Chapter 9
DATA INTERPRETATION AND PERFORMANCE EVALUATION OF LID MONITORING STUDIES

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. Data obtained from LID monitoring studies can differ in important ways from data obtained in studies of conventional Best Management Practices (BMPs). Differences include:

- LID strategies tend to emphasize reduction in volume rather than reduction in concentration.
- The concept of an "influent" stream is not relevant in the context of a site-level study.
- Time scale of monitoring required to obtain representative data may be much longer than for a site-level LID study than a conventional study.

The careful interpretation and evaluation of data is critical in reaching appropriate conclusions about volume reduction and water quality benefits of LID. The purpose of this chapter is to recommend ways to interpret and evaluate hydrologic and water quality data obtained from LID monitoring studies to quantify the performance of the LID system, both absolutely and in comparison to conventional BMP implementations. This section first discusses volume reduction, which is perhaps the most important mechanism of LID and has important effects that carry through into water quality benefits and load reduction. This discussion considers both site-level studies and practice-level studies. Water quality benefits and load reductions are discussed primarily for LID site-level studies because the interpretation of water quality data from individual BMP studies is already considered in Chapter 7. Finally this section discusses ways of comparing volumetric and water quality performance of LID practices and sites to that of other BMPs.

9.1 Drawing Appropriate Conclusions Regarding Volume Reduction

Surface runoff volume reduction is an important component of the overall effectiveness of LID and BMP systems. Surface volume that is eliminated in BMPs does not directly discharge to the downstream drainage systems, reducing demand on system capacity and the hydraulic/sediment entrainment and transport impacts that increased runoff volumes may cause. In addition, reduction of surface runoff volume plays an important role in reduction in pollutant loadings to surface waters.

In general, LID monitoring studies attempt to answer one or more of the following questions regarding runoff volume reduction:

- How much runoff volume is reduced by a LID practice or a LID site on a long term average basis?

- How much runoff volume is reduced by a LID practice or a LID site under conditions specified for regulatory purposes (e.g. a specific design storm)?

- What affect does a LID practice or a LID site have on the frequency and timing of runoff leaving the site?

- How does a LID practice or a LID site impact the overall water balance of the site on a long term average basis? (i.e., How are deeper infiltration, evapotranspiration, and runoff balances changed?)

Because these questions generally relate to long-term hydrologic performance, and because hydrologic conditions at any given time are usually not average, volumetric data obtained from monitoring studied must be interpreted in the context of the hydrologic conditions preceding, during and following the study. Because monitoring studies are seldom conducted over a sufficiently long period to ensure average conditions have been documented, a major goal of data interpretation should be to appropriately extrapolate measured data to a broader context.

9.1.1 Data Recorded in the BMP Database

Exhibit 9-1 shows data fields recommended to be reported in BMP/LID studies and their relevance in interpreting volumetric results.

Exhibit 9-1. Recommended Reported Data and Relevance in Reaching Volume Reduction Conclusions

Reported Data	Currently Included?	Relevance in Volume Reduction Conclusions
Watershed Location	Yes	This permits analysis of precipitation patterns characteristic of the study location.
Watershed Area	Yes	This establishes total area tributary to monitoring point, coupled with precipitation depth and watershed rainfall-runoff characteristics. This represents the "inflow" to the system for site-level studies.
Watershed Imperviousness	Yes	This is an indicator of development density, related to quantity of runoff. It can be used as one of several factors to normalize runoff volume in comparisons between sites.
Predominant In-situ Surface and Near Surface Soil Types (developed condition)	Yes	This is an indicator of quantity of runoff in the monitored condition and is useful in understanding the importance of runoff, evapotranspiration, and deeper infiltration patterns from pervious areas of the watershed.
Reporting Period (Start and End Date/Time)	Yes	This establishes the time scale of the study, the season of year, and various corresponding factors (e.g., vegetation status, precipitation patterns, evapotranspiration rates, frozen ground).
Precipitation Start Time	Yes	This establishes the time of day for start of precipitation and various corresponding factors (e.g., fraction of average, seasonal, or monthly evapotranspiration, temperature).
Precipitation End Time	Yes	This establishes the duration of precipitation.
Precipitation Depth	Yes	This establishes the total input to system. When coupled with watershed area, this represents the "inflow" to the system for site-level studies. In above-ground practice-level studies, this represents the volume added directly to a practice.
Average Precipitation Intensity (Computed from Depth and Duration)	Yes	This is an indicator of the amount of runoff likely from pervious areas of the watershed and the average loading rate of pervious areas receiving run-on from impervious areas.
Antecedent Dry Period	Future	This is an indicator of antecedent watershed conditions and potential for dry weather pollutant build up.
Description of Antecedent	Future	A narrative description of conditions immediately prior to the start of monitoring, including key field notes,

Reported Data	Currently Included?	Relevance in Volume Reduction Conclusions
Watershed/Facility Conditions (narrative)		frozen ground conditions, facility storage available, high groundwater, etc.
Total Inflow Volume to BMP (Practice-level Only)	Yes	For practice-level studies, this provides precise quantification of discharge from watershed and inflow volume to LID practice.
Total Surface Discharge Volume (from BMP if Practice-level Study; from Watershed if Site-level Study)	Yes	This establishes the total discharge volume from monitored area, inclusive of the effects of LID practices in watershed and monitored LID practice (if present).
Observed or Estimated Drawdown Time of Total Storage from Brim Full	Yes	This establishes the time required to empty the facility and make storage available for subsequent storms. It is useful in efforts to calibrate models of the system or extrapolate limited datasets to long-term performance through rainfall analysis. This can apply to individual practices or, if designs are consistent amongst distributed controls, to multiple similar features.
Observed or Estimated Drawdown Time of Total Storage from Half Full	Yes	This provides information about the general pattern of the drawn down curve and enables a more robust use of study data.
Describe Key Weather Parameters During Study Period (narrative)	Future	Weather conditions can significantly affect the water balance of LID sites. Frozen soils can reduce infiltration rates; conversely, high ET can increase evapotranspiration rates. Characterization of ET, temperature and other similar factors are important in normalizing comparisons among LID sites.
Hydrologically Available Temporary Storage in Watershed (LID site level only as described in Section 8.2.4)	Future	This information helps to normalize the relationship between source areas and storage areas, both in terms of routing and relative volume for purposes of comparing LID sites. Tabular estimates of detained, retained and excess volume for a range of storm events are beneficial in developing these estimates. A PDF providing this information can be attached separately, or this information can be summarized narratively. Also provide units of measurement (e.g., acre-feet, watershed inches).
Storage Recovery Rate in Watershed (LID site-level only; described in Section 8.2.4)	Future	This describes the time for the LID site to recover hydrologically available temporary storage. Estimates of minimum, maximum and average recovery rates for retained and detained volumes should be provided.

