the water should be directed to an infiltration basin or rain garden to recharge groundwater.

- Permeable Pavements, Pavers, and Permeable Overlays: Parking lots and roadways contribute a significant portion of the runoff from a typical development area. Pervious pavements and paver systems are designed to allow stormwater to percolate or infiltrate through the surface into the soil below or to filter runoff through a subsurface media thereby reducing runoff volumes, decreasing peak flow rates, and improving water quality.

8.1.3 LID Monitoring Philosophy

LID monitoring is currently (late 2009) in its infancy and continues to evolve as LID practices and site designs are implemented in more communities. The majority of the currently completed or published LID studies focus on monitoring individual LID practices, such as a single bioretention cell or a single green roof on a building to identify and understand the mechanisms governing treatment and to assess performance of the individual practice. Although the specifics of monitoring individual LID practices can present significant challenges, the means and methods are fundamentally similar to approaches for monitoring more conventional systems.

Fundamentally, the overall goal of incorporating LID into developments is to affect the ways in which overall site design and implementation impact hydrology and water quality. It is this level of monitoring for which there is not currently adequate guidance. It is the intent of this chapter to focus on this site level monitoring and to suggest approaches to assess the collective effects at this scale. A number of researchers have realized the critical importance of assessing the performance of LID sites at this scale. Several studies of this nature are listed in Exhibit 8-4 and discussed further in Chapter 10.

As a general starting point, LID monitoring at the site level typically follows a reference watershed approach (Clausen and Spooner 1993) where one or more of the watersheds acts as a control (undeveloped or conventional treatment watershed) for which a baseline for

comparison is formed, and the other watershed represents the treatment (LID treatment watershed) to be analyzed. (Use of the reference watershed approach is discussed in more detail below in Section 8.2.2.) "Nested" monitoring may also be conducted where individual LID practices within the catchment are monitored in addition to the overall watershed whereby providing a means to differentiate normal watershed processes and the effects of individual LID practices. Because of these multiple layers of potential complexity and high number of watershed variables involved in this type of monitoring, it is particularly critical that substantial forethought and planning be completed to clearly identify the objectives of the monitoring project.

In addition to reference watershed studies, "before and after" studies have a great deal of merit for LID site level monitoring as they provide experimental control for a host of variables in the study design. Depending on the goals of the monitoring project, detailed analysis of high frequency and accurate intra-storm data in "before and after" studies may be critical for obtaining information needed to evaluate the likely long-term performance of LID sites.

The seven planning steps described in Chapter 2 should be followed along with the additional guidance presented in this chapter in order to set realistic monitoring program goals and execute the program in an efficient and cost effective manner. In shaping a monitoring program, it is helpful to be aware of some of the common challenges associated with monitoring LID at the overall development scale.

Exhibit 8-4. Past and/or Current Catchment Scale LID Monitoring Studies

Study Location	Study Overview	Source
Jordan Cove, CT	One control and two treatment watersheds (conventional and LID). Low density single family residential. Evaluated construction-phase and post-construction runoff water quantity and quality.	University of Connecticut. http://www.cag.uconn.edu/nrme/jordancove/
Cross Plains, WI	Before/After, Control/Impact study. Treatment watershed included LID practices on-site and detention and infiltration basin at outlet. Monitored several years of runoff water quantity and quality.	Selbig and Bannerman 2008. http://pubs.usgs.gov/sir/2008/5008/
Somerset, MD	One control and one treatment watershed. Limited LID in treatment watershed. Monitored in parallel for two years at time of publication. Monitored flowrate and water quality	Cheng et al. 2003. http://www.scdhec.gov/environment/water/lid/pdf/somerset.pdf
Burnsville, MN	One control and one treatment watershed. Monitored in parallel without retrofit for calibration period, then retrofit treatment watershed with bioretention. Monitored flowrate and volume only.	Barr Engineering 2006. http://www.co.dakota.mn.us/EnvironmentRoads/EnvirProtect/Stormwater/LID.htm

8.1.4 Site Level LID Monitoring Challenges

Site level LID monitoring presents a number of different challenges above and beyond those already present in traditional BMP monitoring. Traditional stormwater designs typically direct flows to a central location that is designed to store and slowly release flows, often with defined inlets and outlets. This is not the case with many LID systems. The multitude of discharge locations and distributed nature of the controls often does not present an opportunity to select a single monitoring point sufficient to assess site hydrology and water quality. A variety of other challenging factors which may be present on an LID site are listed below.

1) The limits of the "site" may be difficult to define.
2) The extent of LID implementation at the site must be quantified in order to compare results to other sites.
3) Concentrated flow discharge locations may be hard to define or not present.
4) Watershed boundaries may change as a function of factors such as rainfall intensity, antecedent soil moisture conditions, season, winter conditions, and so on.
5) Run-on from uphill areas may commingling with flows from the site.
6) Events may produce no discharge or very low discharge during small events.
7) Soil moisture and antecedent conditions play a critical role in performance.
8) Surface and subsurface conditions across the site may have a high degree of spatial variability.
9) Groundwater/vadose zone monitoring may be necessary to evaluate the overall site water balance and evaluate groundwater contamination potential.
10) Evapotranspiration can be a critical performance factor and is understood to vary as a function of climate and weather.
11) Infiltration rates can be a critical performance factor and is understood to vary with temperature, including the effects of freezing on facility operation.
12) Vegetation characteristic exhibit seasonal variations.
13) Performance is understood to be highly dependent maintenance status.
14) It is often difficult to identify a reference watershed that shares common physical characteristics and is in close proximity. Inevitable differences between the reference and the test watersheds must be accounted for.
15) Greater quantities of data may be needed to achieve statistical significance considering the large number of variables influencing the performance of overall LID sites.

8.2 Monitoring Study Design for LID Projects

Monitoring design for LID projects shares many similarities with traditional monitoring projects. However, a few key differences exist. The most fundamental difference is that LID monitoring may occur at both the practice level and the site level. Exhibit 8-5 shows examples of possible LID monitoring locations in comparison to typical BMP monitoring locations. It also illustrates the concept of practice level and site level monitoring.

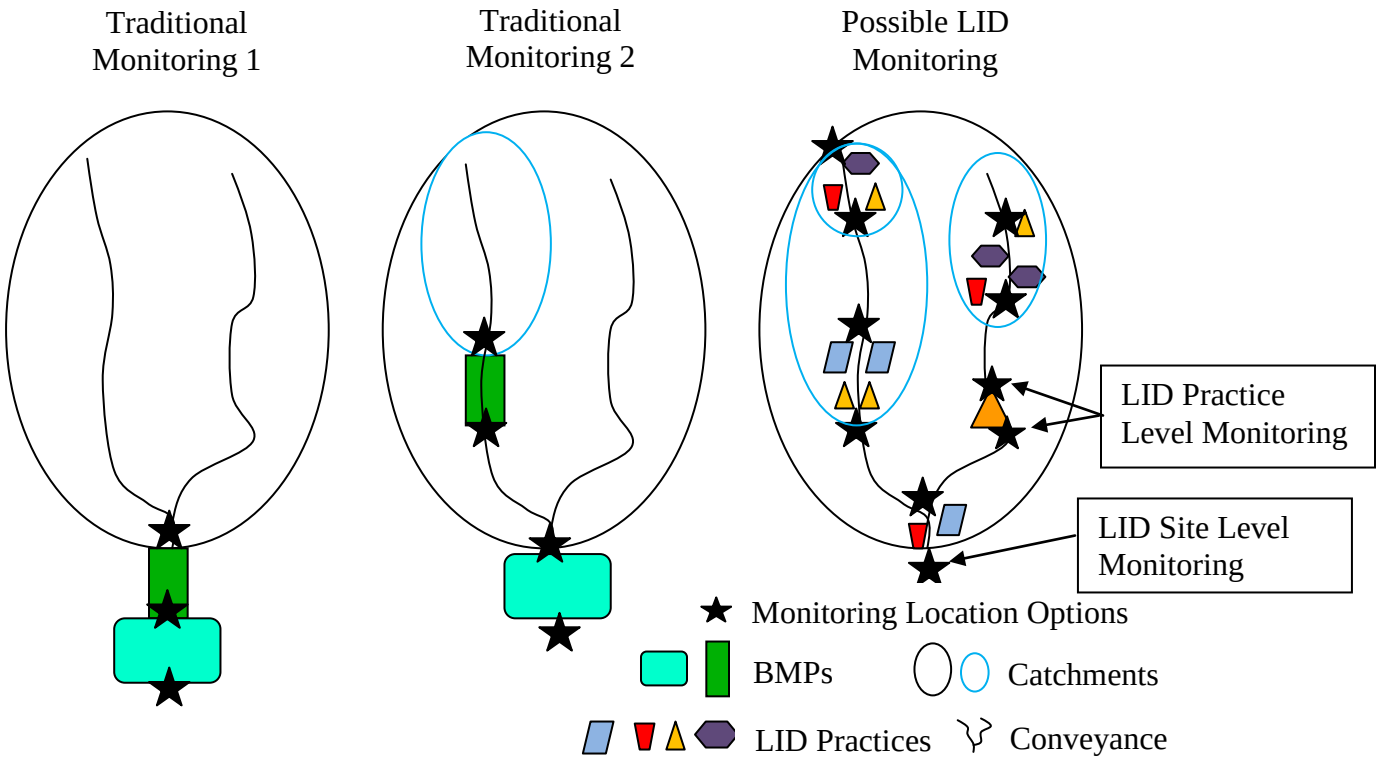


Exhibit 8-5. Examples of Traditional versus Possible LID Monitoring Project Design

This chapter extensively references elements of Chapters 1 through 7 as practice level monitoring is similar to traditional monitoring. The most significant difference between LID practice level monitoring and traditional monitoring is the nature of the practice. LID practices tend to be more focused on site hydrology as they are more dependent on natural processes such as infiltration and evapotranspiration. Because of this, study objectives may slightly differ from traditional studies.

Site level monitoring is different than traditional monitoring, primarily in its spatial scale and study objectives. Traditional monitoring has a readily-available baseline (i.e. the BMP influent) whereas the “influent” to an LID site cannot typically be monitored.

8.2.1 LID Monitoring Study Objectives

The study objectives listed in Chapter 2 are generally applicable or adaptable to LID studies, particularly to practice level studies. The following list is adapted for practice level and site level LID studies (Exhibit 8-6).

Exhibit 8-6. Typical Study Objectives for Practice and Site Level LID Monitoring Studies

Practice Level LID	Site Level LID
How does the hydrology for developed conditions compare with pre-development hydrology in terms of peak flow rates, runoff volume, peak timing, site infiltration capacity, site water balance, and so on?	
What degree of pollution control or effluent quality does the LID practice provide under normal conditions (i.e., representative storm types)?	To what extent does the LID site reduce the concentration of pollutants compared to a site without LID practices under normal conditions (i.e., representative storm types)?
How does this performance vary from pollutant to pollutant?	
How does this normal performance vary with large or small storm events?	
How does this normal performance vary with rainfall intensity?	
How do LID practice design variables affect performance?	How does the combination of LID practices present on a site and the design parameters of these practices affect performance of the site as a whole?
How does performance vary with different operational and/or maintenance approaches?	
Does performance improve, decay, or remain stable over time?	
Does performance vary seasonally? (For example, to what extent is infiltration capacity reduced during cold temperatures?)	
How does this LID practice's performance compare to the performance of other LID practices?	How does this LID site's performance compare to the performance of other LID sites?
How does this LID practice's performance compare to the performance of other types of BMPs?	How does this LID site's performance compare to the performance of other types of BMPs?
Does this LID practice help achieve compliance with water quality standards?	Does this combination of LID practices help achieve compliance with water quality standards?

Ultimately, the study design attempts to answer these questions by obtaining data that can be used to characterize (at least partially) the monitored system as well as interpreted or

extrapolated to quantify (at least partially) one or more of the fundamental descriptions of system performance. Fundamental elements of system characterization include:

- The physical properties of the system as they relate to hydrologic response and water quality
- The conditions of the system at the time of monitoring
- The operation of the system

Fundamental descriptors of system performance include:

- The long-term water balance of the system
- Cumulative flow duration, flow frequency, volume frequency, and other statistical descriptions of aggregate hydrologic response
- Representative distributions of concentrations and frequency patterns of concentration
- Long-term average pollutant loadings and distribution of pollutant loading
- Trends in each of these descriptors by season, maintenance considerations (i.e. time since maintenance, frequency of maintenance), and/or age of system

It is impossible to completely characterize or describe performance of any system; however well-defined systems with limited monitoring points generally are more fully described than systems with less defined inflows and outflows like those found in LID systems. LID monitoring studies typically use surrogate metrics to attempt to partially characterize the system and partially describe performance. Chapters 1 through 7 describe the metrics that are recommended to characterize practice level studies and interpret results. This section describes the metrics that are recommended to be collected to characterize LID sites. Chapter 9 discusses the interpretation of results as they relate to fundamental descriptions of system performance.

