



**INTERNATIONAL
STORMWATER BMP
DATABASE**
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International Stormwater Best Management Practices (BMP) Database

Technical Summary: Volume Reduction

Prepared by

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Disclaimer

The BMP Database (“Database”) was developed as an account of work sponsored by the Water Environment Research Foundation (WERF), the American Society of Civil Engineers (ASCE)/Environmental and Water Resources Institute (EWRI), the American Public Works Association (APWA), the Federal Highway Administration (FHWA), and U.S. Environmental Protection Agency (USEPA) (collectively, the “Sponsors”). The Database is intended to provide a consistent and scientifically defensible set of data on Best Management Practice (“BMP”) designs and related performance. Although the individuals who completed the work on behalf of the Sponsors (“Project Team”) made an extensive effort to assess the quality of the data entered for consistency and accuracy, the Database information and/or any analysis results are provided on an “AS-IS” basis and use of the Database, the data information, or any apparatus, method, or process disclosed in the Database is at the user’s sole risk. The Sponsors and the Project Team disclaim all warranties and/or conditions of any kind, express or implied, including, but not limited to any warranties or conditions of title, non-infringement of a third party’s intellectual property, merchantability, satisfactory quality, or fitness for a particular purpose. The Project Team does not warrant that the functions contained in the Database will meet the user’s requirements or that the operation of the Database will be uninterrupted or error free, or that any defects in the Database will be corrected.

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The Project Team does not endorse any BMP over another and any assessments of performance by others should not be interpreted or reported as the recommendations of the Project Team or the Sponsors.

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VOLUME REDUCTION TECHNICAL SUMMARY

1 INTRODUCTION

The hydrologic performance of stormwater best management practices (BMPs) is an important factor in the overall effectiveness of BMPs in reducing potential adverse impacts of urbanization on receiving waters. In addition to providing water quality data, the International Stormwater BMP Database also provides watershed characteristics and monitoring results for precipitation and flow conditions, enabling assessment of the hydrologic performance of BMPs when such data are provided by the researcher. BMP performance metrics recommended since the inception of the BMP Database project have included:

1. the fraction of long-term runoff volume managed by the BMP (i.e., capture efficiency),
2. the fraction of the captured volume that is lost in the BMP and does not discharge to surface water (i.e., volume reduction), and
3. the level of treatment provided for water that discharges from the BMP (effluent concentration characteristics).

Historically, BMP performance analysis has focused primarily on water quality aspects of BMP performance in terms of pollutant loads and concentrations. Similarly, stormwater management strategies have focused primarily on capture efficiency (through the development and application of sizing criteria) and treatment performance (through the selection and design of BMPs to address pollutants of concern).

Basic Terminology

The following key terms are used throughout this report:

Hydrologic performance: the ability of stormwater BMPs to manage flow rates and volumes of runoff; in the context of BMP effectiveness, refers collectively to capture efficiency and volume reduction.

Capture efficiency: the fraction of long-term runoff volume that is managed by a BMP (i.e., does not bypass).

Volume reduction: fraction of water managed by a BMP that does not discharge to surface water (i.e., is infiltrated, evaporated, transpired, or used). The total fraction of runoff volume reduced is therefore the product of capture efficiency and volume reduction.

Infiltration: the process of water entering soil at the ground surface.

Percolation: the process of water moving downward through the unsaturated zone of soil below the ground surface.

Evaporation: the process by which water changes from a solid to a gaseous state at the interface between liquid water and atmosphere.

Transpiration: the process by which plants uptake liquid water and expel it in a gaseous phase.

Evapotranspiration: the combined processes of evaporation and transpiration.

Water balance: the long-term balance of water fluxes in and out of a control volume; in the context of a BMP, the major fluxes include inflow, outflow, percolation, evapotranspiration, and non-potable use.

Hydromodification: Changes in runoff and sediment yield caused by land use modifications.

Normally-wet BMPs: BMPs characterized by the presence of a permanent pool of water, commonly sustained by a low permeability liner, continuous baseflow, and/or groundwater seepage.

Normally-dry BMPs: BMPs characterized by the presence of discharge pathways at their lowest elevation, such that they are designed to dry between storm events.

More recently, volume reduction has been emphasized as a means of managing site hydrology and controlling stormwater pollutant loads, and the need to quantify the hydrologic performance of BMPs has become more important. The watershed, precipitation and flow data contained in the BMP Database serve as a potentially useful source of data to facilitate better understanding of the hydrologic performance of BMPs.

The purposes of this technical summary are to:

- Discuss the regulatory context for volume reduction and introduce potential goals of volume reduction analysis,
- Provide an inventory of the volumetric data contained in the BMP Database,
- Discuss reliability of these data and recommended uses,
- Provide suggestions for screening criteria to improve the reliability of the datasets,
- Describe methods that may be used for categorical analysis of BMPs and provide categorical analysis results, and
- Discuss potential advanced uses of volumetric data.

1.1 Regulatory Context

Volume is increasingly recognized as a “constituent of concern” in the realm of water quality regulations. Increased runoff volume resulting from urbanization carries with it increased pollutant loads. In addition, increased volumes and peak flow rates carry more energy to receiving channels and can result in channel erosion. The term hydrograph modification (hydromodification) is commonly used in the regulation of volume to describe changes in the volume, rates and timing of runoff, which, coupled with changes in sediment supply, can cause channel instability. The term hydromodification also encompasses changes to the site water balance which can affect the seasonality of flow in receiving water and alter groundwater conditions. Reduced infiltration volume resulting from increased impervious cover and soil compaction can, in some cases, result in lower dry weather base flows and lower groundwater recharge. Conversely, increases in infiltration as a result of imported irrigation or the creation of more direct pathways to groundwater (such as in an infiltration basin in sandy soil or dry wells), can yield unnaturally high groundwater and unseasonal base flows in intermittent and ephemeral streams or increased base flows in perennial streams.

Historically, urban runoff volume has been regulated in the context of flood control, which primarily emphasizes peak flow reduction, but not necessarily runoff volume reduction. Other historic emphasis on volume reduction has been related to groundwater augmentation and infrastructure savings (e.g., use of dry wells rather than a storm sewer system or to reduce combined sewer overflows in areas with very high permeability soils). More recently, National Pollutant Discharge Elimination System (NPDES) Municipal Separate Storm Sewer System (MS4) permits in some parts of the country have begun to emphasize volume reduction in the context of low impact development (LID) objectives (e.g., controlling volumes and flow rates to mimic pre-development conditions) and addressing hydromodification impacts. For example,

recent nationwide regulations for federal facilities have required projects to attempt to maintain pre-development hydrology, “retaining” stormwater on site via infiltration, evaporation, and harvest and use BMPs (USEPA, 2009). (The authors note that stormwater that is evapotranspired, harvested and used, or infiltrated is not actually “retained”; instead, it is prevented from running off. However, the use of the word “retain” to describe limiting surface runoff is gaining acceptance in the stormwater field).

Finally, volume can be the key parameter or contributing parameter in 303(d) listed impairments to receiving waters and can be regulated as part of Total Maximum Daily Loads (TMDLs). Exhibit 1 provides a summary of the 303(d) list impairments and TMDLs that are potentially related to stormwater volumes or base flow rate alterations associated with urbanization.

Exhibit 1. Impairments and TMDLs Related or Potentially Related to Volume, Flow Rates and Channel Erosion

Impairment	Impaired Waters	TMDLs
Flow Alteration(s)	109	0
Sediment	6,178	3,492
Turbidity	3,064	969
Habitat Alterations	669	83

Source: http://iaspub.epa.gov/waters10/attains_nation_cy.control?p_report_type=T
(Accessed 10/01/2010)

1.2 Key Volume Reduction Mechanisms

Volume reduction in the context of BMP effectiveness refers to the volume that enters a BMP that does not discharge to surface water. This water is considered “lost” or “retained”. The fates of lost volume include: infiltration into the bottom and sides of the BMP and percolation to groundwater or shallow interflow pathways, evaporation or evapotranspiration to the atmosphere, or use of the stored water, generally either for irrigation or other non-potable use such as toilet flushing. The key volume reduction mechanisms can be categorized as follows:

- Evaporation of ponded water
- Evapotranspiration of water stored in the root zone below the surface of the BMP
- Infiltration below the BMP and through the side walls (Note: may still reach receiving water via groundwater discharge.)
- Demand for stored water (Note: may still reach receiving water via POTW outfall.)

The relative magnitude of each mechanism is expected to vary by BMP type, underlying soil types, groundwater conditions and connectivity to receiving water, climate, and non-potable water demand.

1.3 Goals of Volume Reduction Analysis²

Volume reduction provided by BMPs can help meet a variety of stormwater management objectives, even if the BMP is not specifically designed to retain stormwater (Strecker et al., 2004). An analysis of the volumetric data contained in the BMP Database can help provide a better understanding of the benefits that BMPs can be expected to provide for volume reduction. Additionally, such analysis may potentially be used in the development and calibration of mechanistic representations of volume reduction processes. Volumetric analyses of the BMP Database may attempt to answer one or more of the following fundamental questions regarding runoff volume reduction:

- How much runoff volume is reduced by a BMP or suite of BMPs on a long-term average basis?
- How does one category of BMPs compare to another category of BMPs with respect to volume reduction performance?
- What effect does a BMP or suite of BMPs have on the frequency of runoff leaving the site?
- How does performance vary with the magnitude of precipitation or inflow event?

In addition, more advanced and specific questions related to volume reduction may be supported in whole or part by volumetric data contained in the BMP Database. In some cases, additional data from outside of the BMP Database would be required to support these studies. Study questions may include:

- How do climatic patterns and seasonality influence the volume reduction performance of a BMP or suite of BMPs?
- How does a BMP or suite of BMPs impact the overall water balance of the system on a long-term average basis? (i.e., How are deeper infiltration, evapotranspiration, and runoff balances changed?)
- How much runoff volume is reduced by a BMP or suite of BMPs under conditions specified for regulatory purposes (e.g., a specific design storm)?
- How do the design attributes of a BMP affect its volume reduction performance compared to similar BMPs?
- What model framework and parameters are appropriate to represent an individual BMP or BMP type?

² Concepts and volume analysis metrics provided in this section have been adapted from Chapter 9 of *Urban Stormwater BMP Performance Monitoring* prepared by Geosyntec Consultants and Wright Water Engineers (2009a), which can be downloaded for more detailed at <http://www.bmpdatabase.org/MonitoringEval.htm>. These concepts are also presented in the International Stormwater BMP Database Project Technical Memorandum “Drawing Appropriate Conclusions Regarding Volume Reduction in Practice- and Site-level Studies of Stormwater BMPs” prepared by Geosyntec Consultants and Wright Water Engineers (2009b), which can be downloaded from <http://www.bmpdatabase.org/BMPPerformance.htm>.