9.1.2 Metrics for Interpreting Volumetric Results

The type of volumetric data obtainable and interpretation of these data differs substantially between practice-level studies and site-level studies:

- Practice-level studies: Practice-level studies are generally able to directly measure the total inflow to the facility and/or the total discharge from the facility. In the absence of a defined inflow, a surrogate such as precipitation depth, tributary area, and runoff coefficient may be used if the watershed is sufficiently well-defined (such as a roof-top or small parking lot). The intent of practice-level studies is to accurately quantify the volume reduction in a specific facility during a set of monitored storm events and, generally, to extrapolate these results to long-term hydrologic performance of that facility.

- Site-level studies: Site-level studies are generally able to measure the discharge from the system directly, but are not able to quantify the amount of surface runoff generated on-site and removed before reaching the outlet. Rather, the precipitation depth over the monitoring period represents the overall inflow to the system. The intent of site-level studies is to quantify hydrologic response during a set of monitored storm events, and generally, to extrapolate these results to long-term hydrologic response in comparison to other sites/watersheds.

Exhibit 9-2 provides a list of simple metrics than can be calculated for each event or monitoring period and analyzed in combination with storm characteristics or monitoring period total precipitation. These metrics are described individually in the paragraphs below.

Exhibit 9-2. Simple Metrics for Interpreting Single-Event Volumetric Data

Metric	Application
Presence/Absence of Discharge	Practice level and site level
Absolute Volume Reduction (In – Out)	Practice level only
Relative Volume Reduction (In – Out)/In	Practice level only
Discharge Volume per Area	Practice level and site level
Discharge Volume per Impervious Area	Practice level and site level

Care must be taken to avoid spurious correlations in the analysis of volumetric data. For example, it is convenient to correlate runoff coefficient to rainfall depth; however, because the runoff coefficient has rainfall volume as its denominator, a spurious correlation would be expected even if no genuine correlation existed.

Care must also be taken when averaging performance metrics from individual events. In some cases, an average may have relatively little utility in describing long term conditions. For example, the average of a ratio-based metric, such as relative volume reduction [(In –

Out)/In], would implicitly be biased towards events that occurred or were monitored most frequently rather than being weighted by event volume. Thus this average could not help provide an estimate of overall long term volume reduction performance. In other cases, averages may be more meaningful in theory, but limited by the representativeness of monitored events. For example the average of absolute volume reduction [In – Out] would only be expected to produce meaningful results if it was based on a monitoring period containing a representative distribution of inflow volumes.

The following methods are suggested for interpreting trends in volume reduction metrics:

- Scatter Plots
- Histograms
- Within-Storm Time Series

Examples of the use of scatter plots and histograms to visualize the simple metrics described above are provided in the sections below. For most studies entered into the BMP Database, time series data are not available. Therefore, the Within-Storm Time Series method is not discussed further in this document.

Presence/Absence of Discharge (Practice and Site Level)

Presence of discharge is a simple, informative metric that can be used to extrapolate the ability of systems to control the frequency of discharge. If a sufficient number of storms are monitored, data may be used directly to support conclusions regarding the threshold of discharge (e.g., the smallest storm to produce discharge was X, or the largest storm to produce no discharge was Y) or a probabilistic description of discharge (e.g., 90 percent of storms less than 1 inch produced measurable discharge, 50 percent of storms less than 0.7 inches produced no discharge). Such conclusions implicitly account for the various antecedent conditions encountered over the monitoring period. Given appropriate consideration for data representativeness and number of samples, these results can be used to make meaningful statements about the performance of the system. As some water quality criteria have an allowable exceedance frequency, information on the frequency of discharge can be important.

For site-level studies, there may be directly connected impervious areas (DCIA) downstream of the lowest LID feature but upstream of the monitoring location. This area would be expected to produce discharge in all but the smallest events; therefore the concept of a threshold of discharge may not always apply. In these cases, this method of interpretation may not yield meaningful results.

Histograms and probability plots can be effectively used to visualize frequency of discharge. Examples are shown in Exhibit 9-3. The bars on the chart represent the number of rainfall events and the number of runoff events, grouped into bins of rainfall depth. Bins are defined by their upper limit. For example, the bin labeled as 0.6 inches includes all events greater than 0.5 inches and less than or equal to (LTE) 0.6 inches. In the example below, 6 storm events fell into this bin and 4 of them produced runoff. The red dashed line plots the percentage of monitored events producing runoff in each bin.

Exhibit 9-3. Example Histogram of Frequency of Rainfall Events and Discharge Events for a Hypothetical Site-level Study