8.2.2 Use of Reference Watersheds

When monitoring LID at the site level, performance can be assessed by comparing hydrologic and water quality characteristics from the LID site to one or more reference watershed conditions. Reference watersheds may include the following:

1) <u>Before-After/Control-Impact (BACI)</u>: This monitoring strategy compares a LID site to a control site, using either or both of these approaches:

    a. The Before-After approach involves monitoring a proposed development site before development of the site using LID and comparing those conditions after development. The “before” time period can be referred to as the “calibration” period and must span enough time to obtain a reasonably characteristic hydrologic record of the site. After development using LID, a

comparable hydrologic monitoring time period is needed to compare the "before and after" watershed response to storm events. Challenges associated with this type of monitoring strategy include the time and cost associated with monitoring to develop an adequate hydrologic record; Clausen (2007) has recommended a minimum of 5 to 10 years.

b. The Control-Impact approach involves selecting a control watershed in a nearby comparable undeveloped watershed and monitoring the "control" and the "impact" simultaneously. Rather than comparing conditions "in time," this approach compares hydrologic performance "in space." While this approach may require less time, it is essential that the control watershed has similar characteristics (e.g., steam order, average slope, canopy, soils, size, and location) to the "impact" watershed prior to LID implementation. Finding an identical watershed is not realistic, so it is important to carefully document differences between the control and impact watersheds and adjust conclusions accordingly.

2) Comparison of traditional and LID developments: In this monitoring strategy, two watersheds with comparable pre-development characteristics are developed with comparable land use; one site is developed using traditional development techniques while the other site is developed using LID techniques. The performance of the two sites can then be compared. When using this technique, it is important to monitor response to a variety of storms (both large and small) so that premature conclusions are not drawn regarding performance of either location.

3) Comparison of a LID retrofit watershed to pre-retrofit conditions: This monitoring strategy is a variation of the approach described above in number two where sites developed with LID techniques are compared to other traditional developments. While sites developed with LID techniques can be compared to other traditional developments as described, it may be most direct and beneficial to compare LID retrofits to pre-retrofit conditions. It is important to characterize the site as a retrofit in study documentation as the extent of LID practice implementation may be restricted relative to a new development implementation of LID.

4) Multiple Techniques: Using a combination of all three monitoring strategies described above is another monitoring approach that can be used in LID site level studies. This combination of strategies can lead to the most robust conclusions about the LID site performance as evidenced in the Cross Plains, WI case study described in Chapter 10. In that study, the LID site is compared to the pre-development hydrology at the site and a nearby traditional development.

It is proposed by the authors that collection of high resolution hydrologic data during a relatively small number of events with adequate variation in precipitation volume, intensity, and antecedent conditions may, in some cases, provide adequate information for accurately predicting long-term hydrologic performance of systems under pre-development, pre-retrofit

and LID conditions. The key to this approach is to use continuous datasets to carefully calibrate and validate hydrologic models of the systems, and then to use longer regional datasets to estimate performance over the long term. It is anticipated that this approach would work quite well for watersheds with short times of concentration in the "before" condition of retrofit projects (e.g., rooftops, parking lots, roadways, other retrofit projects), and for more controlled LID implementations such as green roofs, cisterns, and planter boxes. The applicability of this approach for less defined systems such as disconnected imperviousness, bioretention cells, and so on would be dependent on the ability to measure the performance of these systems accurately and the ability of the selected model to adequately represent the important processes in these systems. This approach should be explored as the practice of monitoring LID sites evolves.

Ultimately, the type of monitoring study designed is based on study objectives and project constraints. For example, if the research objective is to determine how well post-development conditions match pre-development hydrology, then the BACI strategy may be adequate. If the research objective is to compare performance between a traditional and a LID site, then strategy number three described above might be the best choice. If multiple study objectives exist, then a combination of strategies as described in number four may be the best approach. It should be noted that regardless of the monitoring program goals, if the study is well conducted, the results should be useful for drawing conclusions relative to other studies as well as between controls or test sites in the study itself. Also, regardless of the monitoring strategy chosen, thorough documentation of site characteristics and hydrologic characteristics is essential for meaningful results. This documentation is described in the next two sections.

8.2.3 LID Watershed Characteristics

LID watershed characteristics are the physical features and properties of an area containing LID practices, including the practices themselves, that influence its overall hydrologic response to rainfall events. These characteristics are reported as catchment-scale metrics that can be used to help compare performance monitoring data collected at different LID sites. Exhibit 8-7 contains a list of watershed characteristics currently requested in the BMP Database for all studies. Some elements that are currently "nice to have" for conventional watersheds will be "required" for LID watersheds. Likewise, additional metrics are needed to adequately characterize LID watersheds while accounting for the broad variability between these watersheds. These metrics are described in Exhibits 8-9 through 8-12. Since LID is relatively new and research is still evolving, the suggested additional metrics are only considered a starting point for LID and will likely be refined and expanded in the near future. The sub-sections below discuss the watershed characterization concepts to keep in mind when designing a LID monitoring study and explain how they can be used to help differentiate the hydrologic response of various LID watersheds. Exhibit 8-8 lists the acceptable land use categorizations of the BMP database that have been collected in the past. Additional land use categories added at this time are shown in Exhibit 8-10.

Exhibit 8-7. Watershed Characteristics Requested in the Stormwater BMP Database

General Watershed Information	Road and Parking Lot Information
Land Uses (See Exhibit 8-7)	Total Paved Roadway Area
Watershed Description (narrative)	Total Length of Curb and Gutter on Paved Roads
Total Watershed Area	Total Unpaved Roadway Area
Total Length of Watershed	Total Length of Curb/Gutter on Unpaved Roads
Total Length of Grass-Lined Channels	% Paved Roads Draining to Grass Swales/Ditches
Total Disturbed Area	% Unpaved Roads Draining to Grass Swales/Ditches
% Irrigated Lawn and/or Agriculture	Type of Pavement on Roadways
% Total Impervious Area in Watershed	Total Paved Parking Lot Area
% of Total Impervious Area that is Hydraulically Connected	Total Length of Curb/Gutter on Paved Parking Lots
% of Watershed Served by Storm Sewers	Total Unpaved Parking Lot Area
Storm Sewer Design Return Period (years)	Total Length of Curb/Gutter on Unpaved Parking Lots
Average Watershed Slope	% Paved Parking Lot Draining to Grass Swales/Ditches
Average Runoff Coefficient	% Unpaved Parking Lot Draining to Grass Swales/Ditches
Hydrologic Soil Group	Type of Pavement in Parking Lots (% Porous Concrete, % Porous Asphalt, % Modular)
Soil Type	Characterize Highway Conditions (Average Daily Traffic, Number of Lanes, Deicing Method)
Type of Vegetation (narrative)	Narrative description of the type of vegetation present

Exhibit 8-8. Land Use Types in the BMP Database

Land Use Categories Accepted in the Stormwater BMP Database (reporting is based on % of each type)	
Multi-Family Residential	Open Space
High Density Residential	Forest
Medium Density Residential	Rangeland
Low Density Residential	Orchard
Light Industrial	Vegetable Farming
Heavy Industrial	Restaurants
Office Commercial	Automotive Services
Retail	Maintenance Station
Highway	Unknown
Park & Ride	

It is critical to recognize that in site level LID studies the watershed *is* the BMP rather than an external factor to be documented as is the case in a conventional BMP study. In the case of site level "nested studies" (see Section 8.1.3), additional complexities arise because an individual LID practice, which would be considered a BMP in a practice level study, would now be considered just one element of an overall watershed characterization in the site-level study. These studies are complementary; however, as the detailed results from the practice level study can be used to help estimate bulk watershed characteristics at similar facilities throughout the watershed.

8.2.3.1 Watershed Geometry

The general geometry of a study watershed (e.g., total area, slope, overland flow width) is basic information that should be documented as part of any comprehensive LID site monitoring study. These parameters are easy to obtain and provide insight into the typical response that can be expected during a storm event. For example, small and steep watersheds are characterized by intense, short responses in the hydrograph, fast surface flow velocities, and low rates of infiltration. Conversely, watersheds generally described as having shallow slopes will respond more slowly to similar storm events and will yield lower peak discharges during those events. When all other factors are held constant, a flatter watershed will facilitate more infiltration and have higher rates of evapotranspiration. LID practices that depend on infiltration are generally best suited to treat smaller, less intense storm events that occur in mildly sloping watersheds. While this may be the case at present, innovative designs are continually being developed to test the bounds of applicability of LID techniques. Slope and overland flow patterns are easily obtained and should be documented as part of any comprehensive LID site study. Exhibit 8-9 shows watershed geometry information that is currently requested for practice level studies as well as the additional information requested for LID sites.

Exhibit 8-9. Existing and Recommended Watershed Geometry Parameters

Currently Requested Information	Relevance to LID Watershed Studies
Total Watershed Area	This is a fundamental watershed characteristic; it expresses potential for spatial variability in hydrologic characteristics (e.g., rainfall, soil properties).
Watershed Description (narrative)	This provides the context and initial screening of comparability to other studies.
Total Length of Watershed	This helps to estimate watershed lag; it expresses potential for spatial variability in hydrologic characteristics (e.g., rainfall, soil properties). It is too coarse to describe differences between conventional and LID site design (see Overland Flow Width).
Average Watershed Slope	This helps to estimate watershed lag, but it is not as important as defining the average slope of overland flow paths in developed areas (see Slope of Overland Flow Path).
Additional Information for LID Watershed Characterization	**Rationale**
Average Overland Flow Length	This is different from the total watershed length. It describes the area-weighted average drainage path length to an inlet or hardened conveyance.
Maximum Overland Flow Length	This is different from the total watershed length. It describes the maximum drainage path length to an inlet or hardened conveyance.
Narrative of Flow Patterns	This allows the user to describe watershed geometry-based LID practices that modify the flow patterns of the site in order to increase time of concentration and promote losses. The potential metrics that may be used to describe flow patterns include, but are not limited to, the following: • Time of concentration to a hardened conveyance; accompanied by method used to compute Tc and inputs • Hydraulic width per Stormwater Management Model (SWMM) documentation • Average lot depth • Average slope of pervious area

8.2.3.2 Vegetative Cover and Land Uses

Vegetative cover and the land uses in a study area are two major factors influencing the quality and quantity of runoff and should also be documented as part of a comprehensive LID monitoring study. The land use categories contained in the BMP Database are shown in Exhibit 8-8. Vegetation in a catchment, for example, stabilizes soils to prevent erosion, facilitates infiltration, and influences the site water balance through evapotranspiration. Vegetation is also a key component of many LID practices, such as green roofs, bioretention cells, and revegetation. The location of the vegetation on a LID site as well as the type, density, height of vegetation should be documented. In addition, the percent canopy coverage should be described for the individual LID practices as well as for the overall site. Documenting these types of characteristics is important because the vegetation at a LID site changes over time. Even after a LID site has been fully developed, these vegetation-related characteristics may require several years to fully mature, thereby delaying their beneficial effects.

The land use area breakdown is another fundamental descriptive component of any new development or redevelopment project. This information can be useful to describe how LID practices are implemented and distributed within a study watershed. For example, a LID site may include cisterns on 50 percent of the single family homes or bioretention cells treating 20 percent of the residential roads. Documenting a land use area breakdown for a study site can help classify the extent of LID implementation and can be used for future comparisons of LID site performance. Because land use trends are always changing, it is valuable to document the nature of imperviousness of the individual land uses in a watershed. Coupled with the information above, this information permits quantification of the amount of impervious area controlled by LID practices.

The preservation of natural soils, forests, and hydrologic features such as wetlands is a central LID principle. These natural areas provide a means to disperse, infiltrate, store, and evapotranspire stormwater runoff. Any preservation of natural land use or changes of the land use characteristics at a LID site should be documented. Exhibit 8-10 shows land use and vegetation information that is currently requested for practice level studies as well as the additional information requested for LID sites.

Exhibit 8-10. Existing and Recommended Land Use and Vegetation Parameters

Currently Requested Information	Relevance to LID Watershed Studies
Land use breakdown as percentage of total watershed	This describes the type of development and may be used as a surrogate for flow patterns, imperviousness, and expected water quality.
Watershed Description (narrative)	This provides the context of the study and allows an initial screening for comparability to other studies.
Total Disturbed Area	This describes the extent of site potentially producing greater runoff as a result of incidental compaction of pervious areas.