Fundamental metrics for evaluating volume reduction performance are provided in Exhibit 2. The analysis methods and analyses presented in this technical summary are based on the fundamental elements of one or more of these metrics. Practice-level studies refer to specific BMPs with a defined inflow and outflow, while site-level studies refer to LID sites for which there is not a defined inflow and the hydrologic performance of the entire site is of interest. The BMP Database currently accepts site-level studies; however, at the time of publication of this technical summary no site-level studies had been submitted.

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

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

Source: Geosyntec and Wright Water Engineers, 2009a&b.

Practice-level: refers to studies that monitor inflow and outflow volumes at defined monitoring locations.

Site-level: refers to studies in which the entire site hydrologic performance is of interest; outflow is measured, but inflow cannot be defined by a monitoring location.

1.4 Organization of Report

Volume reduction analysis is a complex undertaking, particularly as it relates to datasets for studies conducted by many researchers under diverse circumstances and with regard to studies conducted with varying study objectives. As a result, a substantial portion of this report carefully outlines steps that must be taken to avoid misleading or erroneous conclusions when conducting volume analysis, both in general and with regard to the BMP Database dataset. The authors of this report have made extensive efforts to appropriately present and caveat conclusions based on the dataset contained in the BMP Database. The general organization of the remainder of this summary includes these sections:

- Section 2 provides an inventory of volumetric data and a discussion of the reliability of these data for use in volume reduction analysis.
- Section 3 describes recommended methods of using the data from the BMP Database to attempt to answer simple study questions.
- Section 4 provides results of volume reduction analyses on a BMP categorical basis and conclusions from these analyses.
- Section 5 provides an introduction to more advanced analyses which may be useful for answering the advanced study questions listed above.
- Section 6 provides overall conclusions.

2 INVENTORY OF VOLUMETRIC DATA

The BMP Database contains a variety of data that are potentially useful for volume reduction analysis. This section introduces the datasets potentially useful for volumetric analysis and their location in the BMP Database. This section also discusses the reliability of these data for use in volume reduction analysis. It is strongly cautioned that some studies in the BMP Database, particularly earlier studies, did not include volume reduction as a study objective and may be less reliable for volume reduction analysis than those which had volume reduction performance as an explicit objective. In addition, flow monitoring data can be very difficult to accurately obtain (Strecker et al., 2001).

2.1 Data Inventory

Data potentially useful for volume reduction analysis contained in the BMP Database include storm event characteristics, watershed characteristics, event inflow, event outflow, event peak flow, and various BMP design characteristics. Data are entered into the BMP Database and stored as storm event totals (and in some cases study period totals). This timescale does not support analyses of intra-event processes and performance; however, it supports most types of volume reduction analysis. Exhibit 3 provides an inventory of the types of data contained in the BMP Database that are potentially useful for volume reduction analysis, the location of these data, and the approximate quantity and completeness of observations. Discussions of the reliability of these data are contained in Section 2.2.

The BMP Database contains “starter queries” to provide an initial basis for querying datasets that can be used to evaluate the hydrologic performance of BMPs. Guidelines for developing queries using the BMP Database can be downloaded from the project website (www.bmpdatabase.org).

2.2 Key Reliability Considerations

Several factors should be considered when using the volumetric data in the BMP Database for runoff volume reduction analysis. Of primary importance, it must be recognized that many studies contained in the BMP Database, particularly older studies, were conducted to evaluate treatment performance (i.e., change in concentration between influent and effluent, or just effluent concentration), and did not have volume reduction as an explicit goal. This consideration has several ramifications that influence the reliability of volumetric and supporting data. In addition, inherent limitations of monitoring study design and instrumentation should also be considered. Key reliability considerations are discussed below.

Exhibit 3. Partial Directory of Volume Reduction and Related Data in BMP Database

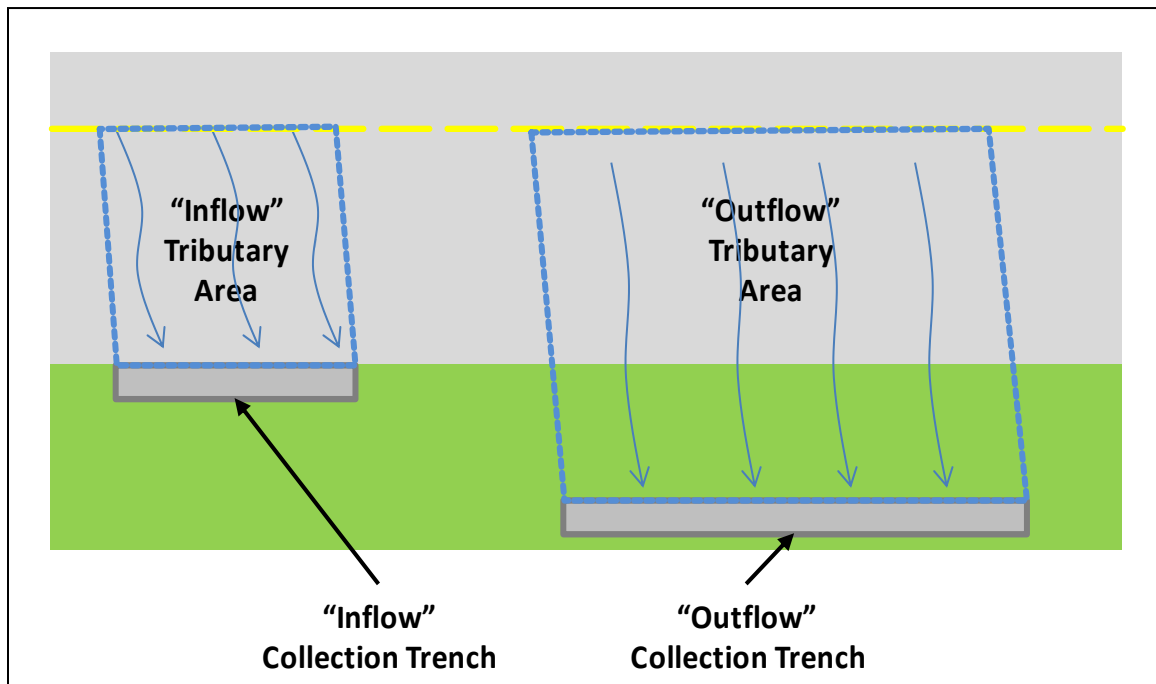
Reported Data	Data Type	BMP Database Field ID	BMP Database Table Name	Inventory of Data (August 2010)
Paired Event Inflow/Outflow Volume	Number	TOTVOLEFF	FLOW	Approximately 2,300 events with paired inflow/outflow out of 3,500 events with either inflow or outflow.
		Monitoring Station Type = "Inflow" and "Outflow"	MONITORING STATIONS	
Event Peak Flow (Inflow and Outflow)	Number	PEAKEFFFLOW	FLOW	≈1,300 events with peak flow out of 2,300 events with paired inflow/outflow
Reporting Start Date (Start Date/Time)	Time/Date	STARTDATE/ STARTTIME	FLOW	Date: all events Time: approximately half of events
Reporting End Date (End Date/Time)	Time/Date	ENDDATE/ ENDTIME	FLOW	Date: approximately half of events Time: approximately half of events
Watershed Location	Text	CITY/ COUNTY/ STATE various other data such as elevation, lat-long, etc.	TESTSITE A01	All flow events have a watershed location; 323 unique watersheds recorded in Database
Watershed Area	Number	WA	WATERSHED NS01	Most studies have watershed area (≈30 paired events <u>without</u> watershed data out of ≈ 2,300 events with paired inflow/outflow)
Watershed Imperviousness	Number	PERI	WATERSHED NS01	≈1,800 events reporting IA out of 2,300 paired flow events
Watershed Directly Connected Imperviousness Area	Number	PERIC	WATERSHED NS01	≈500 events reporting DCIA out of 2,300 events with paired inflow/outflow
Most Common NRCS Hydrologic Soil Group	Select A,B,C, or D	MCHG	WATERSHED NS01	≈70 watersheds with HSG out of 323 unique watersheds
Regional Precipitation Statistics	Number	Multiple	REGCLIME A03	Summary statistics provided for 136 regional climate stations ≈240/290 test sites have a regional climate station assigned
Event Precipitation Depth	Number	TOTALDEPTH	PRECIPITATION	≈1,800 events with precipitation depth out of 2,300 events with paired inflow/outflow
Precipitation Start (Date/Time)	Time/Date	STORMSTARTDATE STORMSTARTTIME	PRECIPITATION	Date: all precipitation events have start date (≈6,100) Time: approximately 75 percent of precipitation events have start time.
Precipitation End (Date/Time)	Time/Date	STORMENDDATE STORMENDTIME	PRECIPITATION	Date: approximately 75 percent of precipitation events have end date. Time: approximately 75 percent of precipitation events have end date.
Study Design Schematic	Graphic	BMPPLAN	LAYOUTS PHOTOS	Approximately two-thirds of structural BMP studies have schematics.

Studies may not have been designed or could not be designed to account for all inflow pathways. Inflow pathways that may have been unaccounted include diffuse inflow (such as area tributary directly to the BMP not via the inflow pipe), lateral inflow (such as along the length of a swale), shallow interflow, groundwater seepage, and precipitation directly on the BMP. For example, when monitoring vegetated swales, it is commonly only feasible to measure concentrated inflow at the head of the swale; however, swales commonly receive inflow along their entire length. As another example, many normally-wet BMPs potentially receive substantial volumes of interflow and groundwater seepage during and between monitoring events that are not reflected in inflow monitoring. These factors should be considered in evaluating the reliability of reported inflow volumes for a variety of BMP types.

Reported inflow and outflow volumes are not intended to be matched because the inflow is a reference station for water quality purposes only. In some studies where the inflow to a BMP was diffuse and could not be monitored directly, a reference station was used to collect water quality samples representative of the inflow concentration to the BMP. For example, in the monitoring of filter strips, it is common practice to collect flow at the upstream edge of one part of the filter strip to represent the influent concentration to the BMP while collecting discharge from another portion of the filter strip to represent effluent concentration from the BMP (see Exhibit 4). The tributary areas to these different points do not necessarily need to be equal for assessment of water quality performance. However, for a valid assessment of volumetric performance, tributary areas must be equal or must be adequately defined by the investigator to allow scaling. In some cases, investigators provided notes with datasets indicating that they were not appropriate for use in volumetric analysis or providing dimensions; however, specifically for historic studies, this potential use was not a primary intent and may not have been noted.