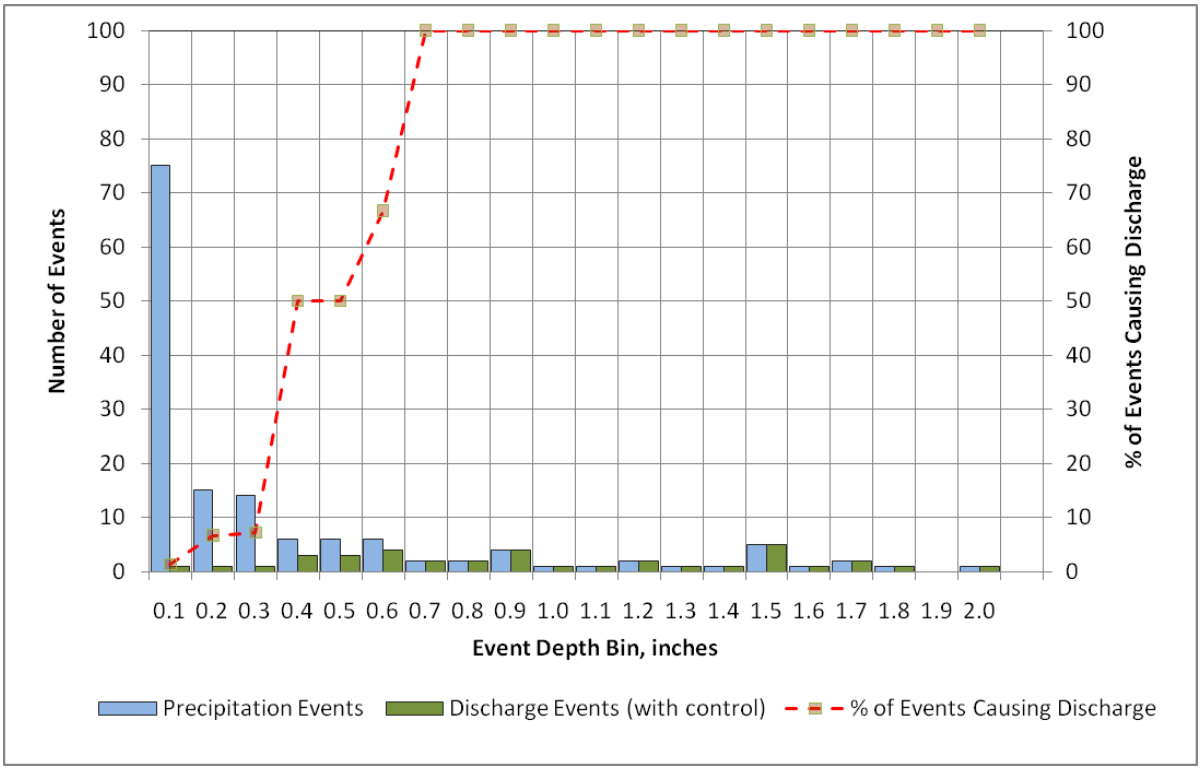


Exhibit 9-3 illustrates a way of visualizing the threshold of discharge from an example LID watershed as a function of depth. During the hypothetical monitoring period, no storm greater than 0.6 inches was completely retained, while at least minimal discharge occurred in one storm less than 0.1 inches. Likewise, during this monitoring period, three out of six events between 0.4 and 0.5 inches (bin labeled "0.5") caused discharge. Similar observations of this nature could be made from this chart.

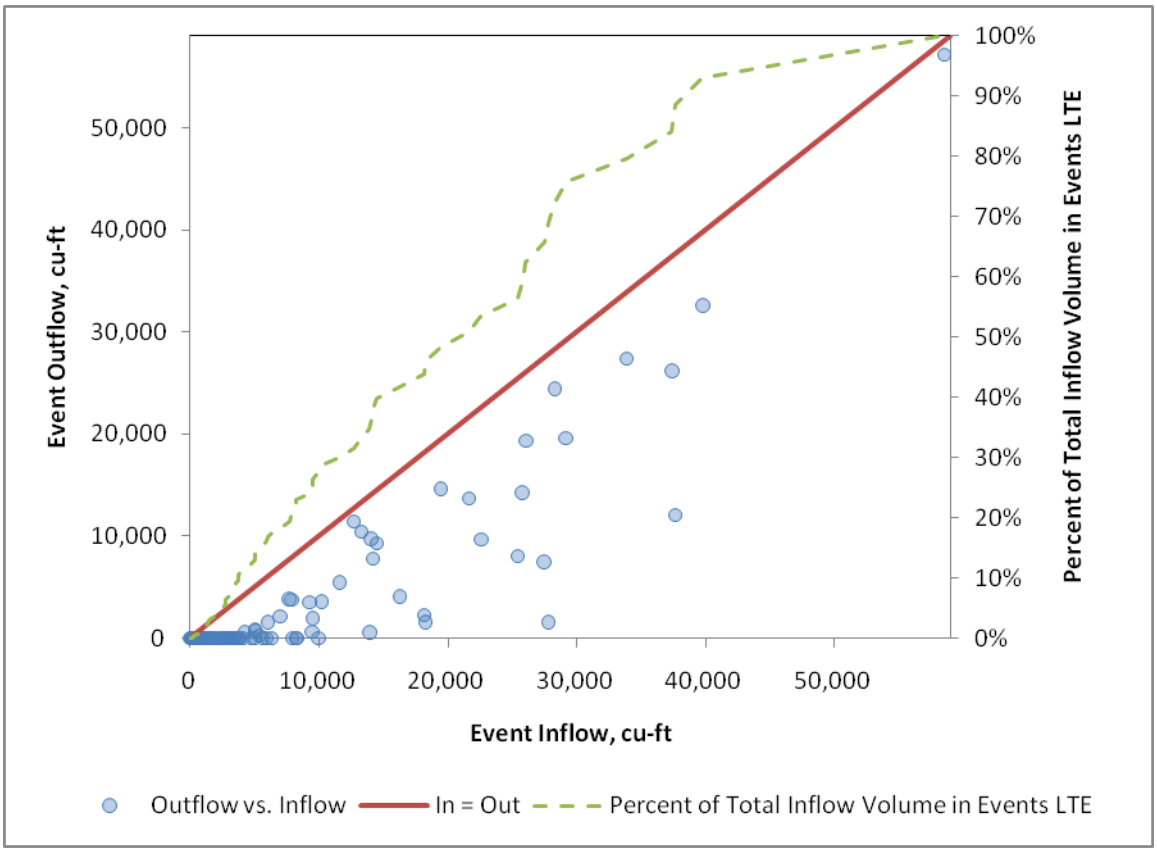
This method of analysis should not be used to estimate the cumulative volume reduction of the system, as the plot contains no data regarding the amount of volume reduced when discharge did occur.

Absolute Surface Runoff Volume Reduction (Practice Level only)

Absolute surface runoff volume reduction is simply the difference between inflow and outflow runoff volume for a specific monitoring event. This metric is informative in describing long-term hydrologic conditions if a sufficient number of events are monitored. To estimate long-term volume reduction, absolute volume reductions should be summed over a representative number of storm events and then divided by the total inflow volume to the facility over the same period of time. The method implicitly accounts for antecedent conditions, and would theoretically provide greater confidence in estimates as more data are added.

A scatter plot of event inflow versus outflow can be used to visualize the performance of the facility as a function of inflow volume (Exhibit 9-4). In this chart, blue circles represent individual event data. The "In=Out" line represents the performance that would be expected if no volume reduction or addition occurred in the practice. Points above this line would represent monitoring events with greater outflow than inflow, which could result from saturated antecedent conditions, high groundwater, and/or measurement errors. The dashed line represents the percentage of the total inflow volume occurring in events with inflow less than or equal to the X ordinate at each point.

