International Stormwater Best Management Practices (BMP) Database

Addendum 1 to Volume Reduction Technical Summary (January 2011)

Expanded Analysis of Volume Reduction in Bioretention BMPs

Prepared by

Geosyntec Consultants
Wright Water Engineers, Inc.

Under Support From

Water Environment Research Foundation
Federal Highway Administration
Environment and Water Resources Institute of the American Society of Civil Engineers
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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's tasks have not included, and will not include in the future, recommendations of one BMP type over another. However, the Project Team's tasks have included reporting on the performance characteristics of BMPs based upon the entered data and information in the Database, including peer reviewed performance assessment techniques. Use of this information by the public or private sector is beyond the Project Team's influence or control. The intended purpose of the Database is to provide a data exchange tool that permits characterization of BMPs solely upon their measured performance using consistent protocols for measurements and reporting information.

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.

Acknowledgements

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[1] Contact Aaron Poresky (aporesky@geosyntec.com) or Jane Clary (clary@wrightwater.com) with questions regarding this summary.

Data Provider Acknowledgements

The Project Co-sponsors and Project Team gratefully acknowledge the following researchers who have shared their work with the Stormwater BMP Database Project. When citing findings associated with specific studies in the BMP Database, the original work of these researchers should be explicitly acknowledged. Standardized statistical techniques adopted by the BMP Database project have been applied to these data sets; however, the original researchers may use alternative analysis approaches in their published work which may differ from the interpretation presented in this technical summary. Additionally, some of the test sites are the subject of long-term data collection efforts and conclusions regarding BMP performance may change over time.

Teresa Culver, P.E., Ph.D., University of Virginia and Leslie Middleton, Rivanna River Basin Commission
- Charlottesville HS Biofilter

William Hunt, P.E., Ph.D., North Carolina State University
- BRC Site A
- BRC Site B
- Graham H.S. Bioretention Cells
- Greensboro bioretention-G1
- Greensboro bioretention-G2
- Hal Marshall Bioretention Cell
- Louisburg bioretention-L1
- Louisburg bioretention-L2
- Rocky Mount Grassed Cell_Year 1 (deeper IWS zone)
- Rocky Mount Grassed Cell_Year 2 (Shallower IWS Zone)
- Rocky Mount Mulch/Shrub Cell_Year 1 (deeper IWS zone)
- Rocky Mount Mulch/Shrub Cell_Year 2 (shallower IWS zone)

Robert Traver, P.E., Ph.D., D. WRE, Villanova University
- Villanova Traffic Island

William R. Selbig, U.S. Geological Survey and Nicholas Balster, Ph.D., University of Wisconsin
- Madison Water Pump House
- Owen Conservation Park

Geosyntec Consultants and MA Department of Conservation and Recreation
- Partridgeberry Place

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ADDENDUM 1 TO VOLUME REDUCTION TECHNICAL SUMMARY (JANUARY 2011): EXPANDED ANALYSIS OF VOLUME REDUCTION IN BIORETENTION BMPs

1 INTRODUCTION

The International Stormwater BMP Database Volume Reduction Technical Summary ("Technical Summary"; Geosyntec and WWE, January 2011) introduced metrics for evaluating volume reduction performance of BMPs and presented results of volume reduction analyses of BMPs in the International BMP Database (Database), building on work completed in 2009 with input from an expert panel[2] (Geosyntec and WWE 2009a&b). The Technical Summary also proposed additional analyses that could be conducted at the BMP category or study level.

Since the preparation of the 2011 report, many new studies have been added to the Database. The bioretention category has had the most substantial growth, expanding from 7 studies to 20 studies considered appropriate for volume-related analysis. Additionally, the bioretention category generally includes studies for which volume reduction was a primary study objective. For these reasons, a reanalysis of this expanded bioretention dataset has been undertaken and is provided in this Addendum. In addition to updating the bioretention analyses conducted in 2011, this Addendum presents the results of several additional types of visualizations, statistics, and regression analyses related to volume.