% Irrigated Lawn and/or Agriculture	This describes the extent of site potentially producing dry weather flows or having soil moisture content above seasonal normal for unirrigated land.
Type of Vegetation (narrative)	This permits the estimate of canopy cover and fraction of reference evapotranspiration (ETo).
Total Paved Roadway Area	This describes a major source of impervious area, which may be lumped with land use totals.
Total Unpaved Roadway Area	This describes a potential source of elevated runoff quantity that may not be characterized as impervious area.
Total Paved Parking Lot Area	This describes a major source of impervious area that may be lumped with land use totals.
Total Unpaved Parking Lot Area	This describes a potential source of elevated runoff quantity that may not be characterized as impervious area.
Characterize Highway Conditions (Average Daily Traffic, Number of Lanes, Deicing Method)	This is an indicator of expected runoff water quality.
Additional Information Recommended for LID Watershed Characterization	**Rationale**
Additional land use categories: • Open Space – Undisturbed • Open Space – Other (Describe) • Disturbed/Construction • Other (Describe)	This provides information for estimating hydrologic response and runoff water quality, and facilitates the interpretation of results. The quantity of undisturbed open space provides a measure of extent of LID implementation (preservation of open space is a central principle of LID).

8.2.3.3 Imperviousness and Connectivity

Following urbanization of a watershed, a significant hydrologic concern is the potential effect of increased imperviousness on receiving waters. In the absence of carefully planned hydrologic controls, the rate and volume of runoff may significantly increase, along with the associated pollutants and thermal loads. Because the basis of the LID design philosophy is to minimize the impact of development and to mimic the site's natural hydrology, it is important to document the types of design practices related to changes in imperviousness that are implemented at a LID site. For example, site design approaches such as splitting driveways, narrowing roads, and installing sidewalks on only one side of a street reduce the imperviousness of a development. Routing impervious areas (e.g., sidewalks, roads, roofs, and driveways) to adjacent pervious areas (e.g., lawns, landscaping, etc.) can reduce the "effective imperviousness" of the site. For example, runoff from roofs at a LID site can be directed into rain gardens instead of storm sewers, or curbs can be eliminated to allow road

runoff to flow to bioswales. Likewise, parking lots can be drained to biofilters instead of road or sewer systems.

Streets and parking lots account for a large percentage of the total impervious area in a catchment. When impervious areas are directly connected to stormwater conveyance systems, they contribute large amounts of runoff compared to the runoff during natural conditions. Curbs and gutters that are traditionally used to concentrate and direct runoff to stormwater systems can be eliminated in a LID site and substituted with vegetated swales adjacent to roadways. Curbs can also be omitted in parking lots to allow runoff to flow into pervious area.

In addition to the total imperviousness of a study area, the directly connected impervious areas and the proportion of impervious surfaces with cover (ISWC) should also be estimated. Directly connected impervious areas (DCIA) are the impervious areas such as roofs and pavement that drain directly to the storm drain system without first draining to pervious areas or LID practices. ISWC is impervious area that is covered by vegetation (e.g., tree canopy) and, therefore, does not receive direct rainfall during some seasons of the year. Various methods to quantifying imperviousness data are discussed in Section 8.3.2.

Based on the above discussion, the useful impervious area metrics that should be estimated for a LID site when possible include: (1) total imperviousness along with estimates of the proportion of ISWC; (2) DCIA; and (3) the impervious area that flows to LID featrues. Additionally, any changes to impervious areas as a result of a LID retrofit should be recorded. For example, if 40 percent of an area was previously parking lots and 20 percent of the parking lot area was converted to a permeable pavement then the reduction in parking lot impervious area would be 20 percent and the overall reduction in impervious area would be 8 percent.

Is should be noted that the concept of disconnecting areas is not absolute. In a large enough storm or in sequential storms, the effectiveness of disconnection (e.g., routing downspouts over lawns, etc.) will typically be reduced, primarily due to decreased soil infiltration rates. For example, if a downspout was routed over a lawn that had been saturated by a previous storm, the expected volume reduction (i.e., degree of disconnection) would be less than if the lawn had been dry before the storm. Considerations of scale and relative volume are important and are discussed further in Section 8.2.3.5. The most recent version of the BMP Database allows data to be entered to help define a “degree of disconnection” rather than regarding disconnected impervious area as an “all or nothing” metric. Exhibit 8-11 shows the imperviousness and connectivity information that is currently requested for practice level studies as well as additional information that is requested for LID sites.

Exhibit 8-11. Existing and Recommended Imperviousness and Connectivity Parameters

Currently Requested Information	Relevance to LID Watershed Studies
% Total Impervious Area in Watershed	This is a fundamental watershed characteristic. It describes the percentage of the site where infiltration does not occur.
% of Total Impervious Area that is Hydraulically Connected (DCIA)	This provides a general description of the connectivity of watershed. It is the amount of area likely to discharge in a small storm event. Larger areas may behave as DCIA in larger events.
% of Watershed Served by Storm Sewers	This is an indicator of time of concentration of watershed, the overall connectivity, and the potential for conveyance losses.
Total Length of Grass-Lined Channels	This is an indicator of time of concentration of watershed, the overall connectivity, and the potential for conveyance losses.
Total Length of Curb and Gutter on Paved Roads	This is an indicator of time of concentration of roads, the connectivity of roads, and the potential for conveyance losses.
Total Length of Curb/Gutter on Unpaved Roads	
% Paved Roads Draining to Grass Swales/Ditches	
% Unpaved Roads Draining to Grass Swales/Ditches	
Total Length of Curb/Gutter on Paved Parking Lots	This is an indicator of time of concentration of parking lots, the connectivity of parking lots, and the potential for conveyance losses.
Total Length of Curb/Gutter on Unpaved Parking Lots	
% Paved Parking Lot Draining to Grass Swales/Ditches	
% Unpaved Parking Lot Draining to Grass Swales/Ditches	
Average Runoff Coefficient	This is the user estimate of runoff potential of watershed considering imperviousness and connectivity. Estimating this parameter without long term monitoring data requires professional judgment. It is typically the intent of LID site studies to quantify the average runoff coefficient.

Additional Information Recommended for LID Watershed Characterization	Rationale
Estimate of Average Imperviousness by Land Use	This allows a direct estimate of total watershed imperviousness and could support estimates of impervious area draining to LID practices if LID implementation is described by land use (e.g., bioretention in 40 percent of residential land use, etc.)
Estimate of Impervious Cover with Canopy (ISWC)	This provides information about the estimated hydrologic response and facilitates interpretation of results. It provides a measure of the extent of LID implementation (minimization of DCIA through vegetative cover is a fundamental principle of LID).

8.2.3.4 Soil Properties and Groundwater Conditions

Detailed soil and groundwater information is required to characterize the effectiveness of LID practices as these methods rely on infiltration and storage in natural soils and engineered media to operate efficiently. Knowledge of a site's soil characteristics can lead to making more economic construction choices that benefit the environment. For example, a building might be constructed on highly impermeable soils, while areas with high infiltration rates can be left undisturbed.

The stratigraphy of a site should be thoroughly assessed to locate any low/high permeability layers, sand/gravel layers, depth to groundwater, and any other factors that can help to determine subsurface flow patterns and the rate at which stored water would infiltrate in to the subsurface. Soil survey data available from the Natural Resources Conservation Service (NRCS) can be a useful resource for identifying site soil properties, and in some cases, depth to groundwater. That said, the NRCS surveys may be too coarse to confidently describe the detailed soil characteristics of a specific site. In addition, disturbance or relocation of soil during construction may reduce the representativeness of soil survey data in describing soil chemical and physical properties. Actual field samples from test pits should be collected when feasible to assess the grain size distribution, texture, organic content, nutrient levels, cation exchange capacity, or other characteristics. Additionally, in-situ infiltration test data can also be invaluable for both design and analysis of LID practices.

The installation of groundwater monitoring wells to obtain accurate and local seasonal high water table information is also very useful. This process can be expensive, however, and site-specific and regional considerations influence whether the cost is justified. For example, this type of monitoring would be important where a shallow aquifer may influence the performance of LID practices or in a community where the response of expansive clay soils to infiltration practices is being evaluated as part of the study. Where soil types and pollutant source areas suggest the potential for groundwater contamination from infiltration practices, groundwater and vadose zone discharge should be monitored to measure pollutant loading

and removal in the soil column. Refer to Pitt et al. (1994) for information on evaluating risks of groundwater contamination and for guidance on monitoring for these effects. Exhibit 8-12 shows site soils information currently requested for practice level studies as well as additional information that is requested for LID sites.

Exhibit 8-12. Existing and Recommended Soil Parameters

Currently Requested Information	Relevance to LID Watershed Studies
Hydrologic Soil Group	This is an indicator of the magnitude of runoff from pervious areas. It may be different in developed conditions than what is reported in the soil survey due to soil compaction or mass grading/relocation.
Additional Information Recommended for LID Watershed Characterization	**Rationale**
Distribution of Hydrologic Soil Groups on Site (Fields for %A, %B, %C, %D)	This allows for a more robust description of larger sites, or sites with a range of compaction-related impacts.
Soil Conditions (narrative)	This allows the user to describe important aspects of the site soils. It may include: • Prevalent soil type (Unified Soil Classification) in developed areas at time of monitoring (not in the pre-development). • Measured saturated hydraulic conductivity in critical locations such as in the vicinity of infiltration-based practices. • Average and minimum depth to seasonally high groundwater in developed areas. • Degree of compaction and envelope of disturbance.

While it is recommended that soil should be sampled and analyzed to characterize site soil types and properties, the BMP database is not structured to handle soil datasets. Users will be able to provide narrative information as described in Exhibit 8-11.

8.2.3.5 Watershed Storage Properties and Conditions

It is impossible to characterize a LID watershed without describing the IMPs (e.g., bioretention, cisterns, pocket wetlands, swales) that may provide significant storage in the watershed. In a site level study, however, it is typically necessary to provide a bulk quantification of these practices instead of a detailed description of each practice, which would require obtaining and reporting larger amounts of data. It is therefore recommended

to characterize the volume of storage integrated into a LID site as a set of bulk watershed attributes by quantifying the storage volume and its related characteristics and describing how storage is regenerated after a storm event. These are described below.

Quantify the Effective Storage Volume. Estimate the volume of storage available on the site that is effective in storing stormwater, and divide this estimate between storage volume that is retained and does not discharge to the surface and storage volume that is detained and discharges back to the downstream system via underdrains or discharge structures. If the overall site water balance is an important feature in a study, the storage that is retained can be further divided by the ultimate fate of the retained water: infiltration, evapotranspiration, or exportation off-site (e.g., toilet flushing). The quantity and distribution of storage volume has important theoretical influence on the amount of stormwater expected to discharge from the site.

The concept of "hydrologically available temporary storage" can be used to describe the storage volume of a LID site. Hydrologically available temporary storage at the site potentially includes the following components:

- Surface storage (e.g., natural, pervious, and impervious depression storage; surface retention) that is not surface discharged. This represents volume that is eventually lost through evapotranspiration and/or infiltration but would not have become surface discharge.

- Surface storage (e.g., natural, pervious, and impervious depression storage; surface detention) that is eventually surface discharged after detention and/or infiltration occurs whereby slowing the surface discharge.