Exhibit 9-4. Example Scatter Plot of Event Outflow Volume Versus Event Inflow Volume from a Hypothetical LID Practice-level Study

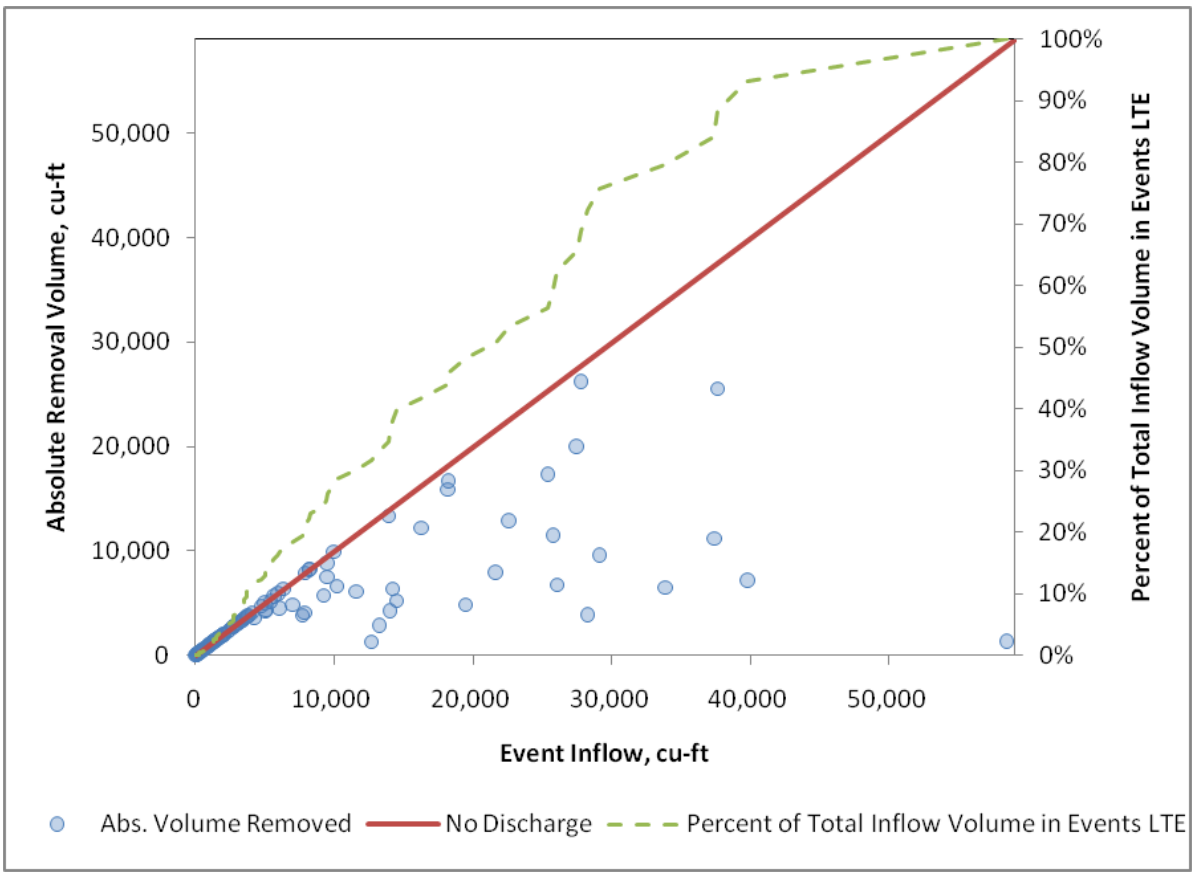


LTE = Less than or equal to (the X ordinate value)

Exhibit 9-4 illustrates the concept of a threshold inflow volume (in this case, approximately 6,000 cu-ft) below which discharge rarely occurs. It also illustrates a range (in this case, approximately 6,000 cu-ft to 30,000 cu-ft inflow volume) over which volume reduction ranges widely, from less than 5,000 cu-ft to more than 25,000 cu-ft. The variability over this range of inflow is explained by this range of inflow volume being similar to the storage volume of the LID practice. Low volume reductions could potentially be attributed to relatively short and intense storms following a previous storms (when the facility may be partly full), while higher volume reductions could potentially be attributed to longer, less intense storms occurring when the storage was at or near "empty" prior to the storm or where the inflow rates did not exceed infiltration rates or a combination.

Meaningful relationships can also be developed between absolute volume reduction and total inflow volume (see Exhibit 9-5). In this chart, the blue circles represent paired X-Y data, where the X ordinate is the inflow volume and the Y ordinate is the absolute volume reduction [In – Out]. The solid "No Discharge" line corresponds to the performance that would be expected if all inflow was removed from surface discharge in the practice. No points are expected to be above this line. For studies with data points showing measured outflow greater than measured inflow, negative Y values would be expected. The dashed line represents the percentage of the total inflow volume occurring in events with inflow less than or equal to the X ordinate at each point.

Exhibit 9-5. Example Scatter Plot of Event Absolute Volume Reduction Versus Event Inflow Volume from a Hypothetical LID Practice-level Study



LTE = Less than or equal to (the X ordinate value)

Exhibit 9-5 represents a different way of looking at the same data as Exhibit 9-4, and the same conclusions can be drawn regarding threshold of discharge and variability of volume reduction. Depending on the characteristics of the dataset, this method of visualization may better facilitate interpretation of these factors.

The cumulative percentage of inflow at each X ordinate relative to total inflow volume (dashed line) is informative in understanding the relative importance of different ranges of inflow volumes on overall performance. For example, storms that rarely result in surface

discharge from the practice (<6,000 cu-ft inflow) account for approximately 20 percent of total precipitation volume. Storms in the range over which volume reductions vary greatly (6,000 to 30,000 cu-ft) account for approximately 50 percent of total precipitation volume. Storms in the range over which practices have little effect on discharge volume (>30,000 cu-ft inflow) account for the remaining 30 percent of rainfall volume in this example.

Relative Volume Reduction (Practice Level only)