The bioretention studies evaluated herein are the work of several original researchers and their students and colleagues, including:

- Dr. William F. Hunt, P.E., North Carolina State University
- Dr. Robert Traver, P.E., Villanova University
- Dr. Teresa B. Culver, P.E., University of Virginia and Leslie Middleton, Rivanna River Basin Commission
- William Selbig, U.S. Geological Survey, and Dr. Nicholas Balster, University of Wisconsin
- Geosyntec Consultants

The International BMP Database team is grateful for the willingness of these researchers to share their work with the broader technical community through submission of their studies to the BMP Database. Although analysis in this Addendum is limited to volume, additional information on

[2] Expert Panel members included: Richard Horner, Ph.D., University of Washington; William Hunt, P.E., Ph.D., North Carolina State University; Robert Pitt, P.E., Ph.D., DEE, University of Alabama; Robert Roseen, P.E. Ph.D., University of New Hampshire; Robert Traver, P.E., Ph.D., Villanova University; Ben Urbonas, P.E., Urban Watersheds Research Institute.

these studies can be obtained from the researchers' original publications and from the BMP Database website (www.bmpdatabase.org).

2 TECHNICAL APPROACH

2.1 Inventory of Expanded Bioretention Datasets

Exhibit 1 presents studies that have been evaluated as part of the expanded volume reduction analysis. Further information on these studies can be found in Attachment B.

Exhibit 1: Inventory of studies evaluated

Site Name	State	Underdrain?	Paired Data Points	Approx. Date Facility Placed in Service
BRC Site A	NC	Yes	61	11/1/2005
BRC Site B	NC	Yes	61	11/1/2005
Charlottesville HS Biofilter	VA	Yes	15	4/1/2010
Graham H.S. Bioretention Cells (North)	NC	Yes	26	6/1/2005
Graham H.S. Bioretention Cells (South)	NC	Yes	26	6/1/2005
Greensboro bioretention-G1	NC	Yes	57	7/1/2003*
Greensboro bioretention-G2	NC	Yes	65	7/1/2003*
Hal Marshall Bioretention Cell	NC	Yes	15	12/1/2003
Louisburg bioretention-L1	NC	Yes	30	5/30/2004*
Louisburg bioretention-L2	NC	Yes	30	5/30/2004*
Madison Water Pump House	WI	No	279	6/1/2003
Madison Water Pump House	WI	No	220	6/1/2003
Owen Conservation Park (Prairie)	WI	No	300	6/1/2003
Owen Conservation Park (Turf)	WI	No	387	6/1/2003
Partridgeberry Place	MA	No	27	6/29/2005
Rocky Mount Grassed Cell Year 1 (deeper IWS)	NC	Yes	78	11/1/2005
Rocky Mount Grassed Cell Year 2 (Shallower IWS)	NC	Yes	73	11/1/2005
Rocky Mount Mulch/Shrub Cell Year 1 (deeper IWS)	NC	Yes	78	11/1/2005
Rocky Mount Mulch/Shrub Cell Year 2 (Shallower IWS)	NC	Yes	73	11/1/2005
Villanova Traffic Island	PA	No	173	8/1/2001

* Not provided by researcher; estimated based on date of earliest recorded samples

Exhibit 2 provides information to assess the seasonality of the data. Higher values represent a higher proportion of the measurements in a given month for that site. In general, less even distributions suggest that a study may have some degree of seasonal bias. For example, because

the viscosity of water is a function of temperature, infiltration rates under stormwater BMPs are understood to be a function of temperature (Emerson and Traver, 2008). Seasonal bias may also potentially result from seasonal groundwater table variations, seasonal variability in precipitation patterns, and other factors.