Monitoring protocol may not have attempted to measure the entire inflow and outflow duration. For studies with treatment performance as the primary objective, flow monitoring is used primarily to pace automatic sampling equipment and/or to volume-weight aliquots. For studies that do not seek to quantify volume reduction, the need to monitor volume theoretically expires after all sample jars are been filled. In historic monitoring studies that did not have volume reduction as an explicit objective, it is possible and perhaps likely that volume measurement was discontinued after water quality sampling had concluded, but prior to the end of inflow and/or outflow. The ramifications of this potential source of error are difficult to quantify, as cases theoretically exist in which sampling would have been discontinued early for either the inflow or the outflow or both.

Exhibit 4. Example Schematic of Filter Strip Study Design with Inflow and Outflow Monitoring Locations Not Adequately Matched for Volume Reduction Analysis



Instrumentation may not have allowed quantification of entire inflow and outflow duration. Typically, flow monitoring apparatuses are designed for a certain range of flows and have higher error outside of this range. Therefore, it may not be possible to accurately quantify both the peaks and the receding limb of the inflow and discharge hydrographs, and in some cases monitoring may have been discontinued when flow dropped below the design range of the monitoring apparatus. The receding limb of a hydrograph may contain a substantial³ portion of the overall volume which would not be taken into account in such a case.

Inter-event processes are not likely adequately accounted for in event volumetric data. Most event volumes in the BMP Database have discrete start and end points, likely based on the period of significant inflow and/or discharge from the BMP. However, for some BMPs such as seasonal wet ponds, important volume reduction or gain processes may occur between monitored events. For example, while the volume reduction achieved by wet ponds during a discrete event may be limited, significant evaporation of retained water between events may provide substantial volume reduction on a long-term basis. Similarly, dry weather base flows may dominate the overall water balance of a BMP, but may not be significant during a discrete monitored storm event. Inter-event processes are believed to be

³ The word “substantial” is used in this document to refer to a quantity that is believed to be non-negligible based on theory or visual observation, but for which statistical significance has not been or cannot be evaluated.

most important for BMPs with large wet pools, including wet ponds, wetland basins, and wetland channels.

Difficulties are inherent in monitoring flow from small urban watersheds. Runoff rates from small, highly impervious drainage areas can be difficult to monitor due to short times of concentration yielding “flashy” hydrographs (i.e., flows rise and fall directly in response to a rainfall). For these watersheds, the range of flows that needs to be measured accurately is relatively large (Strecker et al., 2001). Rapidly changing flow conditions can cause equipment with poor data density recording capabilities to miss brief periods of significant flow as well as cause errors in flow measurement due to unsteady conditions or flows below the minimum that can be measured. It is commonly easier to obtain flow data from the outflow of a volume-based BMP as compared to inflow because of smoothing of event peaks.

Uncertainty in flow measurement can influence reliability of findings, particularly where expected volume changes are minor. Even a calibrated site with control structure may have an error of plus or minus 20 percent due to combined considerations of equipment sensitivity and multiple sources of potential error. Less sophisticated monitoring designs, such as the use of Manning’s equation in a pipe to estimate flow could lead to even more substantial errors. Consequently, it can be difficult to distinguish real changes in volume from noise, particularly where expected volume reductions or gains are of a similar magnitude to experiment error.

Monitoring designs do not commonly include all water balance components. While comparison of inflow and outflow volumes can provide an assessment of total volume lost or gained in the BMP, these values do not allow direct observation of the relative magnitude of volume loss pathways (e.g., ET versus infiltration). Direct assessment of these pathways is not possible without monitoring of percolation, evapotranspiration, and change in soil moisture storage; however, such additional monitoring is not routinely conducted for many studies.

These issues influence the reliability of volumetric data and should be considered whenever drawing conclusions from this or any dataset. However, with appropriate consideration and understanding of these factors, volumetric data can still be useful in supporting studies of BMP effectiveness.

2.3 Recommendations for Improving Reliability of Volume Reduction Analyses

General recommendations for reviewing and screening volumetric data prior to analysis include these practices:

Evaluate study objectives where available. The 2009 version of the BMP Database provides a new field allowing the submitting investigator to document the primary intent of the study and note limitations of the study. For example, the investigator may explicitly document that

volumetric data are not appropriate for volume reduction analysis. Studies that are annotated as such should not be used for volume reduction analysis. (Note: Based on additional review of underlying reports, this field has been completed for some historic BMP studies by the BMP Database Project Team.)

Evaluate study design data where available. Graphics are available in the BMP Database for many studies that depict the monitoring design. Where graphics are available and where the scope of the analysis allows this depth of investigation, these graphics can help determine whether the study volumetric data can be reliably used for volume reduction analysis.

Conduct reasonableness checks on datasets. Reasonableness checks can help identify studies that are very likely unreliable for volume reduction analysis but are not specifically annotated as such. For example, studies with inflow and/or outflow volume much greater than the volume of precipitation over the watershed likely contain discrepancies in entered volume, precipitation depth and/or watershed area; mismatched periods of precipitation and flow monitoring; and/or other factors. A suite of simple reasonableness checks is described in Section 4.2.

In addition, some methods of analyses may be more robust against data quality issues than others. For example, it is generally recommended to perform primary analysis within each study; then normalize for comparison to other studies. Data tend to be more reliably compared within a study rather than across studies. For example, errors in conversion of units, if present, would likely apply across all data in a study, therefore would have less effect on a comparison within the study, but would be problematic in comparisons across studies. Similarly, miscalibration or lack of calibration of equipment would potentially affect all data collected within a study, therefore could potentially “balance out” if analyses are first performed within the study before being compared to other studies.

3 RECOMMENDED USES OF VOLUMETRIC DATA AND LIMITATIONS OF USES

3.1 Theoretical Considerations

This section describes recommended uses and limitations of volumetric data contained in the BMP Database for a variety of purposes. These recommendations are based on three theoretical considerations:

Volume reduction is conceptually linked to design attributes. While water quality data often show little or no dependency on BMP design attributes that are distinguishable from the high variability associated with multiple environmental conditions, volume reduction is conceptually more strongly correlated to design information. For example, a detention basin with a 0.3 meter (1 foot) temporary storage sump (i.e., outlet located 0.3 meters above the bottom elevation), may not show significantly different water quality treatment performance

than a detention basin with no sump; however, all else being equal, the former basin would be expected to yield significantly higher volume reduction than the latter. A variety of other factors such as underlying infiltration rate, average depth of BMP, amended soil thickness and moisture retention potential, and unit design volume would be expected to influence volume reduction in a somewhat predictable way.

Volume reduction is conceptually linked to storm characteristics. Similar to above, it is often difficult to characterize the dependency of treatment performance on storm characteristics; however, there are strong theoretical linkages between volume reduction performance and storm depth. BMPs often have a certain amount of volume they can store before discharging, whether in soil pores, micro-depressions, or designed surface volume below the lowest design outlet. Conceptually, larger storms would be more likely to result in discharge from BMPs, and all else equal, the fraction of the inflow volume lost would tend to decline with increasing storm size. Additionally, where volume loss mechanisms are based on a rate (e.g., the infiltration rate beneath a swale), then a longer duration, lower intensity storm event may allow more water to infiltrate than a short, intense event of the same overall depth. Volume reduction analyses should not ignore the expected nonlinearity of performance with different storm characteristics.

Global screening may introduce bias. As discussed above, a variety of factors may be responsible for error in volumetric data. In some cases, unreliable studies can be excluded based on detailed inspection of individual studies. However, some studies cannot be excluded based on purely evident objective factors. In addition, when attempting to conduct a global analysis of data, it may not be feasible to evaluate every study individually; therefore, it may be necessary to use objective screening rules. These rules may, in turn, introduce bias by excluding some BMPs based on their observed performance. Results of analysis relying on global screening should pay careful attention to possible biases introduced by screening.

Finally, the BMP Database has limited numbers of studies for some BMP categories and subcategories, constraining the types of analysis that can currently be supported.

3.2 Recommended Volumetric Analyses Supported by the BMP Database

With consideration of these factors, a suite of recommended analyses is provided in Exhibit 5. The specific purposes and limitations of each analysis should be understood to avoid inappropriate conclusions.

4 CATEGORICAL ANALYSIS OF VOLUMETRIC DATA

This section provides the results of the categorical analyses described in Exhibit 5 to the extent supported by data available for the categories of BMPs in the BMP Database. While the intended uses of categorical analysis results are relatively narrow, these results may be useful at the

planning level if limitations are carefully observed. In addition, the graphical results of these analyses provide a visual inventory of data contained in the BMP Database.

The first steps of the categorical analyses included screening of data as introduced in Section 2.3 to improve the reliability of the dataset. The following subsections describe the screening processes and associated assumptions, followed by the results of categorical analyses.

4.1 Primary Screening – Filtered Datasets Prior to Reasonableness Checks

Several criteria were applied to the volumetric datasets as part of a primary screening step.

- 1) Studies for which inflow and outflow events could not be adequately paired were removed from the analysis dataset. At least three paired events were required for inclusion of a study in the analysis. This threshold is subjective, and many factors should be considered when determining whether a data set is adequately representative of the range of storms that a BMP is designed to treat. In addition to number of storms, factors such as seasonal distribution of storm events, storm size, storm duration, antecedent conditions, and objectives of the data analysis should be considered. The authors recognize that a three storm threshold is not ideal, but due to the already constrained number of studies included in this analysis, a lower threshold was used for purposes of this broad-level analysis. When evaluating specific studies, studies with more storm events will tend to yield more reliable conclusions than those with fewer numbers of storms.
- 2) Studies and events explicitly annotated as not intended for volume reduction analysis were removed from the analysis dataset. This screening factor primarily applied to newer datasets for which the potential use in volumetric analysis was foreseen by the study investigator and was advised against. This screening factor does not account for studies in which the investigator may not have foreseen this potential use and did not express this limitation.
- 3) Studies for which inflow was assumed by the investigator to equal outflow for the more than two thirds of events were removed from the analysis dataset. In some cases, this assumption was explicit. However, in most cases this assumption is reflected by entry of identical values for inflow and outflow volume (to all significant figures). While the observation of Inflow Volume \approx Outflow Volume may be useful, it is considered to be a narrative observation rather than a quantitative observation and is not considered to be an appropriate generalization for inclusion with studies where inflows and outflows were actually monitored.

Note that a combination of counterbalancing errors may cause an unreliable study to still pass reasonableness checks; therefore, it is always recommended to perform a study-by-study evaluation of reliability where the scope of the analysis allows, rather than relying on universal screening rules. Nonetheless, these screening steps are relatively objective in nature and generally make the resulting dataset more reliable for volume reduction analysis.