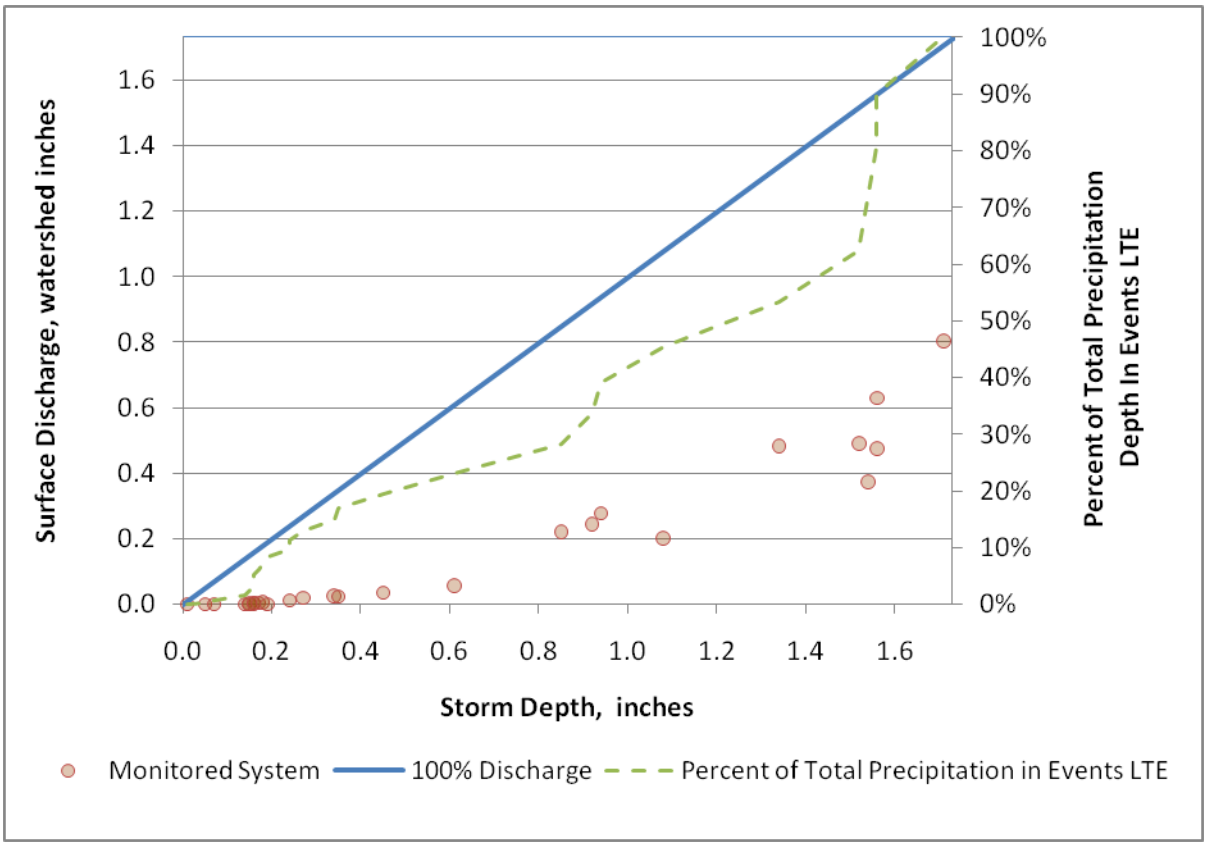
Relative volume reduction or "percent volume reduction" can be calculated for an individual storm as simply the difference between inflow and outflow divided by the inflow. This metric is informative for an individual storm event, but is prone to inappropriate interpretation if the results from individual storm events are simply averaged to yield an estimate of long-term volume reduction. For example, all storms less than the facility retention volume would be recorded as 100 percent volume reduction despite the range of storm depths this could include. Likewise large storms that cause significant discharge (i.e., low percent volume reduction) would only be recorded as one data point despite the fact that they may account for a much larger share of the total volume. Thus, this method of interpretation has limited use in extrapolation to broader conclusions.

Discharge Volume per Area (Site and Practice Level)

The discharge volume per area is calculated as the measured volume of discharge divided by the area of the tributary watershed. For one-to-one comparison to precipitation depth, this volume can be expresses as "watershed inches." The ratio of discharge volume to precipitation volume is typically referred to as the runoff coefficient; however it is expected that this runoff coefficient would be different for different size storm events and antecedent conditions. The trend of discharge volume per area with precipitation depth can be useful in extrapolating the long-term discharge volume from the system.

Similar to Exhibit 9-4, discharge volume per area can be plotted against rainfall to facilitate interpretation of hydrologic response. A hypothetical example is provided below (Exhibit 9-6). In this chart, red circles represent individual event data. The "100% Discharge" line represents the performance that would be expected if 100 percent of rainfall was converted to surface runoff. Values above this line would represent monitored events with greater outflow than inflow, which could result from saturated antecedent conditions, high groundwater, and/or measurement errors. The dashed line represents the percentage of the total precipitation occurring in events with precipitation depth less than or equal to the X ordinate at each point.

Exhibit 9-6. Example Plot of Discharge Volume per Areas Versus Storm Depth



LTE = Less than or equal to (the X ordinate value)

Exhibit 9-6 enables the visualization of several elements of hydrologic response expected to occur in LID sites level studies. First, for storm depths up to approximately 0.2 inches, no runoff occurs, representing the depression storage in the watershed [i.e., the threshold for runoff to occur, even from directly connected impervious areas (DCIA)]. From approximately 0.2 to 0.5 inches, the slope of the data is relatively shallow indicating that only a small portion of the watershed contributes to runoff, theoretically the portion of the watershed that is DCIA. Beyond the 0.5-inch storm, the slope of the data trends up again, signifying that a greater fraction of the watershed contributes to runoff in larger storms, likely as LID storage features become filled/infiltration rates are exceeded. While strong quantitative interpretations cannot be derived from this type of analysis, it is useful in order to gain a better understanding of hydrologic response of a watershed.

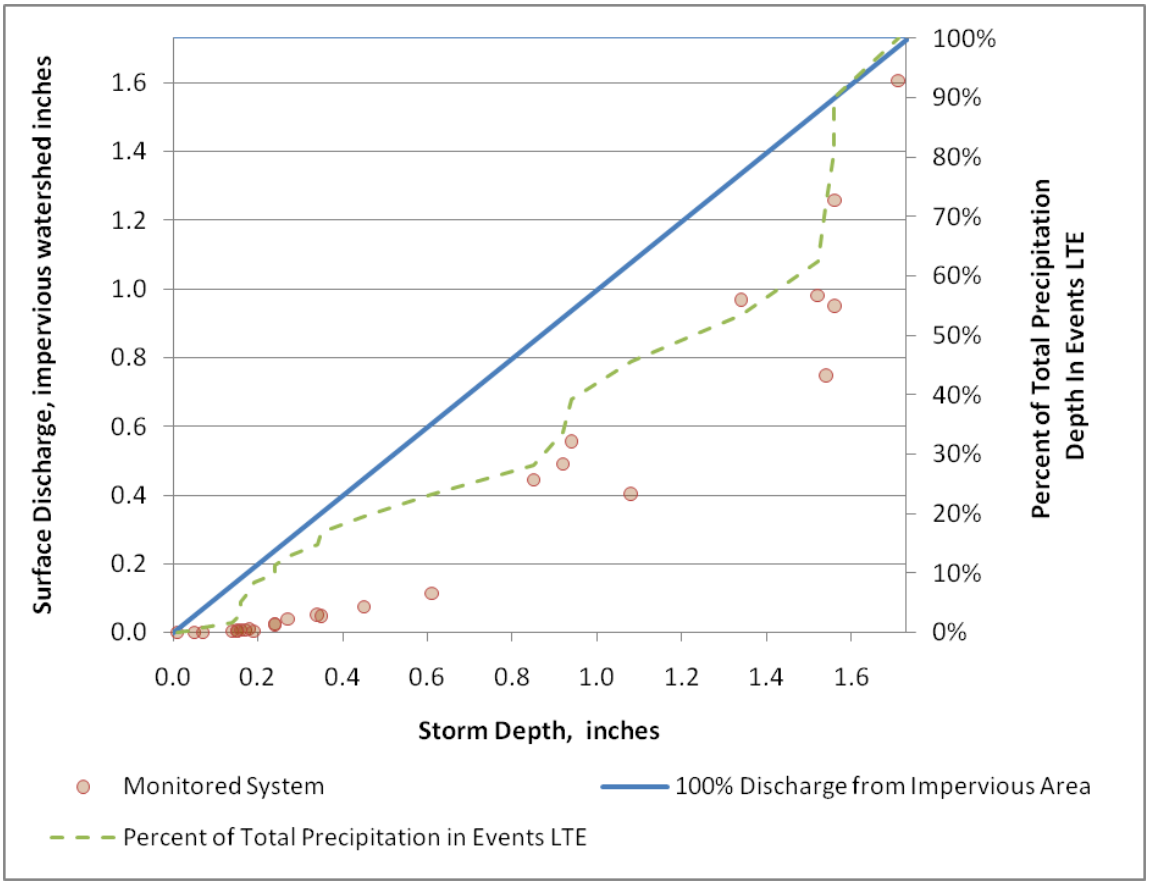
Discharge Volume per Impervious Area (Site and Practice Level)