Exhibit 2: Seasonality of observations

Study Site/Name	Total # of Events	Percent (%) of Total Study Monitoring Events Recorded by Month[1]											
		J	F	M	A	M	J	J	A	S	O	N	D
BRC Site A	61	10	7	2	8	11	3	11	16	10	5	11	5
BRC Site B	61	10	7	2	8	11	3	11	16	10	5	11	5
Charlottesville HS Biofilter	15	0	0	0	0	0	0	33	33	20	7	7	0
Graham H.S. Bioretention Cells (North)	26	0	8	4	23	8	8	12	4	12	12	12	0
Graham H.S. Bioretention Cells (South)	26	0	8	4	23	8	8	12	4	12	12	12	0
Greensboro bioretention G1	57	7	0	7	4	12	11	16	14	12	5	5	7
Greensboro bioretention G2	65	8	0	8	3	11	11	15	17	11	6	5	6
Hal Marshall Bioretention Cell	15	7	20	7	13	7	13	0	0	0	7	0	27
Louisburg bioretention L1	30	0	0	0	0	3	23	17	20	13	3	13	7
Louisburg bioretention L2	30	0	0	0	0	3	23	17	20	13	3	13	7
Madison Water Pump House (Prairie)	279	4	3	9	11	14	12	10	13	8	7	5	4
Madison Water Pump House (Turf)	220	2	3	9	10	15	12	9	15	8	6	6	4
Owen Conservation Park (Prairie)	300	3	9	13	8	11	8	9	12	6	8	7	5
Owen Conservation Park (Turf)	387	4	10	14	9	10	9	9	11	6	7	6	5
Partridgeberry Place	27	0	0	0	0	0	7	41	30	22	0	0	0
Rocky Mount Grassed Cell Year 1 (deeper IWS zone)	78	9	6	6	9	9	3	9	9	8	12	12	9
Rocky Mount Grassed Cell Year 2 (Shallower IWS Zone)	73	7	4	11	3	8	7	11	14	10	5	11	10
Rocky Mount Mulch/Shrub Cell Year 1 (deeper IWS zone)	78	9	6	6	9	9	3	9	9	8	12	12	9
Rocky Mount Mulch/Shrub Cell Year 2 (shallower IWS zone)	73	7	4	11	3	8	7	11	14	10	5	11	10
Villanova Traffic Island	173	8	2	5	12	10	10	9	8	9	8	10	9

1 –because of rounding, sum of percentages may add to slightly more or less than 100 percent

2.2 Data Quality Screening

Thirty bioretention studies are currently included in the BMP Database, with 20 of these studies considered appropriate for volume-related analysis. As part of the original volume reduction analysis presented in the *Volume Reduction* Technical Summary (January 2011), volumetric data studies were subjected to two levels of data quality screening prior to analysis:

- Level 1: Initial screening was conducted to remove studies with fewer than three paired data points or where the study contributor indicated that data were not valid for volume reduction analysis.
- Level 2: Reasonableness screening was then conducted to identify events or studies for which data points may have been inappropriate for volume reduction analysis. This reasonableness screening involved some professional judgment and was intended to improve the reliability of volume reduction analyses.

Based on evaluation of studies in the bioretention category, Level 2 reasonableness screening was not necessary to improve the reliability of the dataset. Generally, the bioretention studies passing Level 1 screening were conducted with the explicit intent of evaluating volume reduction, and notes were provided by the contributing researcher to identify studies or sample points that are not considered reliable for volume reduction analysis. As such, only Level 1 initial screening was conducted for the bioretention dataset. Ten studies were excluded from the analysis based on the Level 1 screening.

As discussed in the Volume Reduction Technical Summary (January 2011), it is recognized that there may be inflows to the system that cannot be measured with study instrumentation such as precipitation directly on BMPs, sheet flow from BMP side slopes and surrounding areas, interflow, and other sources. At this time, the standard practice employed for volume reduction analyses of the International BMP Database is to analyze the volumetric inflow and outflow data as reported by the original researchers and to not implement post-hoc adjustments to attempt to account for unmeasured flows. This assumption has the potential to underestimate inflow volumes somewhat, specifically in BMPs with larger footprints relative to their tributary areas, which in turn may underestimate the volume reduction provided.