Exhibit 5. Recommended Volume Reduction Analyses

Analysis Scale	Recommended Analysis	Description	Intended Purpose(s)	Limitations
Categorical; all events pooled	BMP categorical analysis of inflow vs. outflow	<ul style="list-style-type: none"> Total inflow and outflow volumes are normalized to equivalent depth over the watershed area and plotted on a scatter plot. Normalization eliminates influence of the watershed area on the plot and presents the data in units that are comparable to precipitation depth to allow evaluation of the influence of event depth on volume reduction. The <i>inflow=outflow</i> line is plotted as the dividing line between events with volume reduction and volume gain. 	<ul style="list-style-type: none"> Qualitatively evaluate overall trends and variability in volume reduction by BMP category. Qualitatively evaluate trends in volume reduction as function of the magnitude of the inflow event. Inspect the results of reasonableness screening. 	<ul style="list-style-type: none"> Analysis results do not distinguish between BMPs in the same category with significantly different design attributes. Data reliability issues discussed elsewhere. Potential bias as a result of screening methods discussed elsewhere.
	BMP categorical analysis of inflow vs. outflow by inflow bin	<ul style="list-style-type: none"> Total inflow and outflow volumes are tabulated at each normalized inflow volume bin. The average normalized inflow and outflow at each bin is also reported. The difference between inflow and outflow at each bin represents the volume reduction for that magnitude of event. 	<ul style="list-style-type: none"> Evaluate the influence of event magnitude on BMP volume reduction performance. Limitation: Does not account for differences that event intensity/duration could have on volume loss. 	
	BMP categorical analysis of presence/absence of discharge	<ul style="list-style-type: none"> Inflow and outflow events are counted and binned by normalized inflow volume. The percentage of events discharging at each normalized inflow bin is calculated. 	<ul style="list-style-type: none"> Evaluate ability of a BMP category, in general, to reduce the frequency of discharge and estimate the typical threshold of discharge from a site. 	

Exhibit 5. Recommended Volume Reduction Analyses

Analysis Scale	Recommended Analysis	Description	Intended Purpose(s)	Limitations
Categorical, pooled by study total	BMP categorical analysis of relative total volume reduction observed by study	<ul style="list-style-type: none"> Sum inflow and outflow volumes by study and compute relative volume reduction (Study Total Inflow Volume - Study Total Outflow Volume)/(Study Total Inflow Volume). Pool study total relative volume reduction estimates by BMP category and compute summary statistics on study totals. 	<ul style="list-style-type: none"> Evaluate range and central tendency of relative volume reduction within BMP categories. Provide planning level estimate of ranges of long-term average volume reduction potential achievable by category of BMP. 	<ul style="list-style-type: none"> Analysis does not distinguish between BMPs in the same category with significantly different design attributes. Data reliability issues discussed elsewhere. Potential bias as a result of screening methods discussed elsewhere.
Study-based specific analyses (All analyses described above may be modified for individual studies where data allow)	Correlation of design attributes to relative volume reduction	<ul style="list-style-type: none"> Compute relative volume reduction on study-by-study basis. Identify studies with numeric or narrative design parameters. Conduct correlation analysis and/or population segregation statistical test to identify correlations and/or determine significance. 	<ul style="list-style-type: none"> Develop relationships between design parameters or attributes and volume reduction performance. Support advancement of BMP design criteria to improve volume reduction. 	<ul style="list-style-type: none"> Relative paucity of design attributes and consistency between studies may limit the number of studies that can be included in the analysis at this time.
	Study-based parameterization of mechanistic model	<ul style="list-style-type: none"> Use design parameters and study period to parameterize a mechanistic hydrology and hydraulics model to represent the monitored system. Use inflow and outflow data to calibrate model. 	<ul style="list-style-type: none"> Develop parameter estimates for representation of unmonitored BMPs. Evaluate effect of design modifications to improve volume reduction and capture efficiency. 	<ul style="list-style-type: none"> Data in Database may not be significant for full calibration of multiple models. Intra event flow data are not contained, therefore calibration would need to be based on event performance. May require obtaining additional precipitation and ET data for modeling.

4.2 Secondary Screening – Filtered Datasets with Reasonableness Checks

The data remaining after primary screening were subjected to a suite of simple reasonableness checks intended to exclude studies that are clearly not valid for volume reduction analysis. Reasonableness screening excluded observations based on the following characteristics⁴:

- 1) Inflow or outflow volume more than 120 percent of precipitation volume for greater than or equal to 50 percent of events (entire study removed), or more than 150 percent of precipitation volume for an individual event (individual event removed). Studies or events triggering these criteria likely contain errors in reported watershed areas, precipitation depths, and/or event volume and/or significant base flows that were not reported. This check is believed to improve the reliability of the dataset.

- 2) Greater than 20 percent increase in volume for greater than or equal to 50 percent of events in a study (entire study removed), or greater than 50 percent increase in volume for an individual event (individual event removed). This is the only method used to identify studies in which significant inflow pathways were not accounted for in monitoring design, or in which monitoring duration biased results. This is an imperfect screening method; although it is believed to improve the reliability of the dataset overall, it also has the potential to introduce bias. This screening step may not adequately account for the following conditions:
 - a. Studies in which significant inflow pathways are not accounted for in study design, but volume reduction performance is high enough for the study to pass the screening check. For example, a study in which approximately 20 percent of flow is not accounted for at the inflow monitoring station but which achieves 20 percent removal of captured flow would be theoretically show a near-zero net removal/gain based on reported data. Studies such as this would not be excluded; however, their inclusion would result in estimates of volume reduction potentially biased low.
 - b. Studies in which significant volume addition actually occurs in the BMP, such as by groundwater inflow, truly resulting in increased discharge volumes. In this case, a study may be excluded from analysis that accurately represents volume gain. While volume gain in BMPs is not generally expected to be significant for most BMP types, this screening method prevents a valid analysis of volume gain.

⁴ Note: the reasonableness check methodology described in this section was developed primarily with consideration of normally-dry BMPs (e.g., swales, filter strips, bioretention, detention basins) which are not expected to receive a significant amount of inflow volume via interflow and groundwater seepage, particularly when they are designed to achieve volume reduction. Because normally-wet BMP (e.g., retention ponds, wetland basins/channels, composite BMPs) commonly do receive inflow via interflow and groundwater seepage, it is not possible to distinguish between real and erroneous volume gains via a categorical level screening. As such, the reasonableness screening methodology has not been applied to normally-wet BMPs to avoid introduction of bias.

For BMP types in which significant volume gain is possible, this method may bias estimates of volume reduction performance high. However, this can be discounted with the assumption that use of the analyses results should be limited to BMPs that are not expected to or have not been designed to have significant volume addition.

- c. Studies in which differences between inflow and outflow are primarily a function of errors in measurement and/or reporting, such as mismatched durations of monitoring or miscalibration or lack of calibration of equipment. In a global sense, this criterion is expected to exclude some studies with artificial increase but would not exclude studies with artificial volume decrease, as it is not possible to distinguish artificial from real volume reduction based on this criterion. In this sense, this criterion tends to bias volume reduction high.

Overall, these secondary screening criteria are expected to improve the reliability of the dataset for volume reduction analysis; however, they are somewhat subjective may introduce a bias which cannot be quantified.

4.3 Results of Categorical Analyses

Categorical analysis was conducted on events and studies passing primary and secondary screening. Exhibit 6 provides an inventory of the data remaining for BMP categorical analysis and the analysis conducted for each category. Based on this inventory, several BMP categories were selected for further analysis, including BMP categories deemed to have sufficient quantities of paired volumetric data.

While many manufactured device studies reported flow data, the majority of these studies report identical inflow and outflow volumes to all reported significant figures. As such, the bulk of manufactured device studies did not pass primary screening criteria #3 (see Section 4.1), and this BMP category was not included in categorical analysis. Nonetheless, the observation that *reported outflow equals inflow* for the majority of manufactured devices is important as it indicates that these BMPs generally do not achieve volume reduction considered to be significant by the study investigator(s).

The following sections present the results of BMP categorical analyses and discussions of these results. Refer to Exhibit 5, above, for description of the analyses, intended uses, and limitations.

Exhibit 6. Inventory of Events/Studies Utilized for Analysis Dataset

Category	Category Name	Count of Events Passing Primary Screening ¹	Count of Events Passing Secondary Screening ²	Count of Studies Passing Secondary Screening ³	Dataset Sufficient for Categorical Analysis?
BI	Biofilter - Grass Strip	482	243	16	Yes
BR	Bioretention (with underdrains)	237	227	7	Yes
BR	Bioretention (without underdrains)	195	173	1	No
BS	Biofilter - Grass Swale	113	84	13	Yes
CO	Composite—Overall Site BMP	23	NA ⁴	NA ⁴	No
DB	Detention Basin (Dry) - Surface Grass-Lined	170	112	11	Yes
DC	Detention Basin (Dry) - Concrete or Lined Tank/Basin	8	6	1	No
DU	Detention - Underground Vault, Tank or Pipe(s)	5	5	1	No
FL	Filter - Combination of Media or Layered Media	22	21	1	No
FO	Filter - Other Media	64	64	2	No
FS	Filter - Sand	30	5	1	No
MD	Manufactured Device	15	15	2	No
OT	Other--Uncategorized BMP	11	11	1	No
RP	Retention Pond (Wet) - Surface Pond With a Permanent Pool	414	NA ⁴	NA ⁴	In vs. Out Only ⁴
RV	Retention Underground Vault or Pipes (Wet)	107	NA ⁴	NA ⁴	No
WB	Wetland - Basin With Open Water Surfaces	376	NA ⁴	NA ⁴	In vs. Out Only ⁴ , combined with WC ⁵
WC	Wetland - Channel With Wetland Bottom	44	NA ⁴	NA ⁴	In vs. Out Only ⁴ , combined with WB ⁵

1 – Count of events includes all events passing primary screening.

2 – Count of events includes all events passing primary screening and secondary screening.

3 – Includes all study locations passing primary and secondary screening; each study location contains multiple events.

4 - BMP category is “normally-wet” and therefore secondary (reasonableness) screening was not applied. A limited suite of analyses has been conducted for these categories.

5 – Wetland channels and wetland basins combined for analysis based on similar unit processes for volume reduction and relatively small number of data points for wetland channels.