The discharge volume per impervious area is similar to the discharge volume per total area described above, but is normalized to the impervious area of the watershed rather than the total watershed area. It is calculated as the measured volume of discharge divided by the total impervious area of the tributary watershed. The discharge volume can be expressed as "impervious watershed inches."

Normalization to impervious area has advantages and disadvantages. For ranges of storms for which runoff from pervious areas is negligible, this approach can be used to isolate and compare the effectiveness of LID practices on the site. For example, the effectiveness of LID practices to mitigate runoff could be compared between similar land uses with differences in imperviousness. All other factors being equal, the sites would be expected to discharge different volumes of water per total site area, but would be expected to discharge similar volumes of water per impervious area. However, this approach relies on the implicit assumption that runoff from pervious areas is negligible in both cases, which is not generally the case in larger storms or in the case of pervious areas with little interception storage and lower infiltration rates. Thus, this metric should be carefully applied.

The same example dataset used in Exhibit 9-6 is plotted as impervious watershed inches of runoff versus storm depth in Exhibit 9-7 below. The same trends are noted. In this chart, red circles represent individual event data. The "100% Discharge from Impervious Area" line represents the performance that would be expected if 100 percent of rainfall over impervious area was converted to surface runoff and no runoff occurred from pervious areas. The dashed line represents the percentage of the total precipitation occurring in events with precipitation depth less than or equal to the X ordinate at each point.

Exhibit 9-7. Example Scatter Plot of Discharge Volume per Impervious Area Versus Storm Depth



LTE = Less than or equal to (the X ordinate value)

9.1.3 Consideration of Measurement Error in Interpretation Methods

In interpreting volumetric data, consideration should be given for the precision and accuracy of system inflow and outflow volume measurements. Random measurement errors associated with the resolution of monitoring equipment can be magnified in the evaluation of volume reductions, particularly for practices that achieve relatively little volume reduction, or for which limited number of data points are available. For example, if inflow volume measurements have a precision of +/- 10 percent and outflow measurements have the same precision, the calculated variability in volume reduction may be more a function of uncertainty in measurements than in the performance of the practice, unless the volume reduction is fairly large. The impacts of measurement precision on conclusions can be reduced by using methods that aggregate long-term inflow and outflow volumes (e.g., comparison of total inflow to total outflow volume, or total rainfall to total site discharge). Methods of interpretation that rely on the visualization of individual event data are inherently sensitive to measurement errors. However, recognition of the potential for errors (and the potential magnitude of those errors) as well as larger sample sizes can improve the strength of conclusions drawn from these observations. Note that analysis of relative volume

reduction or "percent volume reduction" on a storm-by-storm basis is especially sensitive to the effects of measurement precision.

The accuracy of volumetric measurement can be diminished by a variety of factors, including improper calibration of equipment and omission of any important factors. Accounting for all inflows and outflows to/from the system is of particular importance in volume reduction studies. Some types of unmeasured volumes may include: volume of direct precipitation on the practice; volume of groundwater seepage into the practice; volume evapotranspirated; other volumes which are not reflected in inflow and outflow volumes measured at discrete monitoring points. These volumes should be estimated where possible and factored into event totals and/or long-term totals as appropriate to prevent inaccuracies in volumetric measurement.

9.1.4 Comparing Performance to Design Objectives and Criteria

Often, an underlying goal of monitoring is to compare LID practice and site performance to prior design objectives or performance criteria. Design objectives and performance criteria applicable to LID practices and sites can take a number of forms. Most commonly LID practices are designed to capture the runoff from a specific design storm or intensity. Capture may include retaining water on site via infiltration, evapotranspiration or reuse, or detaining and discharging treated water. In either case, the time over which storage capacity should be recovered (i.e. the time it takes the facility to empty) is usually specified as an accompanying design objective.

LID practices may also be designed with the direct intent of capturing a specified percentage of average annual (i.e., long term) runoff or reducing discharge volume to a specified level on a long-term basis.[1] In this case, design criteria are typically developed through analysis of precipitation records using continuous hydrologic simulation. Methods of sizing may implicitly or explicitly incorporate the emptying time of the facility (i.e. the time it takes to recover storage capacity for subsequent storms). For example, long-term hydrologic simulation might show that a design volume of 0.8 watershed inches would be required to capture 80 percent of average annual runoff if a bioretention practice was designed to empty in 36 hours, while a design volume of only 0.5 watershed inches might be required if the same facility was designed to empty in 18 hours.

The design objective or performance criteria applicable to the study provides guidance for how volumetric performance data should be evaluated. In the first case described above (design storm-based objective), relatively few monitored events may be necessary to confirm that the facility is meeting its performance objectives (performance under a given design condition). For example, the design objectives of the facility could be evaluated by monitoring and analyzing data from a subset of events similar to the design event, with a range of antecedent conditions, and monitoring the emptying times of the facility under different seasonal conditions. If overall monitored performance is reasonably consistent with

[1] A typical goal is to match the "pre-development" discharge volume, however it is noted that matching overall discharge volumes does not necessarily ensure matching of pre-development peak discharge rates, frequencies or durations, or overall water balance.

design objectives, it can be reasonably concluded that the facility meets the design objectives and the performance criteria implied by those objectives.