2.3 Scope of Analyses Conducted

Three general types of analyses were conducted for the expanded bioretention dataset:

Categorical and Sub-Categorical Analyses. Categorical plots and statistics are presented for all studies and two subsets of the studies: systems with underdrains and systems without underdrains.[3] The following plots and statistics were generated for the entire dataset and each subset:

a) Scatter Plots of Inflow versus Outflow Volume

[3] The presence or absence of underdrains was noted in study descriptions provided by contributing researchers. Underdrains refer to drainage layers or pipes that convey treated discharge that has passed through the bioretention media to the downstream drainage system. The elevation of the underdrain discharge above the native soil interface varies between studies and is not universally reported. Systems with discharge elevation 12 to 18 inches or more above the native soil (often accomplished with an upturned elbow design) are generally considered to have an "internal water storage zone" (IWS). As the bioretention data set grows, it may be appropriate to analyze designs with IWS as a separate subcategory and/or to include the degree of IWS as an independent parameter in regressions.

b) Binned Presence-Absence Plots by Inflow Event Magnitude
c) Binned Relative Volume Reduction Plots by Inflow Event Magnitude
d) Study Average Relative Volume Reduction Table

See Sections 4.3.1 and 4.3.2 of the 2011 Technical Summary for more detailed descriptions of these plots and tables. Reported volumes analyzed in this report include the sum of bypass, overflow, and treated flow where reported. For systems with underdrains, the total discharge is the sum of bypass, overflow, and treated flow. For systems without underdrains, the total discharge is the sum of the bypass and the overflow, as there is no treated discharge.

Categorical Regression Plots. Regression analysis can be used to identify relationships between independent variables and dependent variables. In the case of BMP volume reduction, the study's long-term relative volume reduction performance (percent volume reduction) can be considered to be a dependent (response) variable. Volume reduction performance of bioretention is conceptually understood to be a function of a variety of factors, including surface area, volume, soil infiltration rate, temperature, and other factors. Based on data provided by contributing researchers, potential independent (cause) variables were developed. These were selected based on conceptual understanding, as well as the availability of consistently reported data. Two categorical regression plots were developed:

a) Relative Volume Reduction vs. BMP Surface Area Ratio
b) Relative Volume Reduction vs. BMP Ponded Volume as Ratio of Study Average Event Inflow Volume

The surface area ratio was typically provided by the study or was calculated directly from data provided and is defined as the ratio of the BMP area to its tributary area. BMP ponded storage volume was typically provided by the studies or could be readily estimated from BMP area and ponding depths. These plots are provided primarily as examples of the types of regression analysis that can be conducted on the bioretention datasets, however are not intended to support specific statistical findings at this time.

Individual Study Analyses. Individual study plots and statistics were developed based on the same methodology used for the categorical analyses. These plots and statistics are presented for each study as Attachment A to this Addendum and include:

a) Binned Presence-Absence Plots by Inflow Event Magnitude
b) Binned Relative Volume Reduction Plots by Inflow Event Magnitude
c) Scatter Plots of Inflow versus Outflow Volume
d) Relative Volume Reduction Table

As previously noted, Sections 4.3.1 and 4.3.2 of the Technical Summary provide descriptions of these plots and tables. The representativeness of individual study results may vary depending on sample size and seasonal distribution.

3 RESULTS

Section 3 presents results of analyses, with interpretation of these results provided in Section 4.

3.1 Categorical Plots and Statistics

Exhibit 3 shows scatter plots of all bioretention inflow/outflow data pairs. Values below the 1:1 line represent events in which volume reduction occurred. Values above the 1:1 line represent events in which outflow was observed to be greater than inflow (i.e., volume gain). Exhibit 4 shows the same set of scatter plots for studies with underdrains, and Exhibit 5 shows the same set of scatter plots for studies without underdrains.