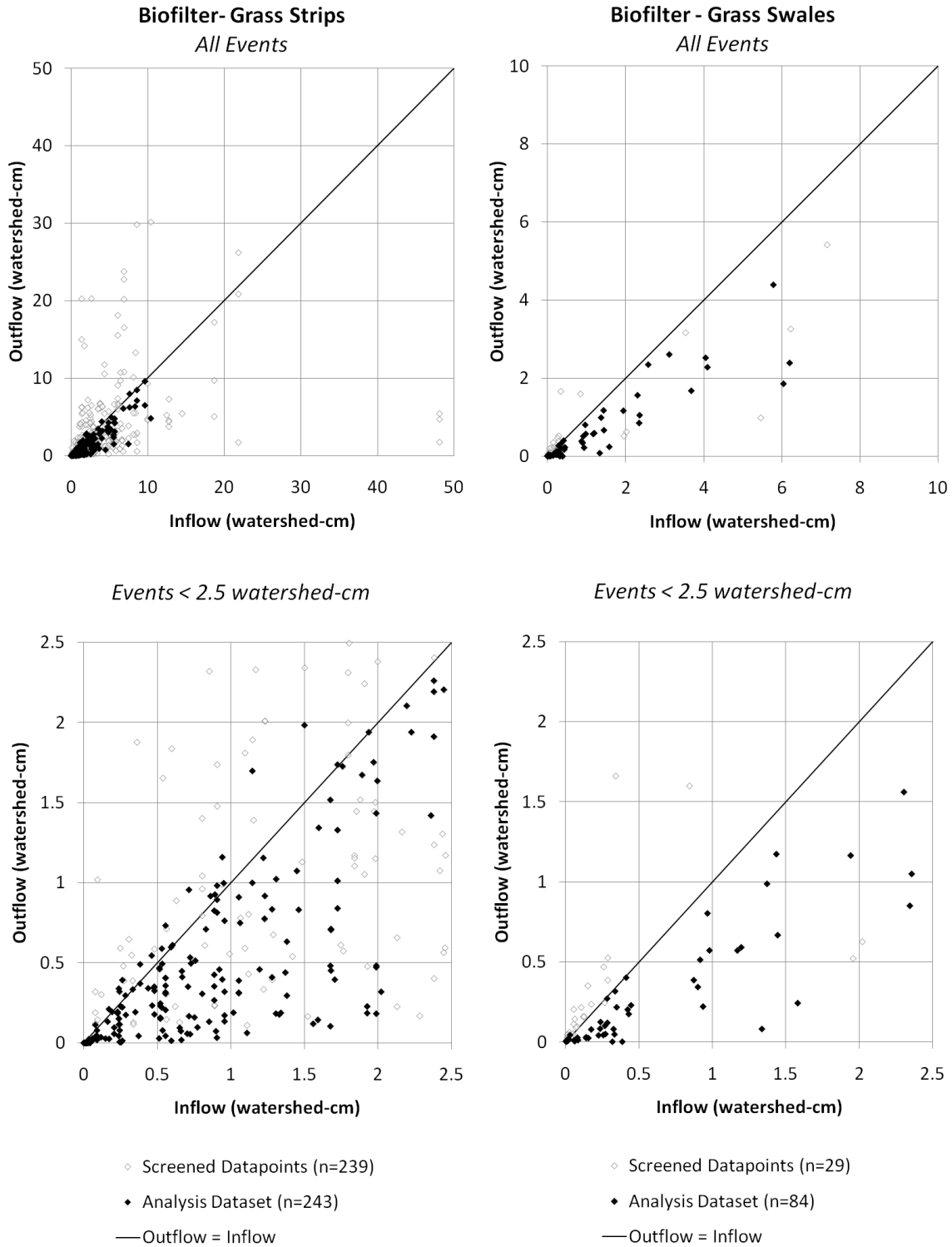
4.3.1 All Events - Pooled by BMP Category

BMP Categorical Analysis of Inflow vs. Outflow

Exhibit 7 presents plots of inflow versus outflow normalized to the equivalent depth of the flow volume over the watershed for all events, pooled by BMP category. Each point on these charts represents the respective ratio of inflow and outflow volume for a single storm event. The location of a point relative to the $Outflow = Inflow$ line indicates whether the BMP lost or gained volume during the event; points below the line indicate volume reduction, and points above the line indicate volume gain. The distance of a point from the $Outflow = Inflow$ indicates the magnitude of the loss or gain, normalized by watershed area. Two sets of charts are provided for each BMP category, with one showing the overall data set and the other “zooming in” on a subset of the data set with storms smaller than 2.5 watershed-cm. For Filter Strips, Swales, Bioretention, and Dry Detention Basins, data points that were removed from the analysis dataset as part of reasonableness screening are shown on this plot in light grey to provide a graphical inventory of all data and the analysis dataset. For retention (wet) ponds and wetland basins/channels, all data points are shown with the same symbology, as secondary (reasonableness) screening was not conducted for these types of BMPs. Data which were removed as part of primary screening prior to reasonableness checks are not shown in any plots. This analysis supports the following general observations:

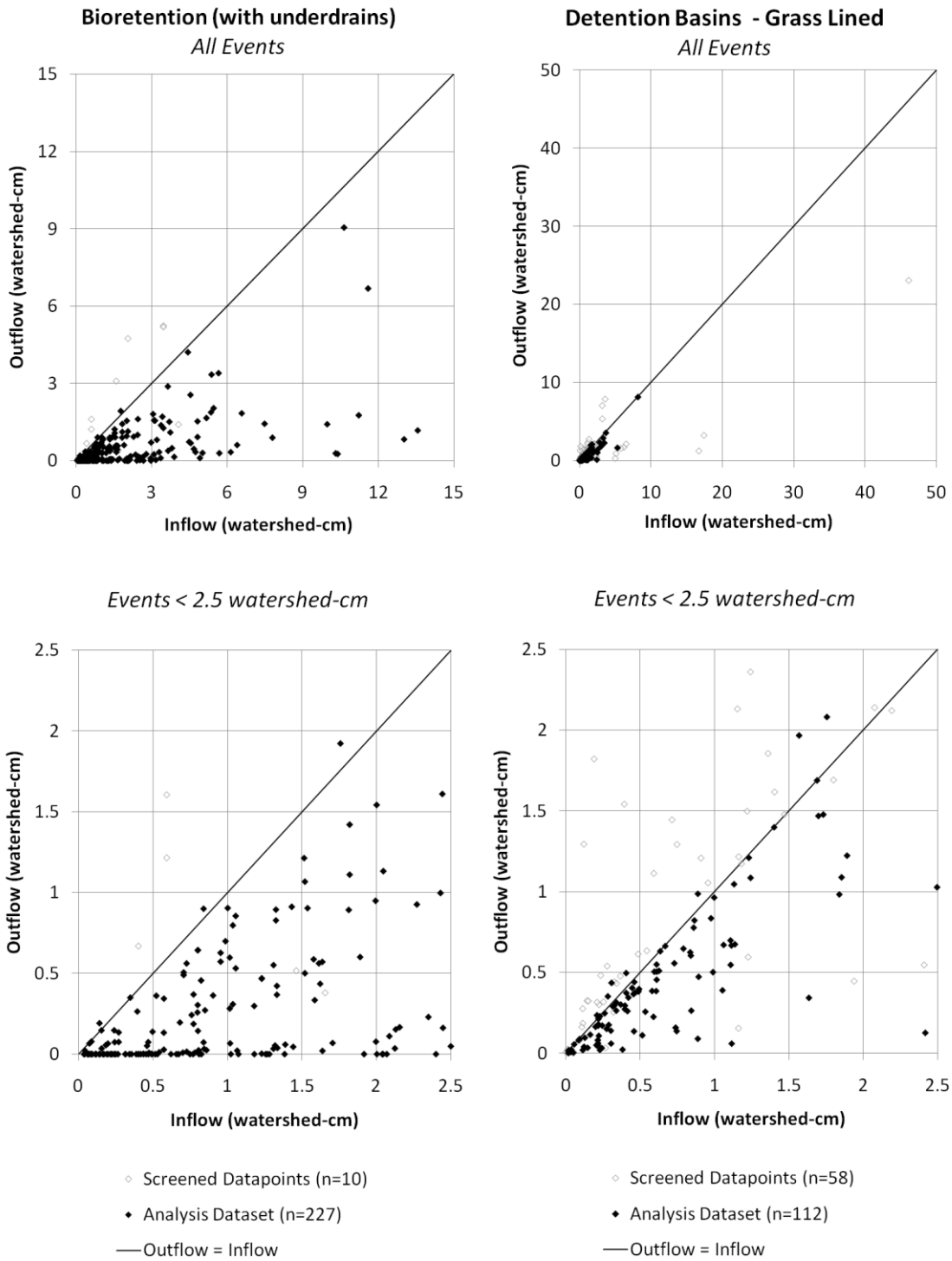
- The scatter plots shown in Exhibit 7 provide a general assessment of the variability of volumetric performance, general trends in performance, and an inventory of the data passing and failing reasonableness checks.
- All categories show substantial variability; which is a reflection of a variety of factors including differences between BMPs, event characteristics, and antecedent conditions.
- Filter strips, vegetated swales, and bioretention with underdrains exhibit relatively high volume reductions, especially for smaller storm events. Bioretention appears especially effective in preventing discharge during small events; the majority of inflow events less than 1 watershed-cm in volume result in very low or zero outflow. (Note: Discharge via underdrains is considered to be surface discharge in these studies.) Grass lined detention basins appear to provide substantial volume reduction, specifically in smaller events.
- General trends in retention (wet) ponds and wetland basins/channels do not show distinct volume loss or gain on average, but many individual events are observed to deviate widely in both directions from the 1:1 line, indicating variability in performance.
- Reasonableness screening was most important for filter strips. For filter strips, the high quantity of data not passing reasonableness checks suggests that some of the observed variability or performance and overall trends in volume reduction may be influenced by unquantified error. However, it appears that data not passing reasonableness checks are relatively equally distributed below and above the 1:1 line.
- Wetland basins and channels showed an increase in volume in a relatively large portion of storm events, particularly at low inflow volumes. Although volume gains are possible in wetland basins and channels, it is not possible to distinguish real volume gains from unreliable data points; therefore, these data did not undergo reasonableness screening.

Exhibit 7a. Scatter Plot of Inflow and Outflow Volume



Note: data inventory (“n=##”) represents the “all events” scale range.