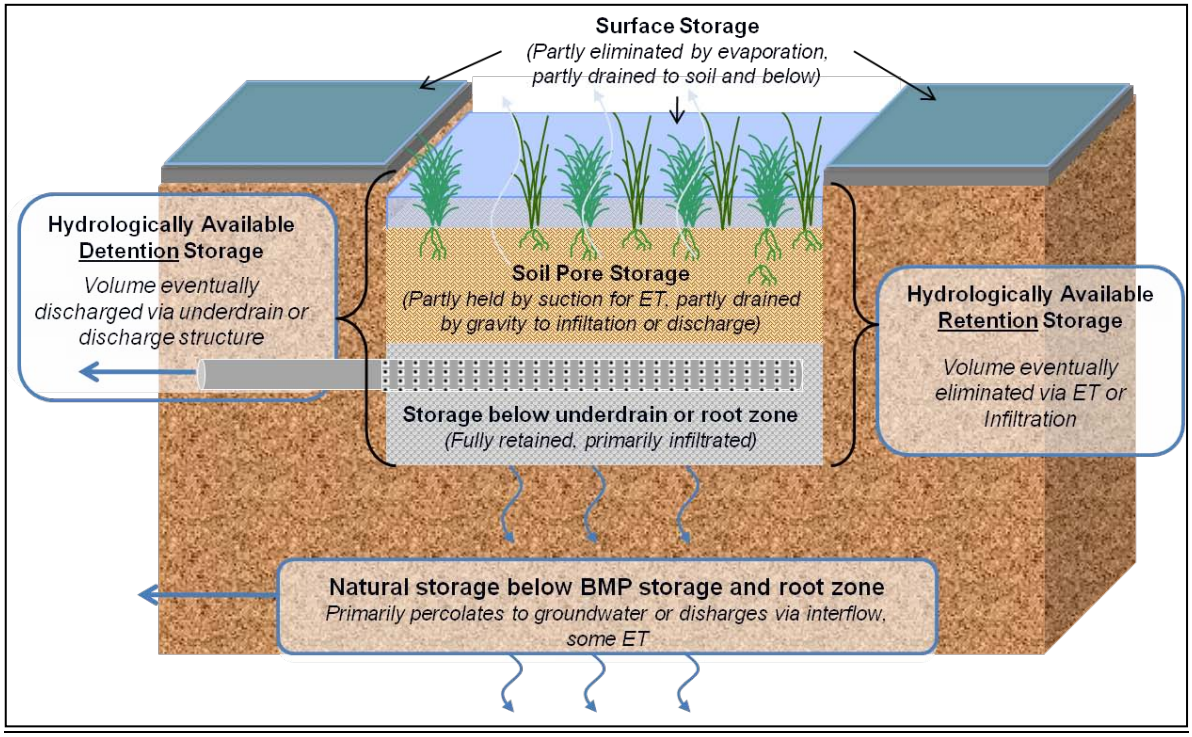
- Subsurface LID practice temporary storage, including all pore space within LID practices (e.g., in bioretention soils, stone infiltration trenches, planter media, green roof media) that is not surface discharged. This also represents the volume that is eventually recovered through evapotranspiration and/or infiltration, but would not have become surface discharge.

- Subsurface LID practice temporary storage, including all pore space within LID practices (e.g., in bioretention soils, stone infiltration trenches, planter media, green roof media) that is eventually surface discharged via an underdrain system.

- Volume in cisterns and rain barrels in excess of average long-term retained volume that is eventually recovered through evapotranspiration (e.g., irrigation reuse, cooling water makeup reuse, drip hose), infiltration, and/or export (e.g. toilet flushing use).

Exhibit 8-13 illustrates components of hydrologically available temporary storage that may be present in an individual practice. The location of available storage relative to sources of runoff is a critical aspect in determining the amount of storage that is "hydrologically available" to store runoff. This concept is further described and illustrated in Section 8.2.4.3.

Exhibit 8-13: Components of Hydrologically Available Temporary Storage Typically Present in LID features



Describe How Storage Is Recovered Following a Storm. Different storage elements may regenerate storage at different rates depending on their characteristics. For example, a bioretention facility with underdrains may draw down its stored volume within 12 hours after a storm, while the same storage volume in a cistern used for irrigation may not begin to draw down its stored volume for a few days following an event and may take a week to draw down completely. Drawdown rate is also influenced by season of year, day of the week, and/or other factors. For example, seasonal variations in temperature can affect evapotranspiration and infiltration rates. Seasonal conditions can also affect irrigation demand, thus affecting drawdown rates for rainwater harvesting practices that commonly use harvested water to for irrigation. The day of the week can also affect regenerated storage rates. For example, the demand for captured water used for indoor toilet flushing in a commercial office building would be expected to be greater during the business week than on the weekend.

The rate of recovery of storage has important theoretical influence on the hydrologic response of watersheds, specifically LID watersheds, in consecutive events. While storage recovery rate is an important component of watershed characterization, it is can be difficult to quantify for a composite site. It is also perhaps one of the aspects of watershed characterization most unique to LID watersheds, and thus has not been well standardized and demonstrated.

Potential methods of standardizing these aspects are discussed in the following section.

8.2.4 Composite Site Characteristics

When comparing LID (and/or other distributed controls) sites, it is helpful to identify a set of composite site characteristics that quantify the extent/type of LID implemented at a site. An ideal set of composite site characteristics would allow for quantification of the extent of LID at a site so that comparisons could be made among LID sites regardless of size, location, and other environmental factors. Ideally, it would be possible to estimate these characteristics for a site regardless of whether LID techniques have been implemented or whether development has yet occurred. For the purpose of this manual, composite site characteristics have been categorized as simple indices and integrated indices, as described below. Hydrologic performance metrics are also proposed as a means of quantifying the extent/type of LID implementation.

Some of these indices/metrics are easier to obtain than others, and some may be better suited to certain types of studies than others. While the indices/metrics listed below have limitations recognized limitations, each of these, or some variation of these, may provide valuable input on a LID site study.

The current body of knowledge does not provide sufficient forum to test these metrics in order to establish their strengths and limitations, therefore broad lists are provided below for consideration. Inclusion on these lists does not necessarily constitute an endorsement by the EPA or the authors of this manual. Likewise, these lists are not exhaustive.

The BMP Database will allow users to input and describe any combination of indices and metrics they choose, however the authors recognize the value that would be added through standardization of site characterization methods. A standardized reporting method can be found in Section 8.2.4.3.

8.2.4.1 Site Characterization Indices

<u>Simple Indices</u>

The following simple indices incorporate watershed characteristics individually or in simple combinations. They are often easy to estimate and may be sufficient to adequately describe simple LID scenarios, especially if multiple simple indices are provided. However, they are not likely to be sufficient to characterize complicated LID scenarios because they do not consider theoretically-important interactions between the various watershed characteristics. Potential simple indices include:

- Total hydrologically available temporary storage in LID features and the percentage split between retained and detained storage in these features.

- Total hydrologically available temporary retained storage relative to average storm depth.

- Maximum, minimum, and/or average time to recover LID feature storage from completely full.

- Average time to fully recover LID storage relative to average inter-event time.
- Estimated volume of pore space within the natural duff layer, compost, mulches, or similar techniques.
- Area weighted saturated hydraulic conductivity and available water capacity of the top foot of native or post construction soils not within LID features.
- Percentage splits of impervious area between impervious area flowing to pervious areas, flowing to LID features, canopy covered only, and directly connected.
- Average ratio of "disconnected" impervious area to pervious area receiving runoff from disconnected impervious area.
- Maximum, minimum, and annual average potential vegetative canopy interception.
- Computed time of concentration of watershed under a range of rainfall intensities (computed by standard method such as Soil Conservation Service Technical Release 55[TR-55]).
- Computed average time of concentration to a hardened conveyance (computed by standard method such as TR-55).
- Area or length of vegetated conveyance per acre of road.

Integrated Indices

Integrated Indices would attempt to integrate multiple watershed characteristics to better describe LID implementation in complex scenarios (i.e., several different LID strategies in the monitored watershed). Such indices would likely require more effort to develop and require more judgment on the part of the study investigator when assigning some input parameters. However, integrated indices could potentially provide a more comprehensive description of the factors likely to affect LID site performance. Preliminary concepts for integrated indices include:

- Spatially-coupled source/sink analysis. Each element of hydrologically available temporary storage at the site would be compared to the cumulative area tributary to each element and the runoff potential of this area. This index could be effective in describing the surface discharge from a watershed in a given storm with given antecedent conditions. If coupled with local rainfall depth statistics and average antecedent conditions, this index could potentially be correlated to average discharge volumes.
- Temporal demand/capacity analysis. The total hydrologically available temporary storage at the site would be assumed to be evenly distributed around the site, and emphasis would be place on the detailed regeneration pattern of each element of hydrologically available temporary storage in comparison to local precipitation

patterns. This index could be more effective than the spatially-coupled source/sink analysis described above if sources and sinks were fairly uniformly matched and if antecedent conditions could not be well summarized with simple statistics. It could potentially be correlated to average discharge volumes and/or frequency of discharge.

It is recognized that any attempt to integrate the broad range of watershed characteristics into a single index would be limited and likely useful at a planning level only. The details of calculating the index (or indices) would need to be developed based on theoretical considerations and on the analysis of studies; however such efforts have yet to be documented.

Regardless, incorporation of a spatial component of study documentation is critical to further the field of study. However, spatial data are not easily summarized or standardized for entry to a database. In the future, the concepts of a graphical interface to standardize spatial data entry or a standardized model development protocol should be investigated. For example, model input files from the EPA Stormwater Management Model (SWMM) could provide a more efficient method of documenting information about spatial relationships and watershed routing than if these watershed descriptions were entered into individual database fields. At this time, it is recommended that detailed PDF figures of the study area be included with user input. Graphical documentation should attempt to illustrate:

- LID practice types.
- Impervious area tributary to each practice type.
- Area and location of each practice.
- Retention and detention volume provided in each practice.
- Storage recovery characteristics of each practice for retention and detention storage (e.g., time to recover 50 percent of storage, time to recover all storage).
- Routing of flow between practice types (e.g., downspout disconnects flow to bioretention if capacity of lawn is exceeded).

8.2.4.2 Hydrologic Performance Metrics

Another way to compare LID sites is to treat certain hydrologic performance metrics as indicators of the extent of LID present at a site and of how well the site is performing, even if only partially.

Hydrologic performance metrics used to describe the extent of LID and how well the site is performing might include:

- Largest rainfall event (depth and duration) producing no discharge.
- Long-term cumulative discharge volume per unit rainfall (long-term volumetric runoff coefficient).

- Largest rainfall quantity producing no discharge with a "wet" versus "dry" Antecedent Precipitation Index (API). API is defined as:

$$API_t = R_{t-1} + k \cdot API_{t-1} \qquad \textbf{Equation 8-1}$$

Where:

API_t: index for day t
API_{t-1}: index for the previous day
R_{t-1}: rainfall depth for the previous day (inches)

k: coefficient reflecting the relative rate of soil drying

The value of k can range from approximately 0.85 (sand) to 0.98 (clay). "Wet" is considered to be API > 0.6 and "dry" as API <0.6. (Linsley, Kohler, and Paulhus 1982).

- Average of storm-by-storm volumetric runoff coefficient under wet and dry API.

- Largest rainfall quantity producing no discharge with a varying 7-day antecedent rainfall.

- Peak flow rates for specific average rainfall intensities over the time of concentration. For example if the time of concentration for a site is 10 min, the peak flow rate resulting from an average intensity of 0.1 in/hr, 0.2 in/hr, 0.3 in/hr, and so on over 10 minutes under varied antecedent moisture conditions.

- Hydrograph lag time.

- Time of concentration under varied rainfall intensities and APIs determined from analysis of hyetographs and hydrographs.

The effects of temperature on the performance of infiltration-based practices should be considered in developing and comparing metrics. Temperature is known to have a significant effect on infiltration rate.

Closely related to some of the concepts identified above, Davis (2008) proposed three metrics for describing the restoration of hydrologic conditions by bioretention facilities: 1) the peak flow rate ratio of effluent to influent (R_{peak}); 2) the peak discharge time span ratio of effluent to influent (R_{delay}); and 3) the effluent/influent volume ratio (f_V). These are defined as:

1) $R_{peak} = q_{peak\text{-}out}/q_{peak\text{-}in}$ **Equation 8-2**

2) $R_{delay} = t_{q\text{-}peak\text{-}out}/t_{q\text{-}peak\text{-}in}$ **Equation 8-3**

3) $f_{v24} = V_{out\text{-}24}/V_{in}$ **Equation 8-4**

Where

$q_{\text{peak-out}}$:	peak effluent flow rate
$q_{\text{peak-in}}$:	peak influent flow rate
$t_{q\text{-peak-out}}$:	time from the beginning of influent flow to peak effluent flow
$t_{q\text{-peak-in}}$:	time from the beginning of influent flow to peak influent flow
V_{in}:	input stormwater runoff volume to a bioretention cell
$V_{\text{out-24}}$:	corresponding outflow volume leaving the cell after 24 hours.

Although these three metrics were developed for bioretention facilities, the concepts could be adapted to evaluate LID sites as a whole. Example application of these metrics to six bioretention sites can be found in Li et al. (2009).

8.2.4.3 Recommended Metrics for Reporting to BMP Database

The list of potential indices and metrics included above may be useful in explaining some aspects of LID site performance and should be considered in developing monitoring studies. The BMP Database will allow for the user to report indices and metrics of his or her choice along with an explanation of how the values were been calculated. There is hope that sufficient data will be reported from LID site studies to facilitate evaluations of various indices and metrics for potential standardization of BMP Database reporting forms in the future.