Exhibit 3: Scatter plots of event inflow versus event outflow volume; all studies

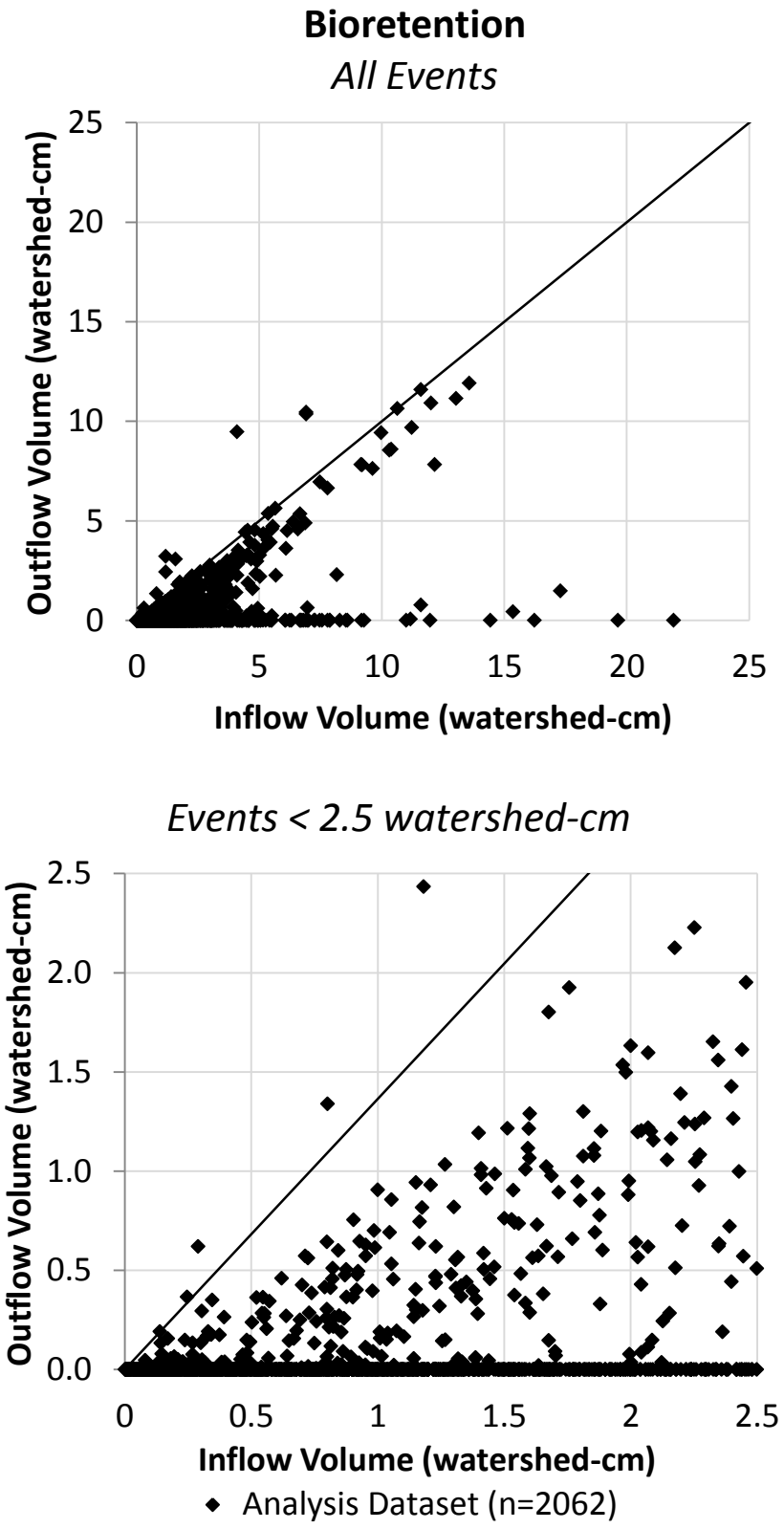


Exhibit 4: Scatter plots of event inflow versus event outflow volume; with underdrains