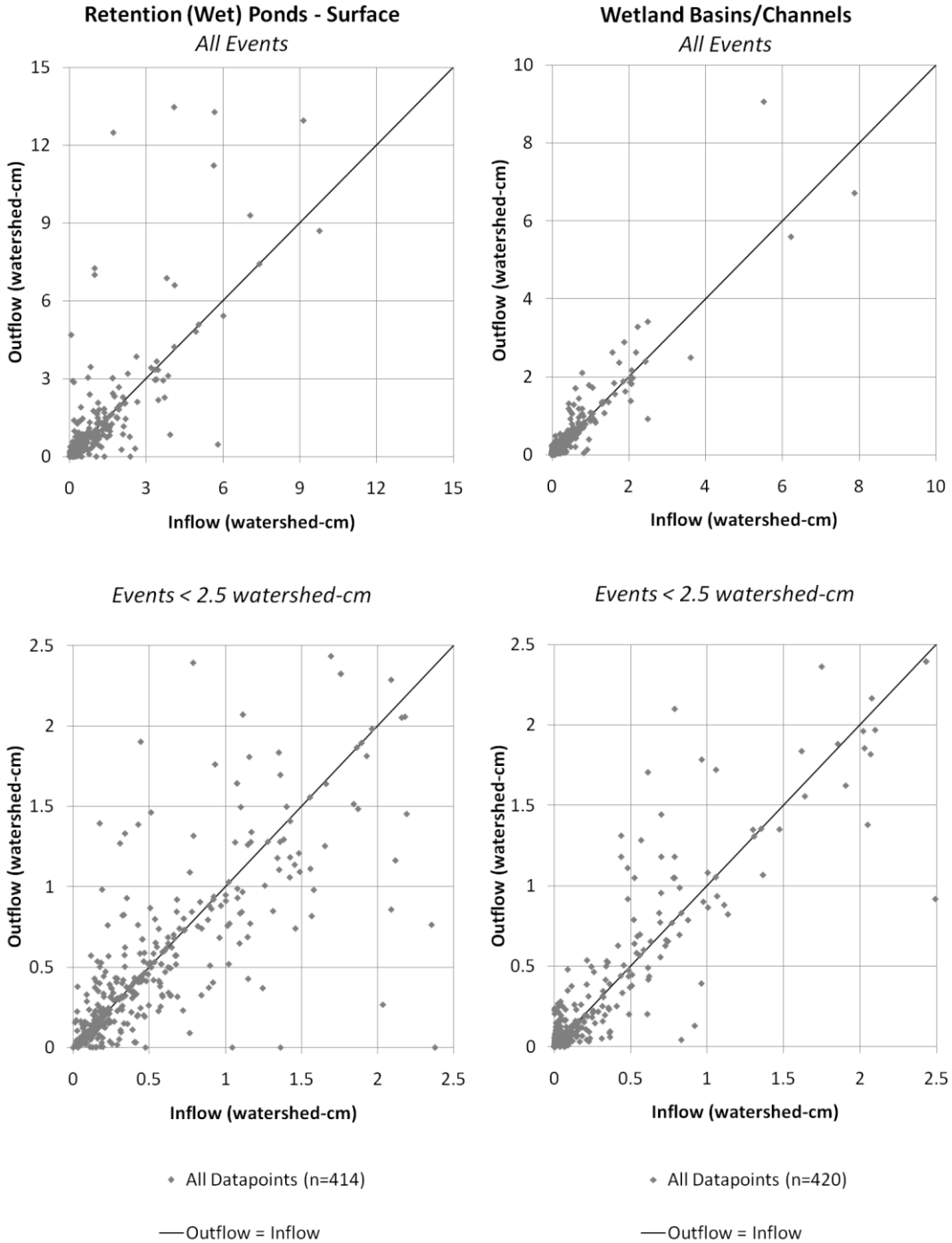
Exhibit 7b. Scatter Plot of Inflow and Outflow Volume



Note: data inventory (“n=##”) represents the “all events” scale range.

Exhibit 7c. Scatter Plot of Inflow and Outflow Volume

(Reasonableness Screening Not Conducted for Retention Ponds and Wetland Basins/Channels)



Note: data inventory (“n=##”) represents “all events” scale range.

BMP Categorical Analysis of Inflow vs. Outflow by Inflow Bins

Exhibit 8 provides plots of inflow versus outflow of all events, pooled by BMP category and summarized by normalized inflow volume bins. The column (bar) data (left axis [primary Y axis]) represent the total normalized volumes measured at the inflow and outflow monitoring locations for all events within each normalized inflow bin. These data provide an assessment of the volumetric performance for each event size bin as well as an assessment of the relative importance of each event size bin in the total volume of runoff. The line data (right axis [secondary Y axis]) represent the average normalized inflow and outflow volume for all events within each normalized inflow bin. The greater the difference between the inflow and outflow lines indicates a larger magnitude of loss or gain. Where the outflow line is below the inflow line, volume reduction is indicated.

These plots include only the screened analysis dataset described in Exhibit 6 (i.e., they do not include data that did not pass reasonableness screening).

The plots shown in Exhibit 8 provide a general assessment of volume reduction performance as a function of event magnitude and BMP category.

- Filter strips and vegetated swales exhibited similar trends: volume reductions were greatest in small- to mid-sized inflow events, and were lower and more variable in larger events. Variability in all plots at larger events is in part a result of fewer data points per bin, but also is likely due to the greater impact of larger events on runoff loss mechanisms (more likely to have saturated soils, etc.).
- Bioretention with underdrains exhibited relatively consistent volume reduction performance across all bins, but was greater for smaller inflow events. Bioretention with underdrains appears to provide the best volume reduction performance of the BMP categories. (Note: at the time of this analysis, the BMP Database contained only one bioretention study without underdrains, the “Villanova Traffic Island”; see Emerson and Traver (2008) or the Villanova Urban Stormwater Partnership <http://www3.villanova.edu/VUSP/> for detailed analysis of findings at this site.)
- Detention basins exhibited relatively consistent volume reduction for smaller events, but much more variable volume reduction for larger events. In part, this is likely due to fewer data points to represent these events, as well as more variable runoff loss capacities.

Exhibit 8a. BMP Categorical Analysis of Inflow vs. Outflow by Event Magnitude

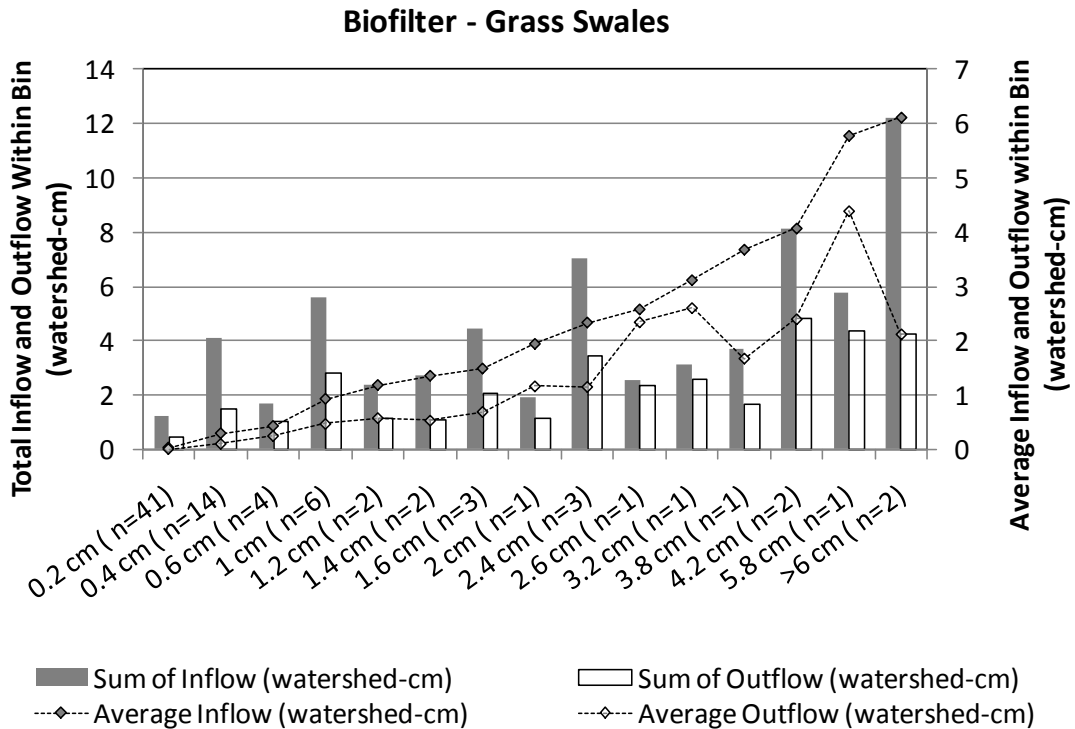
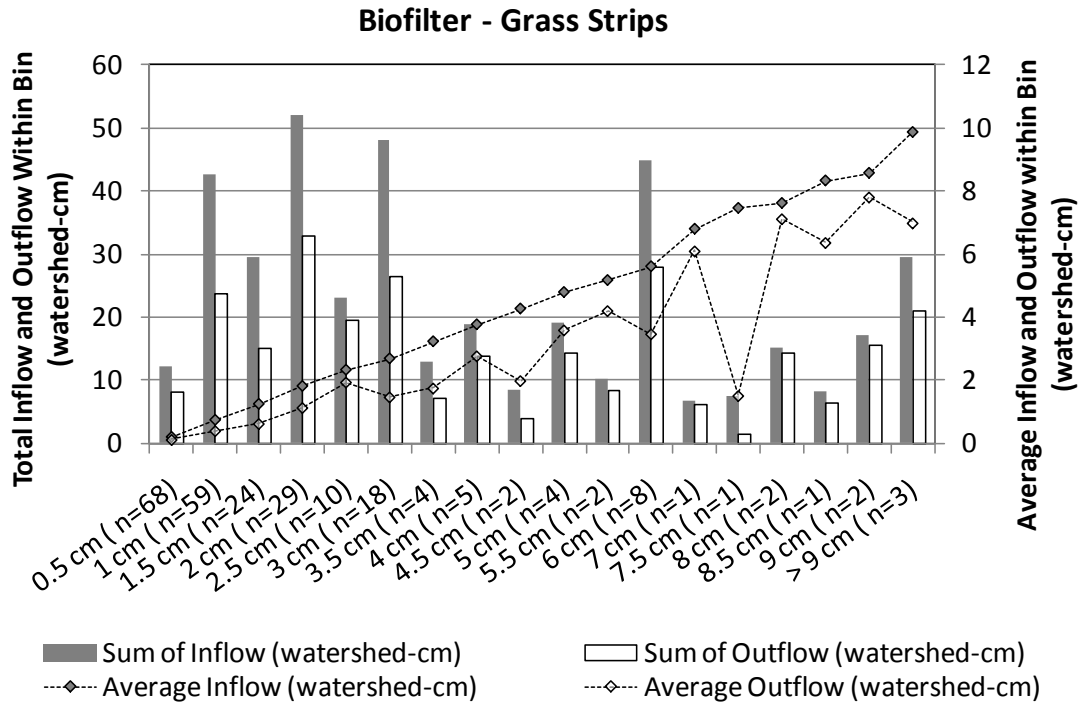
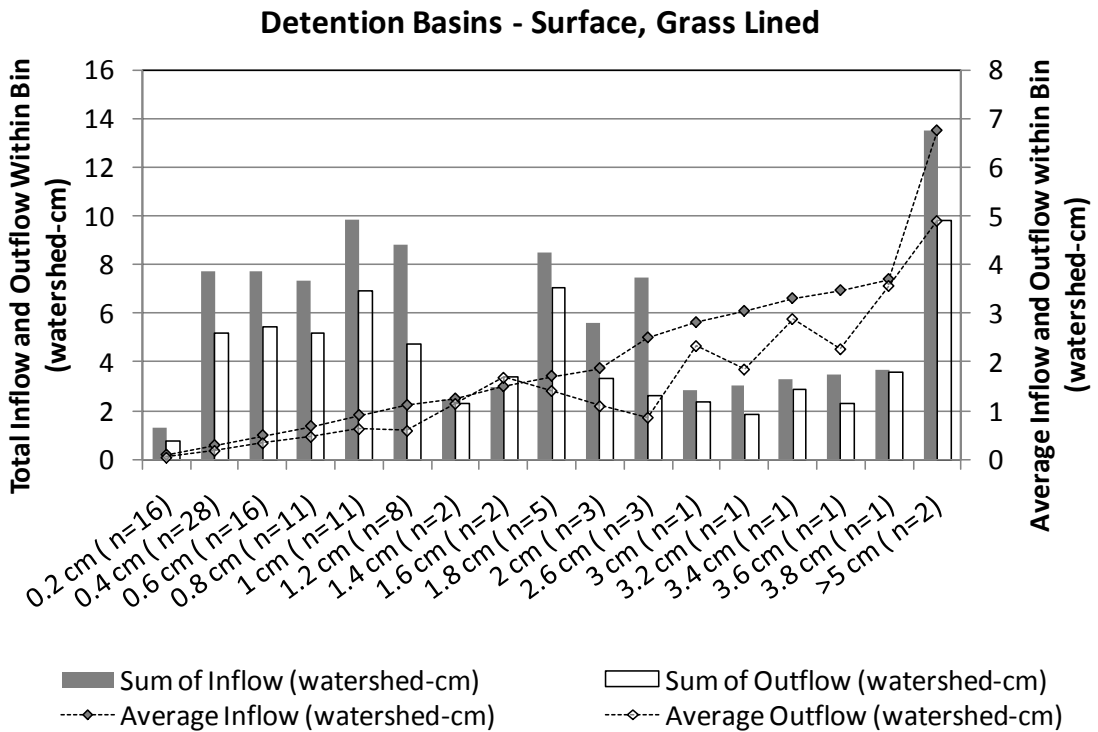
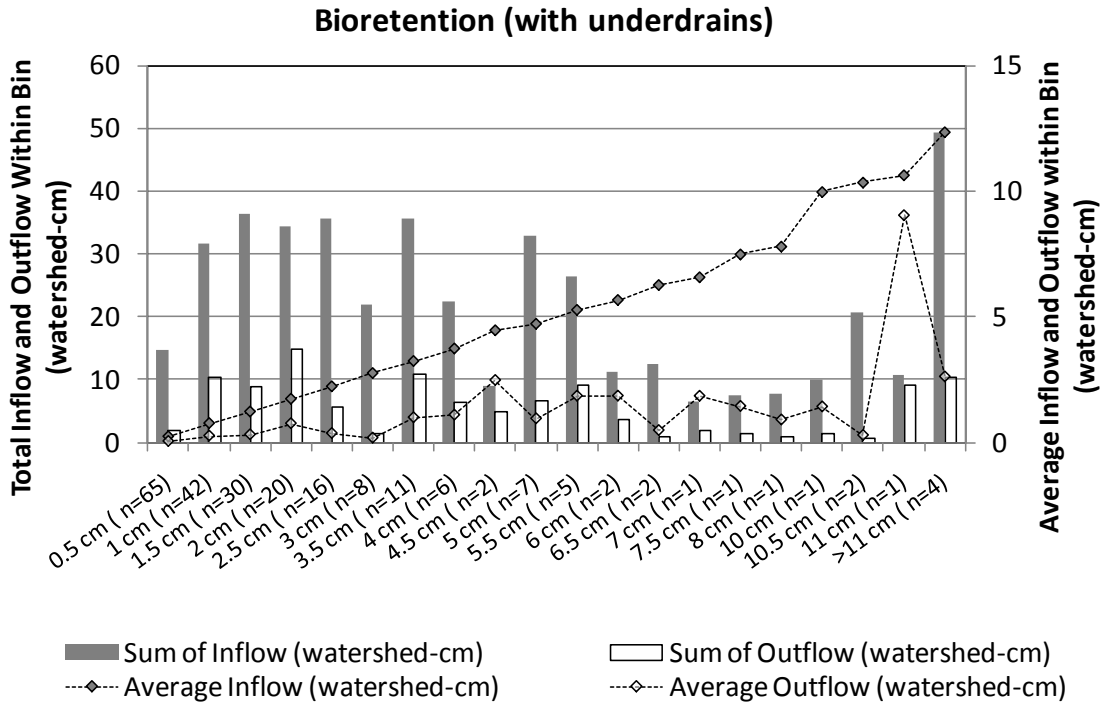