In the meantime, this section proposes a single standardized method that can be used to characterize a site. This "pilot" approach was developed in order to balance input data requirements with the ability to describe spatial and temporal volumetric properties of LID watersheds. The proposed approach was also developed so that it could be readily incorporated into the existing BMP Database structure. It is based on the concepts of hydrologically available temporary storage and temporary storage recovery time. From these two concepts, the "net instantaneous volume" and "storage recovery time" are derived. These two are described below:

<u>Net Instantaneous Volumes</u>

Net instantaneous volume is a metric based entirely on the distribution of tributary area and storage volume in the watershed. It incorporates the concept of hydrologically available temporary storage, which is the amount of storage that can actually be used during a given event. For example, if 10,000 cu-ft worth of storage was located in the upstream end of a watershed where it only received 3,000 cu-ft of runoff from a given storm event, it would only be 3/10^{ths} utilized during that event regardless of whether capacity was exceeded in other parts of the watershed. The hydrologically available temporary storage contributed by this unit would be 3,000 cu-ft for this storm event, not 10,000 cu-ft. An over-simplified bulk measure of total watershed storage that combines all storage volume regardless of its tributary area would inaccurately assume the remaining 7,000 cu-ft was available to storm runoff from other parts of the watershed, which is clearly not the case. Hydrologically available temporary storage thus describes the spatial relationship of source areas and storage

volume, and is expected to vary with storm depth. Exhibit 8-14 illustrates the concept of hydrologically available temporary storage for a simple example catchment.

The net instantaneous volume method compares the volume incident on a catchment during a hypothetical instantaneous event to the storage volume available in the LID practices to which these areas drain. An instantaneous volume is applied over the catchment. The corresponding volume is then transferred to the LID practice receiving runoff from each catchment area. If a LID practice storage volume is exceeded by this volume, excess volume may be transferred to any capacity remaining in downstream practices. For example, if the capacity of a lawn to absorb runoff from a disconnected downspout was predicted to be exceeded by a certain rainfall depth, excess volume could be applied to a street-site bioretention cell. After all hydrologically available storage in the watershed is full, the remaining volume is considered to be the **net excess volume**. All pervious area is considered to be an LID practice, only contributing to runoff if its capacity is exceeded, either by run-on from impervious area or lack of capacity to absorb more volume. The investigator will likely need to use best professional judgment to estimate the storage capacity of pervious areas.

Each LID practice volume is divided between retention volume (i.e., volume that does not discharge to the downstream system) and detention volume (i.e., volume that is captured, treated, and released to the downstream system). Retention volume used during the instantaneous volume calculation is reported as net retained volume. Detention volume used during the instantaneous volume calculation is reported as net detained volume. These two volumes added to the net excess volume should be equal to the total rainfall volume over water area in the hypothetical event.

Note the following when computing the net excess volume metrics: (1) Include directly connected impervious areas (i.e., areas not draining to a LID practice) as these areas always contribute to net excess volume because, by definition, no storage exists downstream of DCIA; and (2) Recovery of capacity during the duration of the event is <u>not</u> considered in computing this index. For example, infiltration under LID practices and hydrograph routing through detention facilities should <u>not</u> be considered. The effect of storage recovery is accounted for in the storage recovery rate, described below.

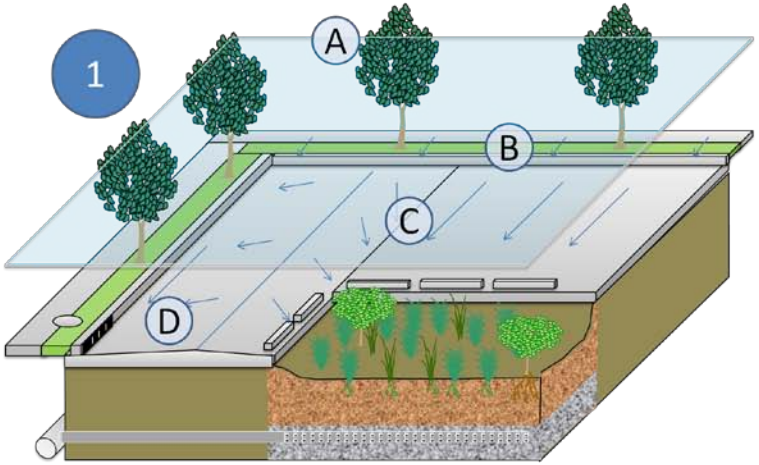
<u>Storage Recovery Rate</u>

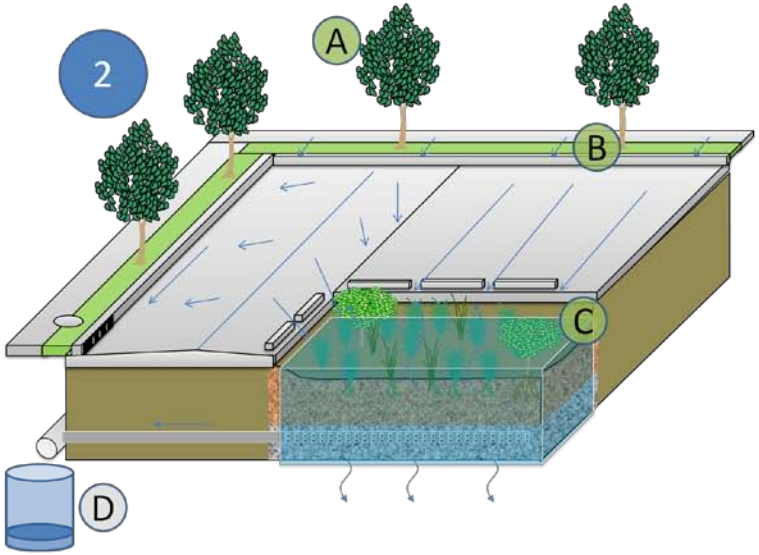
The storage recovery rate is a metric that complements the net excess volume metrics described above. The storage recovery rate describes the rate at which hydrologically available temporary storage is recovered. It is defined as the time it takes to recover the hydrologically available temporary storage from brim full. The user may enter seasonal minimum, average, and maximum recovery times. Seasonal factors are expected to influence evaporation-based practices the most, thus minimum and maximum recovery times are strongly suggested where an LID site relies strongly on evapotranspiration-based practices. Storage recovery times should be estimated assuming no additional rainfall.

Conceptual steps in computing excess volume are demonstrated in Exhibit 8-14 for an example parking lot catchment containing the LID practices: interception storage, sidewalk

filter strips, and bioretention. Steps are provided for computing excess storage for a given storm depth.

Exhibit 8-14: Conceptual Excess Volume Calculations for a Hypothetical Catchment



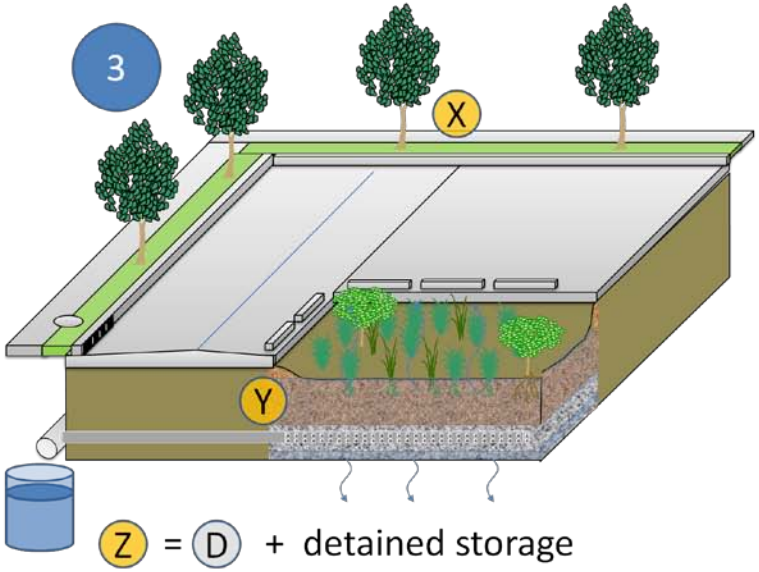


Example watershed combining canopy interception storage, sidewalk filter strips, and bioretention. Steps in extimating "excess volume" for a given storm depth.

1) Storm depth incident over area, converted to volume and divided between:
   A. Volume incident over tree interception area available for interception,
   B. Volume incident on areas draining over sidewalk filter strip,
   C. Volume incident on areas draining to bioretention, and
   D. Volume incident on area discharging directly to storm drain.

2) Respective rainfall volumes are compared to volume available in:
   A. Canopy interception storage,
   B. Sidewalk filter strip , and
   C. Bioretention.
      Excess from canopy interception routed to filter strip, excess from both routed to bioretention or directly to storm drain where applicable
   D. Any overall volume greater than available volume, counted as "excess volume."

3) Volume split between retained and detained volume estimated from system characteristics:
   X. Volume in interception storage and sidewalk filter strip assumed to be retained.
   Y. Volume in bioretention divided between retained and detained volume based on properties of the system (volume held in pores and below underdrain assumed retained, remainder assumed detained).
   Z. Total surface discharge equals excess detained volume plus excess volume.



BMP Database input requirements are shown in Exhibit 8-15.

Exhibit 8-15. Composite Site Characterization Inputs to BMP Database

Field	Description
Net **detained** volume – by event	Calculated by user based on storage volume, routing, and event depth as described above. Entered for storm depths selected by user. Recommended that the user provides calculation results for at least three representative depths.
Net **retained** volume – by event	
Net **excess** volume – by event	
Minimum time to recover retained storage	Calculated as the composite time to recover **retained** storage from brim full. Minimum and maximum should account for temperature and other seasonal factors. Recovery may be asymptotic in which case recovery of approximately 90 percent of volume can be considered full recovery.
Average time to recover retained storage	
Maximum time to recover **retained** storage	
Minimum time to recover **detained** storage	Calculated as the composite time to recover **detained** storage from brim full. Minimum and maximum should account for temperature and other seasonal factors. Recovery may be asymptotic in which case recovery of approximately 90 percent of volume can be considered full recovery.
Average time to recover **detained** storage	
Maximum time to recover **detained** storage	
Methods of estimating above parameters (narrative)	User describes methods used to estimate parameters above, including any supporting documentation.

8.2.5 Hydrologic Characterization

A primary purpose of LID site monitoring is to develop a comprehensive hydrologic characterization of the entire site. Consequently, the design of a monitoring plan must consider all of the major processes of the hydrologic cycle that influence the performance of the LID site. Direct site monitoring coupled with locally available meteorological data allows for the development of a reasonably accurate water balance that accounts for area-specific precipitation, infiltration, runoff, evapotranspiration, and storage (soil/media retention of moisture). Additionally, water balances can also be developed for individual LID practices. The following subsections describe the elements of the water balance approach used to measure or estimate these components, and discuss the importance of long-term monitoring and data representativeness.

Monitoring data may be used in conjunction with data from other sources to estimate water balances and characterize general site hydrologic conditions. The National Oceanic and Atmospheric Administration (NOAA), for example, maintains the most comprehensive

nationwide datasets of meteorological data. It is available through the National Climatic Data Center (NCDC) website (http://www.ncdc.noaa.gov). Some of the relevant data available from NCDC include:

- Wind speed and direction
- Temperature
- Solar radiation
- Precipitation

These data may be available as hourly, daily, or monthly values depending on location.

Evapotranspiration data can also be consulted. These data are most often found on websites maintained by state and regional agricultural agencies that monitor and report this type of information. Some suggestions are: California Irrigation Management Information System (CIMIS) (http://www.cimis.water.ca.gov), Arizona Meteorological Network (http://ag.arizona.edu/azmet/azdata.htm), University of Virginia Climatology Office (http://climate.virginia.edu/va_pet_prec_diff.htm), and Pacific Northwest Cooperative Agricultural Network (AgriMet, U.S. Bureau of Reclamation, http://www.usbr.gov/pn/agrimet/).

8.2.5.1 General Water Balance

A water balance can be described as an accounting of water inflow and outflow to determine change of storage in a system or control volume. A system is defined as any physical domain in space, such as a large regional watershed, an urban catchment, or a specific soil layer or matrix underneath the surface. Defining a water balance partitions the quantity of water into individual mechanisms, which helps build an understanding of the mechanisms that determine the fate of water. This allows the magnitude of treatment between individual processes to be understood. Equation 8-5 summarizes the basic water balance equation:

$$\sum V_{in} - \sum V_{out} = \Delta S \qquad \textbf{Equation 8-5}$$

Where:

V_{in}: total inflow volume over some time period Δt

V_{out}: total outflow volume over some time period Δt

ΔS: change in total storage volume over time Δt

Inflows may include direct precipitation, surface runoff, or groundwater exfiltration. Outflows may include infiltration, evapotranspiration, and surface discharge (treated and bypassed). System storage may include interception on plant surfaces, surface ponding, and water held in soils.