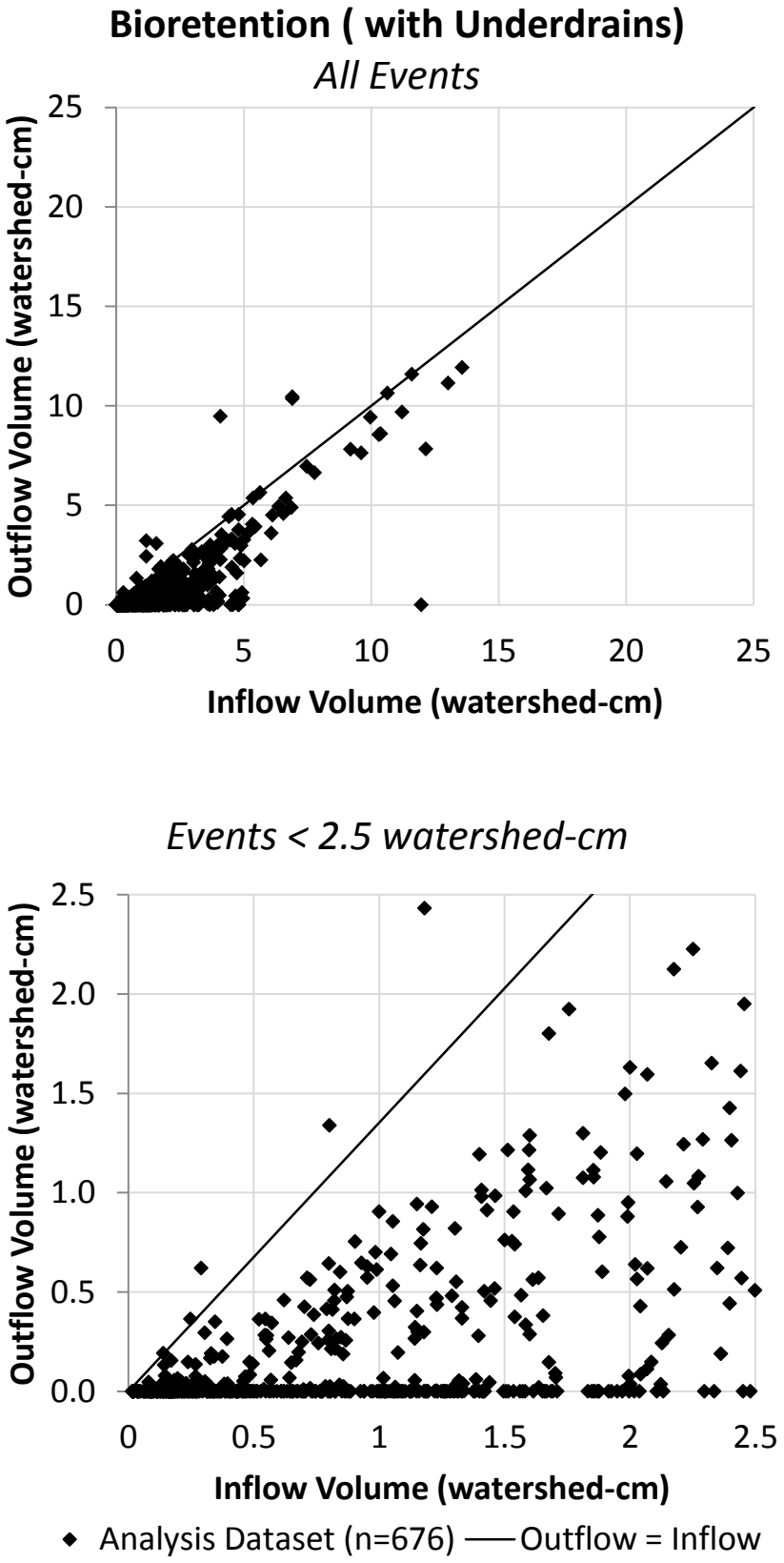


Exhibit 5: Scatter plots of event inflow versus event outflow volume; without underdrains