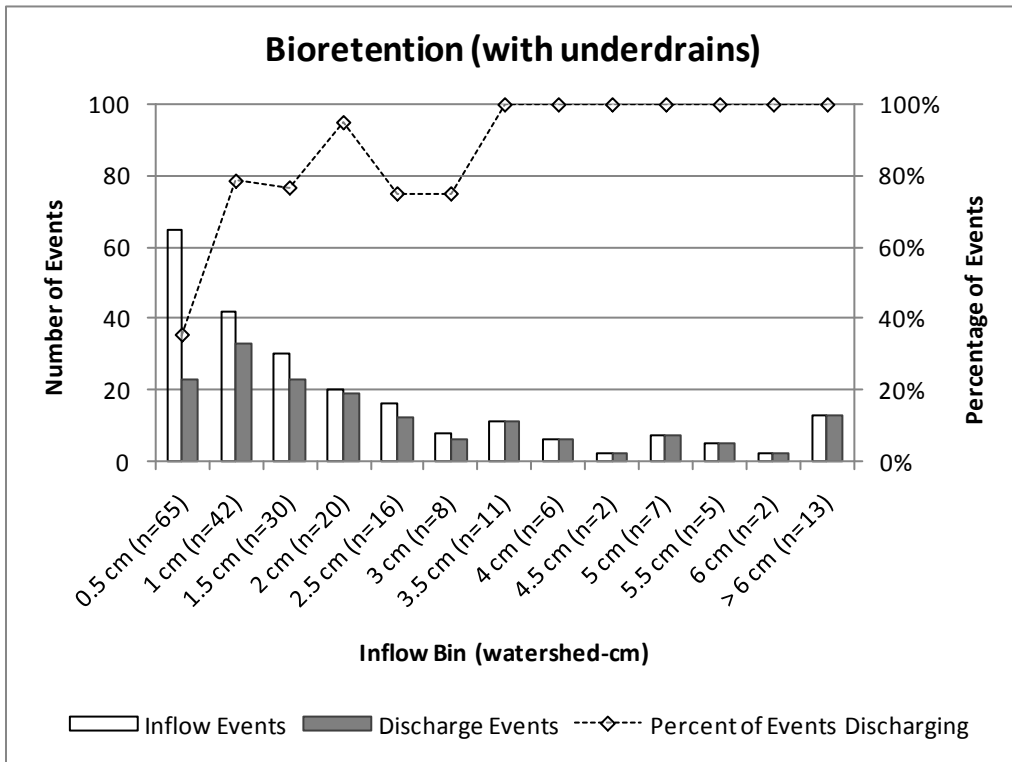
Exhibit 8b. BMP Categorical Analysis of Inflow vs. Outflow by Event Magnitude



BMP Categorical Analysis of Presence/Absence of Discharge

Only the datasets for bioretention with underdrains consistently included events in which inflow was greater than zero and outflow was explicitly reported as zero, therefore this is the only category for which presence/absence of discharge could be evaluated. Exhibit 9 provides a plot of presence versus absence of outflow discharge of all events, pooled by normalized inflow volume bins. Column (bar) data (left axis [primary axis]) provides a count of the total number of events with volume greater than zero at inflow and outflow locations, summed by normalized inflow volume bins. The line data (right axis [secondary axis]) provides the percent of events resulting in discharge for each normalized inflow volume bin. While other categories of BMPs may reduce the frequency of discharge, the available data do not support this evaluation for BMPs other than bioretention. A more advanced analysis could be conducted to evaluate the frequency of discharge below a certain threshold percentage of inflow (e.g., percent of events with discharge less than 10 percent of inflow volume), and results could be interpreted similarly to the presence/absence analysis for a broader range of BMPs.

Exhibit 9. Presence/Absence of Discharge by Storm Magnitude – Bioretention



The results shown in Exhibit 9 are consistent with the expected performance based on typical design characteristics of bioretention with underdrains. Smaller events resulted in discharge much less frequently than larger events, and all events greater than 3 watershed-cm caused at least some discharge.

4.3.2 All Studies – Pooled by BMP Category

BMP Categorical Analysis of Relative Volume Reduction by Study. All events with paired inflow and outflow were summed within studies and relative volume reduction was calculated for each study. These study results were then pooled by BMP category and summarized. Exhibit 10 provides summary statistics of study-based relative volume reduction by category.

Exhibit 10. Study Total Relative Percent Volume Reductions Observed in Recommended Analysis Dataset

BMP Category	# of Monitoring Studies	25th Percentile	Median	75th Percentile	Average
Biofilter – Grass Strips	16	18%	34%	54%	38%
Biofilter – Grass Swales	13	35%	42%	65%	48%
Bioretention (with underdrains)	7	45%	57%	74%	61%
Detention Basins – Surface, Grass Lined	11	26%	33%	43%	33%

NOTES

Relative volume reduction = (Study Total Inflow Volume - Study Total Outflow Volume)/(Study Total Inflow Volume)

Excluded other categories due to lack of sufficiently robust dataset or inability to conduct reasonableness screening.

Summary does not reflect performance categorized according to storm size (bin).

The BMP categories considered in this analysis appear to exhibit significant volume reduction. Variability in study performance is relatively wide. These numeric estimates may be useful at a planning level with consideration of the reliability of input datasets and the theoretical role of design criteria and site conditions on volume reduction performance. As such, it would be appropriate to utilize these results to evaluate the range of performance that could be expected within a BMP category over a range of conditions and design standards, but not to predict the volume reduction performance of a specific BMP designed to specific design criteria for a specific set of site conditions.