With respect to a LID site, a water balance system can be defined based on the objectives and spatial extent of the monitoring project. This can vary from individual LID practices to the cumulative estimated effect of all the LID practices at the watershed's outlet.

As a first step in developing a water balance, flow paths that affect the water balance of a system should be identified in order to organize the monitoring study and to fulfill the study objectives. In general, all inflow, outflow, and system storage variables should be monitored. However, it is typically not feasible or even possible to monitor all of these directly, in those cases the variables should be estimated using indirect methods. At a minimum, most LID monitoring sites should directly monitor rainfall and outflow from the site. Infiltration and evapotranspiration are more difficult to measure directly, but can be estimated by conducting infiltration tests, measuring changes in water level, or using soil moisture profiles to track the wetting front. In order to estimate evapotranspiration, more sophisticated LID monitoring studies can employ weather monitoring stations that record a full suite of meteorological variables such as precipitation, wind speed and direction, temperature, relative humidity, barometric pressure, and soil moisture. With the increasing popularity of "smart" irrigation controllers, "real-time" evapotranspiration data may also be available in some areas from local water utilities or vendors that provide services for such irrigation controllers. Several approaches can be used to develop a water balance using a combination of measured and estimated data. These approaches are described below.

8.2.5.2 Regional Water Balance

Evapotranspiration and infiltration are key water balance components of LID practices. These factors need to be estimated rather than measured directly as they depend on meteorological conditions (e.g., temperature, humidity, wind speeds), soil properties (e.g., field capacity, hydraulic conductivity), and vegetative cover.

The average evapotranspiration of a watershed can be estimated using Equation 8-6. It shows the regional water balance for a single catchment (Dingman 2002). While looking at a site's long-term water balance and consulting Exhibit 8-16, it may be possible to assume that groundwater fluxes in and out cancel each other out, on average, and that the change in storage is negligible over a long period of time. With these assumptions, an average evapotranspiration can be calculated by subtracting the average flow from the average precipitation. Although this is a simplistic method, it provides a general indication of the effects of soil soaking and drying across the watershed.

$$P + G_{in} - (G_{out} + Q + ET) = \Delta S$$ **Equation 8-6**

Where:

P: rainfall
G_{in}: groundwater flux into the control volume
G_{out}: groundwater flux out of the control volume

Q: surface flow
ET: evapotranspiration
ΔS: change in storage

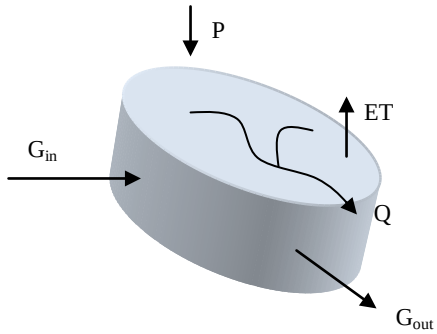


Exhibit 8-16. Components of the Regional Water Balance Equation (Dingman 2002)

8.2.5.3 Thornthwaite Monthly Water Balance

The Thornthwaite monthly water balance is a lumped, conceptual model that estimates evapotranspiration from potential evapotranspiration (PET) and tracks monthly water balance volumes using a simple soil-moisture accounting procedure. Assuming the maximum soil moisture capacity, ϕ, can be estimated for any amended soil areas and non-amended soil areas of a LID study watershed, the monthly depletion and regeneration of the soil moisture can be estimated using monthly rainfall measurements, P_i, and monthly PET, PE_i, estimates. Moisture surplus, Q_i, occurs whenever the actual soil moisture, S_i, exceeds its capacity. This surplus translates to either runoff or groundwater recharge. If monthly runoff volumes, R_i, are available for the watershed, the monthly volume of soil moisture surplus infiltrating to groundwater, G_i, can be estimated. This method incorporates the moisture surplus in the previous month, Q_{i-1}, and the actual soil moisture in the previous month, S_{i-1}. The following Thornthwaite monthly water balance equations (all in units of depth) have been adapted from Alley (1984):

$$S_i = S_{i-1} \exp\left(\frac{-(PE_i - P_i)}{\phi} \right)$$ **Equation 8-7**

$$\Delta Q = \begin{matrix} (P_i - PE_i) + S_{i-1} - \phi \\ 0 \end{matrix} \quad \text{if} \quad \begin{cases} S_i = \phi \\ S_i \neq \phi \end{cases}$$ **Equation 8-8**

$$G_i = Q_i \left(1 - \frac{R_i - \Delta Q}{Q_{i-1}} \right)$$ **Equation 8-9**

Where:
S_i:: soil moisture
S_{i-1}: soil moisture for previous month

P_i: monthly rainfall
PE_i: monthly PET
ϕ: maximum soil capacity
ΔQ: moisture surplus
Q_i: monthly moisture surplus
Q_{i-1}: monthly moisture surplus for previous month
R_i: monthly runoff volumes
G_i: monthly volume of soil moisture surplus infiltrating to groundwater

Values estimated for a certain month depend on those of the previous month, so models using climatic average values should be iterated until equilibrium values are reached. Actual monthly time series are preferred if available. Soil moisture capacity can be estimated as the difference between the field capacity and the wilting point multiplied by the depth of the root zone. These soil properties can be obtained from soil survey data or estimated by experimentation. Monthly PET can be estimated using a reference crop coefficient method or the Penman-Montieth equation as described below in Section 8.3.3.2. For a LID site with multiple distributed practices, the monthly water balance would need to be computed for each practice as well as for the remaining pervious areas of the site. The remaining pervious areas should be divided based on whether they have been impacted by construction and whether they have been restored or amended. Estimates of monthly runoff volumes from impervious surfaces would also need to be accounted for in the water balance. Impervious areas draining to LID practices would need to be carefully estimated and the monthly runoff contributions would need to be accounted for using an appropriate hydrologic method.

In areas with snowfall, temperature data are needed to estimate the snow melt and the buildup of snow pack. Dingman (2002) describes a simple procedure for using a temperature index model to account for the contribution of snow melt. Exhibit 8-17 illustrates the monthly water balance method with consideration for snow melt as proposed by Dingman (2002) for three U.S. cities. The Atlanta, GA water balance shows a relatively constant amount of water input in the form of precipitation (rainfall) throughout the year. There is sharp a decrease in the soil moisture during the heat of the summer months, ostensibly due directly to a dramatic increase in evapotranspiration. There is, however, a soil moisture surplus that occurs in the mild winter months. Omaha, NE, on the other hand, receives its rainfall primarily in the late spring through early fall. A significant amount of snow pack occurs in the winter months and there is a fairly abrupt peak in soil moisture late in the spring that quickly drops down to a low and constant value by the end of summer. In stark contrast to both Atlanta, GA and Omaha, NE, Portland, OR receives nearly all of its water input from late fall through the spring, with very little precipitation throughout the summer months.

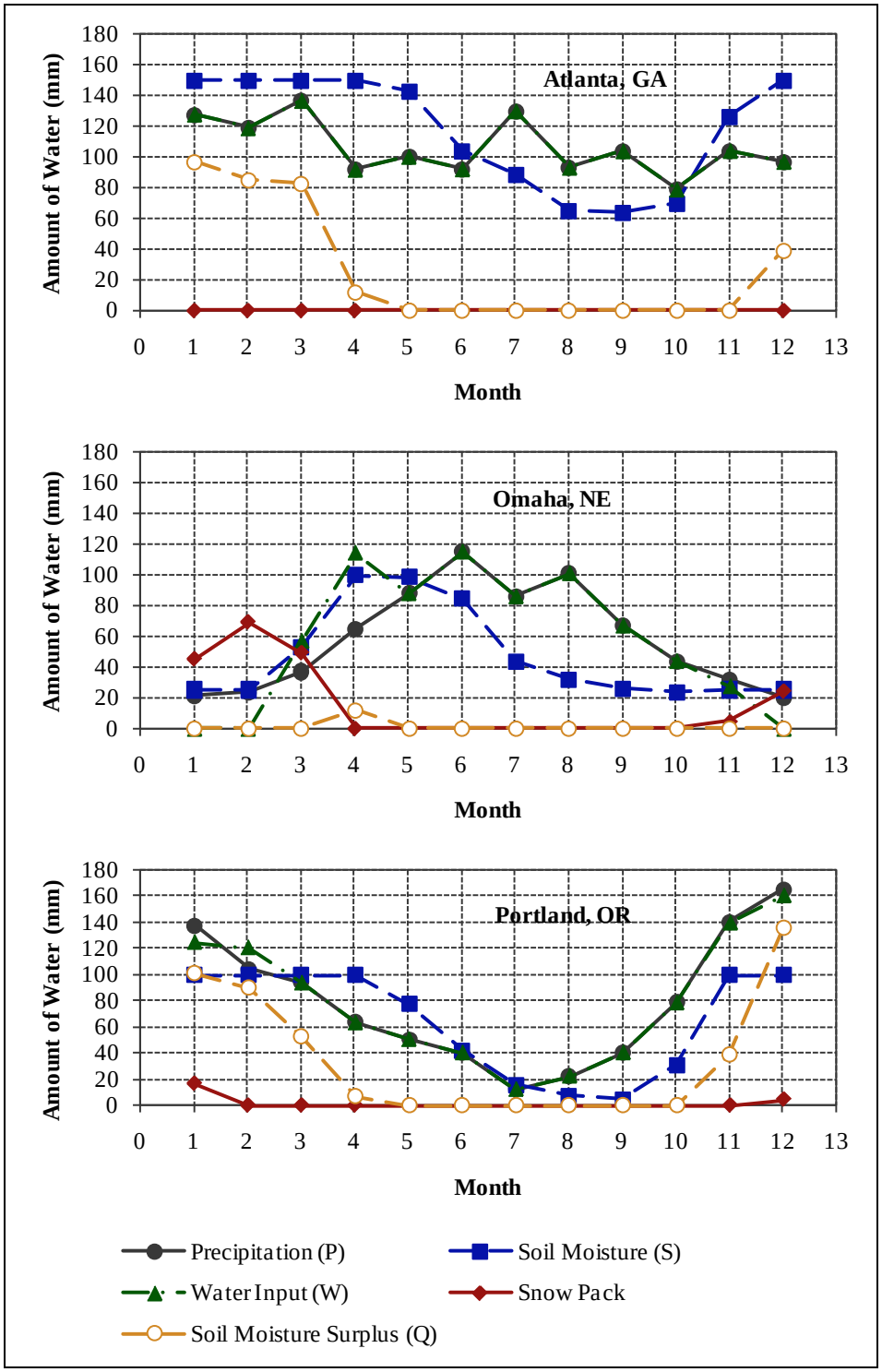


Exhibit 8-17. The Thornthwaite Monthly Water Balance of Three U.S. Cities

8.2.5.4 Long-Term Monitoring and Data Representativeness

When sufficient funding is available for LID monitoring projects, long-term monitoring (e.g., 5 to 10 years) should be seriously considered. Some of the benefits of long-term monitoring of LID sites include:

1) Long-term monitoring helps answer many questions that persist about the effectiveness of LID practices seasonally and over time, as opposed to short term LID monitoring which only provides limited information about the immediate response of the LID catchment.

2) Long-term monitoring helps determine the long-term water balance for a LID catchment and allows for a greater likelihood that hydrologically representative conditions have occurred.

3) Long-term monitoring increases the number of data points, which helps decrease uncertainty due to measurement errors or the collection of unrepresentative storms or seasons. By increasing the data points, long-term monitoring increases the potential meaningfulness of the comparisons that can be made between watershed conditions before and after LID practices are implemented.

4) With multiple sites containing different LID concepts, long-term monitoring facilitates confident comparisons of treatment efficiency between different test sites.

If long-term monitoring is not feasible due to budget constraints, then care must be taken to characterize the hydrologic conditions under which the sampling is conducted so that collected data from appropriately similar events, or periods within events, are compared. Important hydrological conditions to record are total rainfall depth, average and peak intensity, duration, and preceding inter-event time. These data should be interpreted in the context of the local meteorological patterns. To provide context for monitoring results, it may be useful to estimate the recurrence interval of various characteristics of a monitored storm or to estimate the cumulative contribution of additional storms (i.e., storms that are smaller than or equal to the monitored storm) to the overall rainfall. However, in order to compute these metrics, professional judgment is required as well as an in-depth knowledge about how these metrics will be used to support the study assumptions. In order to reduce problems associated with misinterpreting the data or disparity in methods, these metrics are not requested for input into the database. Instead, only directly measured storm characteristics are requested in the database.