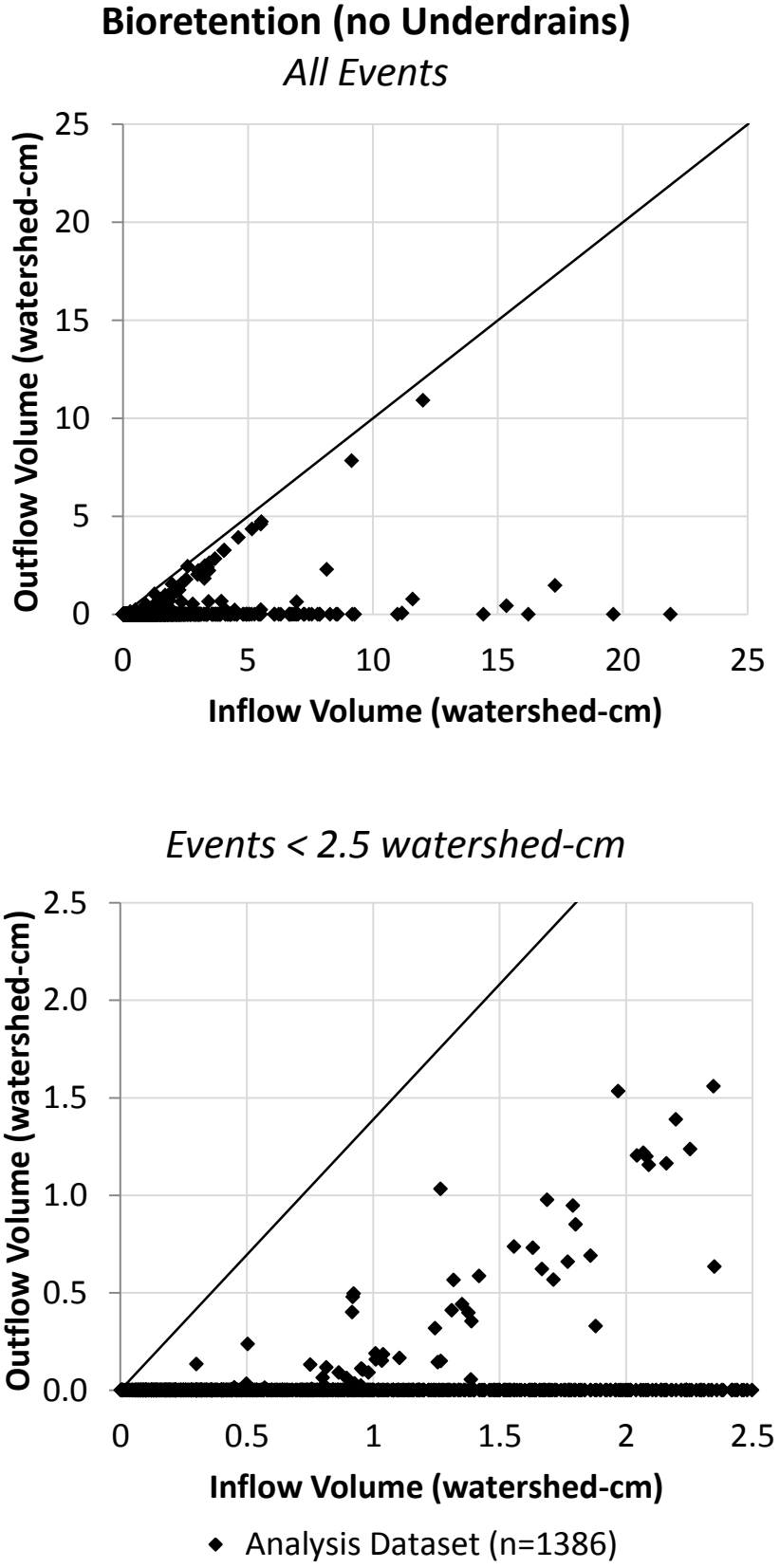


Exhibit 6 shows binned presence-absence plots by event magnitude for all studies. The bars represent the count of inflow and outflow events greater than zero reported in each bin of inflow event magnitude. The line chart plots the percentage of events in each bin for which outflow was