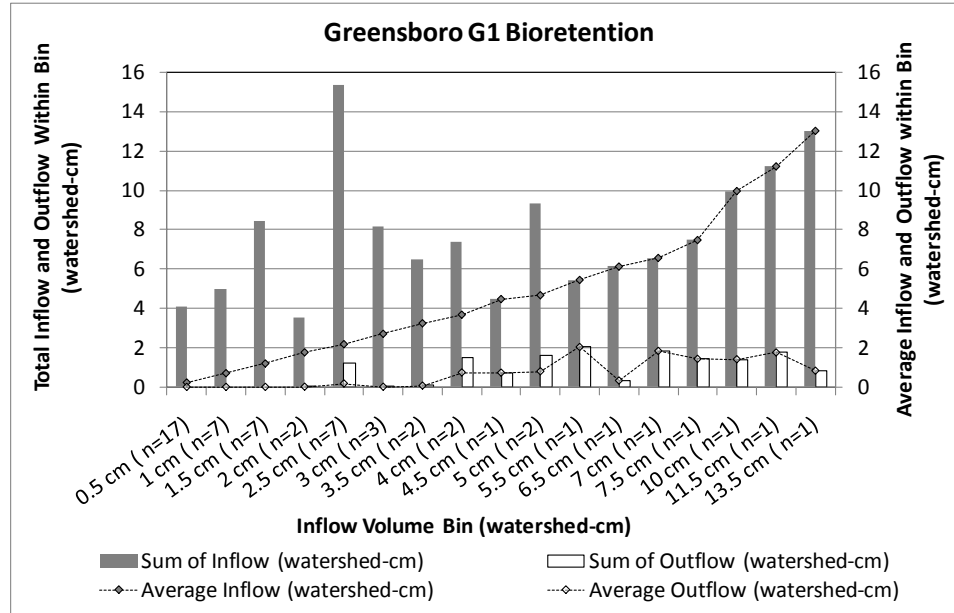
5 ADVANCED ANALYSIS OF VOLUMETRIC DATA

Three potential types of advanced analyses are introduced in Exhibit 5 and discussed further in this section.

First, it may be useful to conduct the same types of analysis performed for BMP categories on a study-by-study basis. The patterns and trends in data from a single study may in some ways be more useful than for a BMP category as a whole because there are fewer sources of variability within a single study and one can better match performance to design attributes. For example, the binned inflow vs. outflow analysis described above was applied to a single bioretention area (Greensboro G1) (see Exhibit 11). Similar trends are noted in this study as the categorical

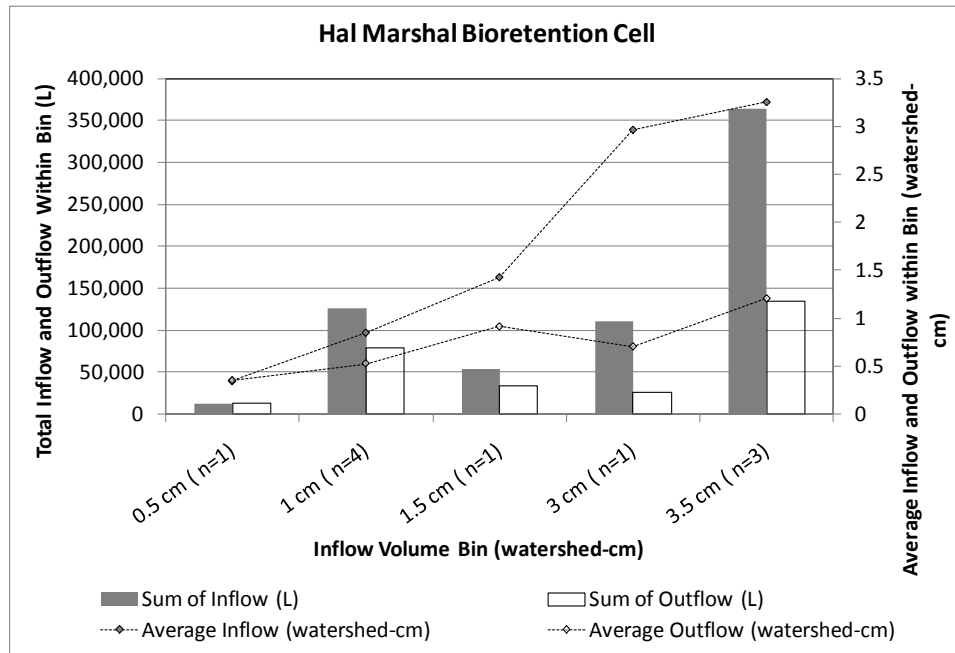
analysis presented in Exhibit 8, however data appear to be “better behaved” and are perhaps more explainable.

Exhibit 11. Study-level Analysis of Volume Reduction Performance by Event Magnitude for Greensboro G1 Bioretention Cell (Study Source: Hunt et al. 2006)



Second, it may be useful to expand the scope of analysis to include design criteria and attributes where available to develop relationships between design criteria and attributes and BMP volumetric performance. For example, the same analysis conducted for the Greensboro G1 bioretention cell (Exhibit 11) was applied to the Hal Marshall bioretention cell (Exhibit 12). Results show substantially less volume reduction and lower threshold of discharge in the Hal Marshall cell than the Greensboro G1 cell. Further investigation into the differences between these BMPs and other bioretention BMPs in the BMP Database should eventually help to refine BMP design and selection criteria with regard to volumetric performance.

Exhibit 12. Study-level Analysis of Volume Reduction Performance by Event Magnitude for Hal Marshall Bioretention Cell (Study Source: Hunt et al. 2008)



Finally, data contained in the BMP Database may be useful for parameterization and calibration of mechanistic models to specific sites or multiple sites which would allow study findings to be extrapolated to other sites or to different design criteria and configurations. For example, the development and verification of soil moisture retention curves for several monitored bioretention areas could potentially allow reliable use of these curves for facilities beyond those monitored.

6 CONCLUSIONS

6.1 General Conclusions

Over time, the objectives of BMP monitoring data have changed; specifically over the last several years, greater emphasis has been placed on management of stormwater runoff volume. In general, the volumetric data contained in the BMP Database reflect this trend. Older studies for which volume reduction was not a study objective theoretically contain greater sources of potential bias and error than newer studies. A greater portion of recent studies were conducted specifically to quantify volume reduction along with water quality characteristics. For this reason, volumetric analysis based on the BMP Database must be carefully conducted, and limitations of the dataset should be understood. This technical summary has presented several key considerations for reliability.

With appropriate consideration for reliability of the dataset and screening of data to remove unreasonable studies, meaningful results can be obtained from volumetric analyses of the BMP Database on a categorical basis. In addition, more focused volume reduction analysis of more

recent studies can potentially allow more confident, although narrower, conclusions about volume reduction performance.

Finally, analysis of the limitations of existing volumetric datasets provides fertile ground for improving study design where volume reduction is a study objective. The *Urban Stormwater BMP Performance Monitoring Manual* (Geosyntec Consultants and Wright Water Engineers, 2009a) provides updated guidance on monitoring of BMPs and LID sites, including significantly enhanced guidance for monitoring volumetric performance.

6.2 Recommendations for BMP Selection

Based on the performance data available to date in the BMP Database, only general inferences regarding BMP selection are appropriate at this time. General recommendations include:

- Normally-dry vegetated BMPs (filter strips, vegetated swales, bioretention, and grass lined detention basins) appear to have substantial potential for volume reduction on a long-term basis, on the order of 30 percent for filter strips and grass-lined detention Basins, 40 percent for grass swales, and greater than 50 percent for bioretention with underdrains. Therefore, these BMPs can be an important part of an overall strategy to manage site hydrology and control pollutant loading via volume reduction.
- Normally-dry vegetated BMPs also tend to provide better volume reduction for smaller storms, which tend to occur more frequently than larger storms; this can lead to reduced frequency of discharges or much smaller discharge volumes. Both of these would tend to reduce the frequency of water quality impairments. Developers of BMP design and performance criteria may want to consider the role of BMP volume reduction in reducing pollutant loadings when developing design requirements.
- Retention ponds and wetland basins and channels do not appear to provide substantial volume reduction on average and should not be selected to achieve volume reduction objectives. In some cases, normally-wet BMPs can be designed to provide some incidental volume reduction. Climate and other site-specific characteristics will also affect incidental volume reduction. For example, evaporation will tend to be more significant in arid areas.
- Variability in volumetric performance between studies indicates that design attributes and site conditions likely play keys role in performance. Therefore, when using categorical analysis results to select BMPs to maximize volume reduction, it is important to also ensure that design features to promote volume reduction are explicitly included in design and the site characteristics are conducive to allow volume reduction. For example, where facilities will likely be lined to prevent infiltration or soils are poor, volume reduction would likely be lower on average than observed in the BMP Database studies. Conversely, for sites with soils conducive to infiltration and design characteristics provided to promote infiltration (e.g., storage volume below the lowest outlet, etc.),

volume reduction would likely be higher on average than observed in the BMP Database studies.

7 REFERENCES⁵

- Emerson, C.H. and Traver, R.G. (2008). "Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices." *J. of Irrigation and Drainage Engineering*. 134(5): 598-605.
- Geosyntec Consultants and Wright Water Engineers (2009a). *Urban Stormwater BMP Performance Monitoring*. October 2009. 355 pp. Prepared under Support from U.S. Environmental Protection Agency, Water Environment Research Foundation, Federal Highway Administration, Environmental and Water Resources Institute of the American Society of Civil Engineers. www.bmpdatabase.org
- Geosyntec Consultants and Wright Water Engineers (2009b). *Memorandum: Drawing Appropriate Conclusions Regarding Volume Reduction in Practice- and Site-level Studies of Stormwater BMPs*. December 11, 2009. 17 pp. Prepared under Support from U.S. Environmental Protection Agency, Water Environment Research Foundation, Federal Highway Administration, Environmental and Water Resources Institute of the American Society of Civil Engineers. www.bmpdatabase.org
- Hunt, W. F., Smith, J.T., Jadlocki, S.J., Hathaway, J.M., and Eubanks, P.R. (2008). "Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, NC." *ASCE Journal of Environmental Engineering*, 134(5): 403-408.
- Hunt, W. F.; Jarrett, A. R.; Smith, J. T., and L. J. Sharkey. (2006). Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. *Journal of Irrigation and Drainage Engineering*, 132(6): 600-608.
- Strecker, E., Mayo, L., Quigley, M. and J. Howell. (2001). *Guidance Manual for Monitoring Highway Runoff Water Quality*. FHWA Report No. FHWA-EP-01-021, 206 pp.
http://www.fhwa.dot.gov/environment/h2o_runoff/h2oroff.pdf
- Strecker, E., Quigley, M., Urbonas, B. and J. Jones., 2004. Analyses of the Expanded EPA/ASCE International BMP Database and Potential Implications for BMP Design, In Proceedings of the World Water and Environmental Resources Congress, Salt Lake City, Utah, American Society of Civil Engineers.
- U.S. Environmental Protection Agency (EPA) (2009). Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act. EPA 841-B-09-001. December 2009. 63 pp.
http://www.epa.gov/owow/NPS/lid/section438/pdf/final_sec438_eisa.pdf

⁵For additional references, see the *Urban Stormwater BMP Performance Monitoring Manual* (Geosyntec and WVE 2009a), particularly Chapter 9.