Regardless of whether long-term monitoring is feasible, the usefulness of intra-event measures of performance should be strongly considered to evaluate LID performance (e.g., depression storage, peak lag, changes in time of concentration, slopes of rising and falling hydrograph limbs). As introduced in Section 8.1.3, high-resolution intra-event data may also permit the calibration and validation of continuous simulation hydrologic models that can be used to develop estimates of runoff patterns and long-term hydrologic performance extending well beyond the period of monitoring.

8.3 Data Collection and Reporting

Data collection and reporting for LID studies generally follow the same protocols as those discussed in Chapters 2 through 6 for traditional BMP studies. However, LID studies place more emphasis on documenting the watershed characteristics, as well as the infiltration and evapotranspiration components of the water balance. Following a brief overview of the BMP Database approach to reporting LID, additional guidance is provided about the approaches to characterize impervious area as well as directly and/or indirectly quantify evapotranspiration and infiltration at the site level. Additionally, due to national interest in the costs of LID relative to traditional development, guidance for reporting LID cost information is also provided.

8.3.1 BMP Database Requirements for LID

LID monitoring data requirements for the BMP database are being revised in 2009 and are provided in draft form in Appendix A. These revisions expand the 2008 structural changes that have already enabled incorporation of LID at the overall development level. Examples of features of the database enabling entry of LID studies include:

1) Test Site. An individual test site or monitoring study can include data for multiple test and reference watersheds. PDFs containing detailed photography or geographic information system (GIS) maps to clearly define the spatial location of LID practices in the watershed can be uploaded with the study. These should include an annotation of land treatment (e.g., unimpacted, disturbed, restored, amended soils) and a graphic display of routing patterns (e.g., flow paths of disconnected impervious area over pervious area, delineation of tributary area to IMPs). Additional guidance in preparing these figures/datasets is provided in the User's Guide accompanying the BMP Database Data Entry package.

2) Watershed information. Many watershed characteristics important for documenting LID studies are already included in the BMP Database as described in Exhibit 8-7. Additional fields have been added as part of this revision to more adequately characterize LID watersheds. In the case of nested studies, for example, the same LID feature can be entered into the database differently depending on whether it is one of many components in a site level study or whether it is the focus of a practice level study. In the former case, individual practices are not entered separately, but rather as a part of watershed characteristics. In the latter case, the individual practices can be entered as described in Chapters 1 through 7. (For more information, consult "Specific BMP Information" in number four below.) The BMP Database facilitates the documentation of practice level studies within site level studies. New data requirements are described throughout this chapter and are compiled in Appendix A.

3) General BMP information. General BMP information can be entered for multiple BMPs (including LID techniques) in each watershed monitored. Additionally, researchers can enter a "treatment train BMP" to represent the performance of multiple BMPs in series or a LID watershed draining to a centralized BMP. The 2009

revisions to the BMP Database request additional information on parameters such as maintenance, basis of design and other parameters.

4) Specific BMP information: Reporting parameters for specific individual LID practices are included in the 2009 revisions to the BMP Database for bioretention, green roofs, stormwater harvesting (cisterns), permeable pavement, and site level LID, as summarized in Appendix A. Additional guidance related to nomenclature is provided in the User's Guide accompanying the BMP Database Data Entry package.

5) Monitored events: Reporting requirements generally remain the same as the previous version of the BMP Database; however, finer resolution monitoring can allow researchers to accurately capture the relatively lower flows and durations of flows expected to occur in small subcatchments with LID practices. The total duration of LID monitoring events should be carefully considered because LID practices utilize mechanisms that have larger time scales for treatment (i.e., evapotranspiration and infiltration). Event monitoring duration should be representative of the time scale of the treatment and any temporal changes that might affect treatment, such as seasonal effects. If continuous hydrologic records are obtained, data can be reported for individual events within the record or for longer timescales (i.e., by month or by season). As long start and end recording times are accurately entered for each study, reporting of overlapping periods is acceptable. In fact, recording overlapping periods may even enable a more robust interpretation of results.

6) Monitoring stations and monitoring results: Flow and water quality monitoring results for LID practices is the same as the previous version of the BMP Database. Additional fields for user estimates of the infiltration and evapotranspiration volumes over the duration of the monitoring study may be provided to complete the water balance. (Exhibit 8-18)

7) Subsurface Water Quality: If subsurface water quality is monitored, the user can report the quality of infiltrated water reaching groundwater. The user may enter event mean concentrations for a specific monitoring point, average annual concentrations for either a specific monitoring point or for the entire LID site, and/or estimated total annual pollutant load.

8.3.2 Impervious Surface Data Collection

Quantifying the overall imperviousness of a watershed or a LID study area can be done using a number of techniques such as direct measurement, digitization, or analysis of remotely sensed data. The method chosen depends largely on the size of the study area and available budget.

Direct measurement is the most accurate and the most labor intensive method for estimating imperviousness. All impervious surfaces (e.g., roadways, roof tops, driveways) within the area of interest must be discretely measured using either a global positioning system receiver or a surveyor's total station. For very small areas, an engineer's level and a tape measure can suffice.

Digitization is another method for estimating imperviousness. This method involves delineating impervious surfaces using aerial photographs, satellite images, development plans, as-built drawings, or other spatial data sources that accurately and clearly depict the land cover. Digitization is best done using GIS software. The accuracy of digitization is a function of the spatial and spectral resolution of the data, as well as the accuracy (and meticulousness) of the digitizer and/or robustness of the digitizing algorithms. If aerial photographs or satellite images are used, the impervious surfaces may be partially or fully obscured by mature trees or other vegetation which may also affect the accuracy of the digitization process. However, it should be noted that impervious surfaces with canopy (ISWC) would not have the same hydrologic response as impervious surfaces without canopy (ISWoC) because a significant amount of rainfall could be intercepted on the leaves and stems of trees. If a study area has significant vegetative cover over impervious areas during the wet season, then both the ISWC and ISWoC should be estimated and reported. When interpreting these data, however, note that the amount of water intercepted in tree canopies may depend on the intensity of rainfall and the strength of wind.

More automated and accurate methods for estimating impervious surfaces using GIS techniques are also possible with the increased availability of high-quality, remotely-sensed data, such as multi-spectral satellite imagery, panchromatic aerial photography, and light detection and ranging (LiDAR) data, Rogers et al. (2004) used QuickBird satellite data (4-band including near-infrared and true-color) and the Feature Analyst™ extension for ArcGIS™ to identify pervious and impervious areas at the sub-meter level in a study conducted in Santa Barbara County, CA. This study found that the method was 91 to 95 percent as accurate as the manual digitization yet required only a fraction of the labor involved. Similar to digitization of aerial photos, this method only captures ISWoC. Hodgeson et al. (2003) developed a rule-based approach for classifying impervious and pervious surfaces using a combination of high resolution color imagery and LiDAR data that helped identify the height and density of vegetation. This approach resulted in an estimated percent error of 6 to 10 percent. The authors noted that if near-infrared band data had also been included (as in the Rogers et al. study), the estimated percent error may have been less because surfaces within shadows could have been more accurately identified. While more research in the field of digital image processing and spatial data analysis is needed, the high quality data and analytical tools that are currently available allow for cost effective and reasonably accurate estimates of impervious surfaces.

In addition to using these techniques for estimating total impervious area, it is also important to estimate the breakdown of impervious surfaces between directly connected impervious area, area draining to IMPs, and areas that are disconnected via a sheet flow over pervious surfaces. While these estimates are critical for comparative evaluations of LID sites, they can be extremely difficult and tedious to obtain especially for large areas. These estimates are most accurately obtained by direct field assessments of land surfaces and drainage features. For large sites, statistical sampling methods can allow a number of small survey areas to be extrapolated to study level averages. Alternative methods may also include manually analyzing elevation data within computer-aided design or GIS software or using flow direction and flow accumulation procedures within a GIS. Note that rooftops are not well represented using these methods.

8.3.3 Hydrologic Data Collection

The collection of hydrologic data is needed to quantify all elements of the water balance over a specified monitoring period. As discussed above, precipitation and flow monitoring is not significantly different for an individual BMP as it is for an overall LID site. Therefore, the discussion of flow monitoring techniques provided in Chapter 3 is not repeated here. Instead, methods for quantifying infiltration and evapotranspiration, the two most important processes for LID sites, are discussed in detail below. Although development of a precise water balance is likely unrealistic at most sites, it is important to develop at least an approximate understanding of basic water balance components.

8.3.3.1 Quantifying Infiltration

The infiltration rate is a measure of the rate at which soil is able to absorb water during a rainfall-runoff event. Monitoring the subsurface hydrology of a LID site can help determine both the infiltration and subsurface runoff portions of the water balance. Subsurface flows can be estimated using the basic principles of Darcy's Law along with the hydraulic conductivity and piezometer data measured manually or over time with pressure transducers. Lysimeter data should also be collected where possible to monitor soil moisture. Likewise, any shallow bedrock or aquitard layers should be identified. Possible methods and instruments used to determine the bulk infiltrative properties of soils are discussed in the paragraphs below.

Soil Survey Data

The Natural Resource Conservation Service (NRCS) is a federal agency that provides free or low-cost soil survey data. Field Office Technical Guides provide basic soils and soil conservation information about a region. The NRCS website (http://www.nrcs.usda.gov) also provides electronic datasets for use in GIS applications from several federal agencies (e.g., USGS, US Census Bureau). The datasets contain information about the basic soil types and distributions. This information can be used to estimate soil properties, such as infiltration and field capacity, and appropriate site comparisons. These characteristics affect the sponge factor of the site. A general LID design principle is to preserve soils with naturally high infiltration capacities, opting instead to disturb those that are less pervious.

Lab Classification of Soil Samples

Lab classification of soil samples can also be an effective way to estimate infiltration rates. When using this method, care should be taken to obtain samples at sufficient horizontal and vertical resolution in order to adequately characterize the variability of soil properties. This is especially important when conducting a site level study. Various methods of extrapolating soil properties and infiltration rates exist. Estimating *in situ* infiltration rates should be conducted to whatever degree possible.

Ring Infiltrometers

Ring infiltrometers are impermeable rings that can be used to measure the vertical infiltration at the ground surface. Either sealed at the ground or slightly inserted into the ground, water

is fed into the infiltrometer at a rate which induces ponding. The rate of infiltration can then be calculated by measuring the rate at which the water level falls, the flow rate required to maintain a constant water level, or by solving a basic water balance for the ponding water. Single-ring infiltrometers can lead to artificially high measurements due to horizontal migration of the infiltrating water. To mitigate this, double-ring infiltrometers can be used. While both rings are filled equally with water in a double-ring infiltrometer, the outside ring provides a saturated buffer for the inner ring while data are collected from the inner ring only. While double ring infiltrometers may overpredict infiltration rates compared to what might actually occur if the entire area is saturated during an event, they can still produce useful data. Further discussion about the scientific basis and application of infiltrometers is beyond the scope of this document.

Water Level Observations

Monitoring can be regularly conducted using standard water level indicators. For example, piezometers and monitoring wells can be used to measure the piezometric head of the groundwater system. Pressure transducers can also be employed to continuously record the levels at sampling rates selected by the design team. Implementing these techniques allows scientists and engineers to see how the groundwater responds to storm events, drought periods, and seasonal changes. These same techniques can be used to measure the water level in storage structures and small streams in order to further refine LID site water balance estimates.

Sprinkler Plot Studies

Sprinkler plot studies can be performed on a control parcel of land with vegetation that is representative of the overall site. Constant rainfall is artificially simulated at such a rate that produces the condition of saturation from above requisite for infiltration studies. The difference between the known water input rate (w) and the measured runoff as a function of time (q) is the measured infiltration rate as shown below:

$$I(t) = w - q(t)$$ **Equation 8-10**

Where:

- I: infiltration rate
- t: time
- w: water input rate
- q: measured runoff

Soil Moisture Profiles

Tensiometers can be installed at several depths within a soil profile to measure the moisture content. A tensiometer is a device that contains a tube of water that is sealed off from atmosphere at the top and capped with a porous stone at the bottom. The soil surrounding the device is free to pull water through the porous stone, creating vacuum pressure inside the tube. By monitoring this pressure through time, the moisture content and suction head of the soil can be determined. Tensiometers can indicate a dramatic increase in soil moisture as the

wetting front progresses downward. The infiltration rate can then be estimated from those data. Similarly, the drying of the soil profile due to evapotranspiration can be observed.