However, this is not likely a common case. If the design objectives are not confirmed through comparison of design storm performance to design storm objectives, if performance criteria are based on long-term performance, or if study objectives include the explicit quantification of long-term performance, the study must either continue for a long period of time or other methods must be employed to extrapolate the performance of the system.

In the case of LID sites, specific design objectives, such as design storm methods, are less common than for specific LID practices, thus it is more common that extrapolation of long-term performance will be required to meet study objectives.

Extrapolating Study Results to Long-Term Volume Reduction Performance

Extrapolating a limited monitoring dataset to long-term volume reduction performance may be critical in meeting study objectives and evaluating LID practice or site performance against established criteria. The following are two common ways of extrapolating these results:

1) Precipitation analysis: Monitoring datasets may permit the development of average relationships between precipitation and system performance. These relationships could potentially be probabilistic in nature. For example, the average discharge volume in events between 0.4 and 0.5 inches is 32,400 cu-ft and the standard deviation is 15,500 cu-ft. If similar relationships could be developed for each rainfall "bin", a statistical sampling routine could be implemented in combination with storm events extracted from long-term rainfall records to estimate total discharge. Alternatively, a moving average of response could be developed and applied directly to each event. For example, a moving average of watershed discharge per area versus event depth could be applied to a long-term cumulative distribution of storm depths to estimate total long-term discharge. The critical element of this approach lies in the strength of the relationships that can be developed between precipitation records and practice performance or site responses.

2) Continuous Simulation Models: These models represent a potentially valuable tool for extrapolating a relatively small number of monitored events to long-term performance. Guidance on effective and appropriate use of models is beyond the scope of this Manual, however the user should consider data needed to calibrate and validate hydrologic models in developing a study design. Hydrologic models can facilitate highly detailed analysis of system performance over a long time scale. Critical to this approach is minimizing model-induced errors and using a model within the limits of its applicability.

9.2 Water Quality Benefits and Load Reduction

Water quality benefits and load reductions from LID practices and sites are a function of both water quality treatment functions and volume reductions provided by LID practices. Methods of interpretation of water quality benefits of practice-level studies should be consistent with methods described in Chapter 1 through 7 of this Manual and are not described in this chapter. Likewise, methods for analysis of event mean concentrations and pollutant loadings at a discrete monitoring station are described in Chapter 7 of this Manual and are not described in this chapter.

Description of the water quality benefits and load reductions achieved by LID sites should account for the pollutant loads removed through treatment in the LID practices on site as well as pollutant load reduction achieved via volume reduction. To quantify these components directly would require estimation of the quality and quantity of runoff prior to entering a LID practice, as well as the runoff avoided or increased through LID site design practices. Clearly, measuring pollutant removal from LID sites directly will not generally be feasible. Of greater interest is how water quality benefits and load reductions should be interpreted from before/after or control/impact studies.

9.2.1 Interpreting Water Quality Benefits of LID Sites through Reference Watershed Studies

LID sites can have water quality benefits over uncontrolled development sites by reducing the frequency of discharge, reducing the average concentration of discharge, reducing pollutant loads, or by all three. When comparing to a reference condition (either a pre-retrofit condition or control condition), an attempt should be made to quantify each of these potential benefits.

Reduction in frequency of discharge is a strictly volume-based phenomenon that can be interpreted as described in Section 9.1. It may also be of interest to compare frequency of discharge from the monitored site to pre-development frequency of discharge if these data can be estimated from local hydrologic observation or model results.

Concentration of discharge can be interpreted as an average long-term discharge volume (i.e., the average event mean concentration) or as a distribution of event mean concentrations. For example, it may be of interest to know how frequently the concentration of a given pollutant exceeded a concentration-based water quality standard. In comparing such results between a LID and control watershed, it is important to consider the potential for fewer discharge events from the LID watershed, thus for appropriate comparison, a common normalizing variable should be used. In this case, expressing exceedance of a water quality threshold as a count per year would be more appropriate than expressing it as a percentage of total discharge events. It is also important to consider that concentration reductions may not be expected in sites that achieve significant volume reduction. For example, an increase in concentration of some pollutants might be expected from a site that has volume reduction practices applied to relatively “cleaner” land uses, but less volume reduction on relatively “dirtier” land uses. A larger fraction of the discharge water in the controlled condition would

originate from the "dirtier" land use, thus potentially increasing the concentration. In this case, a reduction in loads would still be expected.

Estimates of load reduction should carefully consider the non-linearity of runoff response that is characteristic of LID watersheds (i.e., a few large storms can dominate overall discharge volume) and the potential for concentrations of some constituents to be greater in more intense storms. A comparison of total loading over a representative period of record is the most appropriate way to compare study and reference watersheds. If possible, individual event mean concentrations (EMCs) should be multiplied by individual event discharge volumes to compute event loads. While average EMCs of discharge should be applied with caution when computing total pollutant loads, they may be useful in estimating the loading over a monitoring period if not all storms were sampled but the discharge volumes from all the storms were monitored. In this case, the average of EMCs could be applied to the volume that was not sampled in the study. Care should be taken to avoid the interpretation of volume and/or load reductions based on results from a non-representative period of record. For example, if only small storms were monitored, the benefits of an LID site could be drastically over-predicted, and vice versa.

9.2.2 Potential Groundwater Impacts

LID systems tend to emphasize infiltration and thus have the potential to impact groundwater quality and quantity. If subsurface monitoring is conducted, it will be necessary to interpret these data to describe potential groundwater impacts. Subsurface water quality monitoring studies should attempt to describe:

- Presence or absence of flow of infiltrated water to groundwater and frequency patterns of presence of discharge (i.e., seasonal, wet year vs. dry year)
- Increases in groundwater levels and/or downgradient surface discharges (shallow groundwater discharges)
- Average long-term concentration of infiltrated water reaching groundwater
- Average long-term annual loading of pollutants to groundwater
- Patterns of concentration and loading of infiltrated water reaching groundwater
- Long term trends in concentration and loading with time

Fundamentally, subsurface data may be interpreted in the same way as surface water quality and volumetric data. Representative conditions must be monitored to support direct conclusions about long-term average water levels, concentrations, and loading. Ideally, loading over a monitoring period would be calculated from incremental periods of flow and the average concentration over those periods. Error may be introduced if total discharge volume is multiplied by average concentration.

Modeling may help extrapolate limited monitoring periods to long-term averages and patterns.