8.3.3.2 Quantifying Evapotranspiration

Evapotranspiration is the process through which liquid water and ice is converted to water vapor in the atmosphere: surface water can evaporate directly into the atmosphere; plant leaves can transpire water collected by their roots and leaves; and ice can sublimate directly into gas form. The amount of evapotranspiration that occurs at a particular place in time depends on many factors such as the ambient relative humidity, amount of water available to the atmosphere, and the vegetative cover.

Evapotranspiration can be measured with varying degrees of confidence. Consequently, it is important to pair the sophistication of the measurement method with the accuracy required in the study. For example, evapotranspiration is a critical performance factor for green roofs and should be measured with a high level of accuracy. However, evapotranspiration is less important for bioretention BMPs without underdrains because losses tend to be dominated by infiltration. In this case, less sophisticated measurements may be satisfactory. The following paragraphs describe some methods of measuring or estimating evapotranspiration.

It is important to note that equations for estimating evapotranspiration and the coefficients to adjust measured evapotranspiration are generally based on crops growing in fields, and not BMPs. Appropriate consideration should be given to microclimate, vegetation type, and vegetation density in estimating evapotranspiration from BMPs. The Landscape Coefficient Method (University of California Cooperative Extension, 2000) is a recommended method for translating reference evapotranspiration values to evapotranspiration rates of various landscaping.

Potential Evapotranspiration

The potential evapotranspiration (PET) is a measure of the ability of local climate or meteorological conditions to remove water from the surface landscape. Basically, PET is the maximum amount of water an atmosphere can accept from the ground and vegetation below. It does not depend on the amount of water actually present, which if limited would cause the actual evapotranspiration to be less than the PET. PET is often estimated through the use of a reference crop, typically alfalfa or a short grass. The reference evapotranspiration (ETo) represents the PET from the selected reference crop in full sun with constant supply of water, and can be measured with atmometers as discussed in Chapter 3. The measured ETo can be adjusted for different types of vegetation, vegetation densities, and microclimates (University of California Cooperative Extension 2000).

Lysimeters

Weighing lysimeters are vegetated enclosures of soil through which the flow of water (precipitation and drainage) can be measured by determining the mass of the entire enclosure. The evapotranspiration can thus be determined by completing the water balance within the control volume defined by the lysimeter boundary. Typically, the volume of a lysimeter

ranges from 1 m^3 up to 150 m^3, though portable ones with areas of 0.2 m^2 are also available. Construction drawings for lysimeters have been previously published in Dunne and Leopold (1978), Brutsaert (1982), and Shaw (1988). Water quality monitoring lysimeters are used to sample water from the pore space in soil, however they do not provide the data needed to estimate evapotranspiration.

Note that some researchers use the term "lysimeter" to refer to devices that measure the suction head of a soil. A tube is typically filled with water, capped at the bottom with a porous stone, and then sealed up top. By measuring the pressure inside the tube, the suction head of a soil can be measured. Throughout this document, these devices are referred to as tensiometers as discussed previously in Section 0. The term "lysimeter" will exclusively refer to the device described in the previous paragraph.

Use of Meteorological Data

Basic meteorological data is required to characterize the hydrologic performance of a site LID. Precipitation data must be available and are preferably collected on site rather than from a nearby weather station because of the significant spatial variation associated with storm events. Precipitation in the form of snow fall should also be carefully considered as the runoff from the event can be delayed by weeks or even months. Additionally, rain events coupled with a thawing snow pack can lead to intense runoff events. Care must also be taken to determine an appropriate snow-water equivalent value; heated and mass-based precipitation gages can facilitate this. Other meteorological quantities such as humidity and wind speed can also be used to estimate the evapotranspiration at a site. While this information can help refine the water balance calculations, it is not necessary for sufficiently accurate estimations.

Pan Evaporation Data

According to Chow et al (1988) and Dingman (2002), evaporation pans are a simple and direct approach used to estimate the free-water evaporation of a site. A cylindrical, open pan of water is used to solve the basic water-balance equation:

$$E_{pan} = W - (V_1 - V_2)$$ **Equation 8-11**

Where:

E_{pan}: evaporation
W: precipitation
V_1: volume of water at the beginning of study period
V_2: volume of water at the end of study period

The precipitation is measured in an adjacent gage, and the volumes are estimated by recording the water level in the pan. Care must be taken to install protection that prevents animals from drinking or bathing in the water. Similarly, when pans are placed over or near open bodies of water, measures should be taken to prevent water from splashing into the pan.

Due to additional heat absorbed by the metal walls of the pan during evaporative summer months, evaporation is typically overestimated. A calibration factor, or pan coefficient of 0.7 is applied throughout the United States. With the pan coefficient, the free-water evaporation can be estimated with the following empirical equation:

$$E_{fw} = 0.7 \cdot \left(E_{pan} \pm 0.064 \cdot P \cdot \alpha_{pan} \cdot \left(0.37 + 0.00255 \cdot v_{pan}\right) \cdot \left| T_{span} - T_a \right|^{0.88} \right) \qquad \textbf{Equation 8-12}$$

Where:

E_{fw}: free-water evaporation
α_{pan}: the ratio of energy exchanged through the sides of the pan to evaporation
T_{span}: surface temperature of the water in the pan
T_a: temperature of the atmosphere
v_{pan}: wind velocity 15 cm above the pan.

Note: The expression to the right of E_{pan} is added (+) if $T_{span} > T_a$ and subtracted (-) if the opposite is true. The value of α_{pan} can be estimated as shown:

$$\alpha_{pan} = 0.34 + 0.0117 \cdot T_{span} - \left(3.5 \times 10^{-7}\right) \cdot \left(T_{spac} + 17.8\right)^3 + 0.0135 \cdot v_{pan}^{0.36} \qquad \textbf{Equation 8-13}$$

<u>Penman-Montieth Equation</u>

Estimating the evapotranspiration of a vegetated surface can be done via the Penman-Montieth equation. It has been widely tested and has been accepted for use over a variety of vegetated land surfaces, though it cannot be applied to bodies of open water. The equation is very data intensive and requires monitoring and calculation of such quantities as humidity, vapor pressure of water in air, atmospheric resistance, and net radiation flux of the ground surface among others. For this reason, Penman-Monteith is typically best implemented with numerical modeling. The equation has the following form:

$$\lambda ET = \frac{\Delta\left(R_n - G\right) + \rho_a c_p \left(\dfrac{e_s - e_a}{r_a} \right)}{\Delta + \gamma \left(1 + \dfrac{r_s}{r_a} \right)} \qquad \textbf{Equation 8-14}$$

Where:

R_n: net radiation
G: heat flux of the soil
ρ_a: density of air
c_p: specific heat of air
e_s: saturated vapor pressure of air
e_a: actual vapor pressure of air
Δ: slope describing the relationship between e_s and temperature
γ: psychrometric constant

r_s: surface resistance
r_a: aerodynamic resistance
λ: latent heat of vaporization
ET: mass of water evapotranspired per unit area

To calculate the various quantities required to use the Penman-Monteith equation, the reader should refer to any number of hydrology textbooks such as Dingman (2002).

The PET estimated through the Penman-Monteith equation or with similar equations can be reported in real-time by using weather stations that collect the necessary inputs for those equations. This is a common method, especially when the accuracy of evapotranspiration measurements is not crucial.

8.3.3.3 Reporting of Water Balance Results

The new BMP Database facilitates reporting of water balance results for site level LID studies. Water balance may be estimated based on regional inputs or site level monitoring. In either case, it is recognized that water balance cannot be directly observed and professional judgment is required. Exhibit 8-18 describes the data entry fields associated with water balance.

Exhibit 8-18. Reporting Format for Water Balance Results

Entry Field	Description
LID Watershed ID	This should correspond with the ID entered with the watershed characterization data.
Time Scale of Estimate	The options include: • Discrete monitoring period • Long-term estimate
Start Date (if discrete monitoring period)	This is the beginning of period for which the estimate applies.
End Date (if discrete monitoring period)	This is the beginning of the period for which the estimate applies.
Total Precipitation	This should be entered as totals for discrete monitoring period, or as an annual average water balance for long-term estimate.
Total Evapotranspiration	
Total Surface Discharge	
Total Discharge to Groundwater	
Method of Estimate	This is a user narrative that includes supporting calculations; it is encouraged to be submitted with entry.

8.3.4 Water Quality Data Collection

Water quality monitoring guidance provided in Chapter 4 is also applicable when considering an entire LID site. The same water quality field parameters and pollutants at a LID site should be measured and controlled per applicable local, state, and federal regulations and permits. However, monitoring strategies for LID sites change when monitoring the distributed controls. For example, determining event mean concentrations for runoff events requires accurate flow rate measurements and frequent sampling, often with expensive automated sampling equipment that may be uneconomical to apply to multiple distributed controls. In this scenario, grab samples of surface runoff at locations of interest may be the only feasible monitoring strategy.

Sampling techniques for subsurface water largely depend on the type of water to be monitored. For example, groundwater can typically be pumped from a monitoring well and sampled after a certain purged volume has been removed. Pore water in the unsaturated zone can be extracted by applying vacuum pressure to a tensiometer and sampling the removed water. Tensiometer sampling at increasing depths can track pollutant removal with depth at infiltration-based practices such as rain gardens and roadside swales.

Depending on the study objectives, subsurface water quality data monitoring locations may be strategically selected to monitor critical contamination pathways. Pitt et al. (1994) suggest a three pronged approach for assessing the risk of groundwater contamination based on:

- Abundance of pollutant in stormwater (relative to concentrations of concern)
- Treatability of pollutant through sedimentation (based on dissolved fraction)
- Mobility of pollutant in vadose zone (based primarily on partitioning)

Subsurface monitoring should be primarily focused where runoff concentrations of critical pollutants are high enough to potentially impact groundwater, where treatability of runoff pollutants is low, or where pretreatment of pollutants is limited. This type of monitoring should also focus on areas where the mobility of the pollutant in the vadose zone is high or not well understood.

8.3.5 Cost Data

Currently, many communities have significant questions about the economics of LID and the costs and benefits of LID relative to traditional development practices. The EPA (2007) summarizes the economics of 17 LID field case studies by directly comparing the LID design cost with an expected traditional design cost for each site. The case studies are located in many different regions of North America. The EPA study found that nearly all cost studies aggregate all material or all labor costs into large cost items rather than dividing or itemizing costs into individual LID elements within the watershed. Because of this, it is difficult to assign unit cost benefits based on individual LID practices.

Another challenge when analyzing costs studies is the lack of common baseline in which to compare different LID and traditional cost studies. Thus far, cost studies only address the capital savings from the construction of LID projects, such as a reduction in infrastructure, materials, and labor costs. Few studies assess the larger picture (life cycle) or potential benefits from LID concepts. This is mostly due to the uncertainty and difficulty of monetizing ancillary benefits of LID, such as the environmental benefits. The list below outlines points that should be included in future cost studies.

1) Potential increase of property values because of aesthetics, reduction in flooding, and so forth.

2) Savings by avoiding fines for failure of compliance with regulations (e.g., combined sewer overflow reduction).

3) Savings or additional costs associated with maintenance.

4) Savings by avoiding other potentially costly water quality treatment methods.

5) Savings from potential environmental benefits downstream.

6) Stormwater compliance credits.

7) Full life cycle costs.

Currently, the BMP Database includes cost data inputs. Cost data related to LID currently include a field to represent the "differential cost" of the site compared to traditional development. As LID concepts are added and finalized, some changes or additions may be made to include costs of LID practices.

It is recommended that the Water Environmental Research Foundation (WERF) Whole Life Cycle (WLC) cost models (Pomeroy et al. 2009, adjunct to Lampe et al. 2005) be used to document the whole life cycle cost of proposed BMPs in order to ensure the transparency of estimates for individual facilities. BMPs supported by the WLC model include:

- Retention Pond
- Extended Detention Basin
- Swale
- Permeable Pavement
- Green Roof
- Large Commercial Cistern
- Residential Rain Garden
- Curb-Contained Bioretention
- In-Curb Planter Vault

Users are encouraged to submit WERF WLC cost sheets with BMP Database study entries.

8.4 Conclusions

LID site monitoring introduces a variety of challenges and requires careful study design, documentation and implementation. It is recommended that study design be based on monitoring objectives, site specific conditions, budget, and desired accuracy. Generally a reference watershed approach is necessary to achieve monitoring objectives, and factors associated with the selected reference system are expected to heavily influence study design. Compared to conventional practice-scale monitoring, more thorough site characterization is recommended and additional instrumentation may be required to provide this characterization. Factors critical to LID site characterization include flow patterns, imperviousness characteristics, soil and groundwater conditions, watershed storage conditions, and water balance components. Composite characterization indices and metrics may be useful to quantify the extent of LID implementation and allow comparison between studies.

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