9.3 Comparison of LID to other BMPs

LID practices in themselves are not fundamentally different from many other BMPs and their performance can be interpreted and described identically. Most commonly, performance should be described as a probabilistic description of influent and effluent quality, average load reduction, and/or average volume reduction. Studies with comparable tributary watersheds and comparable study design may facilitate further comparisons such as frequency of discharge, frequency distribution of concentration, and temporal pattern of loading.

One major difference between LID practices and conventional BMPs is the typical dependency of LID practices on volume reduction. Fundamentally, volume reduction processes can be considered within the framework of a normalized storage volume and a storage recovery rate, regardless of BMP type or scale. While magnitudes of storage and recovery rates vary between LID sites, LID practices, and conventional BMPs, this overall framework provides a basis for comparison between studies in the same category, as well as across categories. A comparison of normalized storage volumes and recovery rates between sites can be used to help interpret or predict differences in performance. As described in Section 8.2.4, spatially linking tributary areas to storage volumes and recovery rates provides a stronger basis for comparison between sites in which storage is distributed differently (i.e., evenly distributed storage volume versus lumped or unevenly distributed storage volume).

Because LID practices and sites typically depend on volume reduction, LID practices often do not discharge “treated” water. Instead, everything that is captured is retained and only the overflow or bypass is discharged. Therefore a comparison of average discharge concentration between a conventional BMP that treats and releases water back to the surface and a LID practice that only discharges bypass or overflow may not provide a representative description of overall performance. While it is important to recognize that volume reduction-based LID practices could indeed result in higher average discharge concentrations than conventional treat-and-release BMPs, the total load discharged from the system and the load removed in the practice or BMP provides a better basis for comparison of overall performance.

While LID site-level studies are notably different than individual LID practices level studies and conventional BMP studies, comparison between these systems is still possible. LID studies attempt to provide a long term description of discharge water quality and discharge loads, which are both comparable to conventional BMP studies. Likewise, LID site-level studies attempt to quantify the volume of runoff mitigated by the composite suite of LID practices, which is also comparable to conventional BMP studies. Finally, LID site scale studies attempt to quantify the frequency of discharge and threshold conditions for discharge to occur. While conventional BMPs may or may not include mechanism to change the frequency of discharge, the frequency/timing of discharge is a fundamental factor in receiving water protection and is a valid basis for comparison even if other BMPs do not have measureable benefits.

9.4 Conclusions

Appropriate methods of data interpretation are necessary to support valid comparisons between different practices and sites. The emphasis on volume reduction that is inherent in LID principles requires that appropriate conclusions about volume reduction are made from monitoring studies. Methods of interpretation of volumetric data that can be readily extrapolated to long term performance are preferred. Because LID practices and sites are expected to perform differently under different storm magnitudes, methods that do not factor in event magnitudes are discouraged. Visual observation of data as scatter plots, histograms, and cumulative density functions is recommended as it allows interpretations of hydrologic response that may not be as apparent in statistical summaries. LID practices and sites can be compared to conventional studies on the basis of discharge frequency, discharge volumes, and distributions of concentrations and loads.

9.5 References

Barr Engineering Company. 2006. *Burnsville Stormwater Retrofit Study*. Prepared for City of Burnsville.

Cheng, M.S., Coffman, L.S., Zhang, Y., and J.Z. Licsko. 2003. *Comparison of Hydrological Responses from Low Impact Development with Conventional Development*. In Proceedings of World Water & Environmental Resources Congress 2003. Environmental and Water Resources Institute (EWRI), American Society of Civil Engineers, Philadelphia, Pennsylvania, June 23-26, 2003.

Chow, V.T., Maidment, D.R., and W.M. Mays. 1988. *Applied Hydrology*. First Edition. McGraw-Hill, Inc., New York, New York.

Claussen, J.C. 2007. *Jordan Cove Watershed Project: Final Report*. Prepared for U.S. Environmental Protection Agency (EPA) and Connecticut Department of Environmental Protection.

Claussen, J.C. and J. Spooner. 1993. *Paired Watershed Study Design*. Prepared for U.S. Environmental Protection Agency (EPA) Office of Water, Washington, D.C. 841-F-93-009.

Davis, A.P. 2008. *Field Performance of Bioretention: Hydrology Impacts*. Journal of Hydrologic Engineering, Volume 13, Issue 2. 90 p.

Dingman, S.L. 2002. *Physical Hydrology*. Second Edition. Waveland Press, Inc., Long Grove, IL.

Hunt, W.F., Smith, J.T., Jadlocki, S.J., Hathaway, J.M., and P.R. Eubanks. 2008. *Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, NC*. American Society of Civil Engineers (ASCE) Journal of Environmental Engineering (in press).

Law, N.L, Fraley-McNeal, L., Cappiella, K., and R. Pitt. 2008. *Monitoring to Demonstrate Environmental Results: Guidance to Develop Local Stormwater Monitoring Studies Using Six Example Study Designs.* Center for Watershed Protection.

Li, H., Sharkey, L., Hunt, W., and A. Davis. 2009. Mitigation *of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland*. American Society of Civil Engineers (ASCE) Journal of Hydrologic Engineering (in press). April.

Roseen, R.M., Ballestero, T.P., Houle, J.J., Avellaneda, P., Wildey, R., and Briggs, J.F. 2006. *Performance evaluations for a range of stormwater LID, conventional structural, and manufactured treatment strategies for parking lot runoff under varied mass loading conditions*. Transportation Research Record: Journal of the Transportation Research Board (No. 1984). 135–147 p.

Roseen, R.M., Ballestero, T.P., Houle, J.J., Avellaneda, P., Briggs, J.F., Fowler, G., and R. Wildey. 2009. Seasonal *Performance Variations for Stormwater Management Systems in Cold Climate Conditions*. American Society of Civil Engineers (ASCE) Journal of Environmental Engineering (in press) March.

Selbig, W.R., and R.T. Bannerman. 2008. A *comparison of runoff quantity and quality from two small basins undergoing implementation of conventional- and low-impact-development (LID) strategies, Cross Plains, Wisconsin, Water Years 1999–2005*. U.S. Geological Survey (USGS) Scientific Investigations Report 2008–5008. 57 p.

Shaw, E.M. 1988. *Hydrology in Practice*. Second Edition. Van Nostrand-Reinhold, London, UK.

Smith, E.P. 2002. *BACI Design. Encyclopedia of Environmetrics*. El-Shaarawi, A.H. and W.W. Piegorsch (eds.). John Wiley and Sons, Ltd., Chichester.

Underwood, A.J. 1992. *Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world*. Journal of Experimental Marine Biology and Ecology, Volume 161. 145-178 p.