present. Exhibit 7 shows the same plot for studies with underdrains, and Exhibit 8 shows the same plot for studies without underdrains.

Exhibit 6: Binned presence/absence plots by event magnitude; all studies

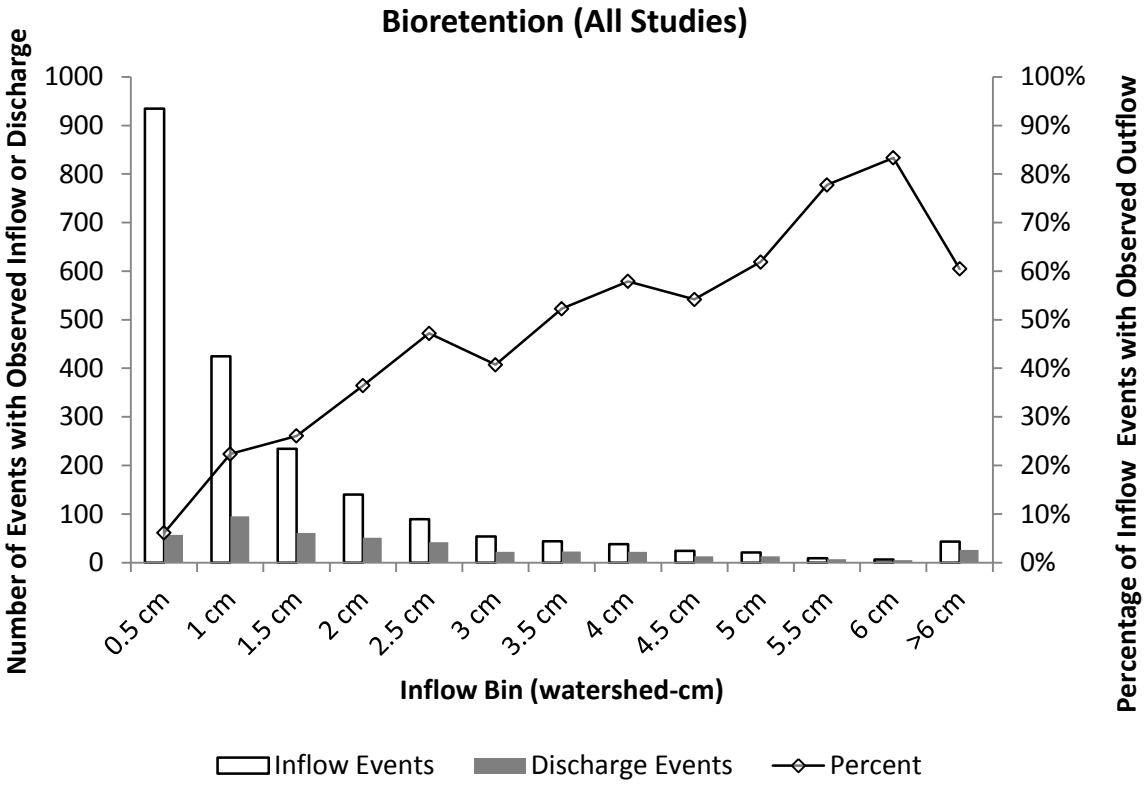


Exhibit 7: Binned presence/absence plots for only sites with underdrains

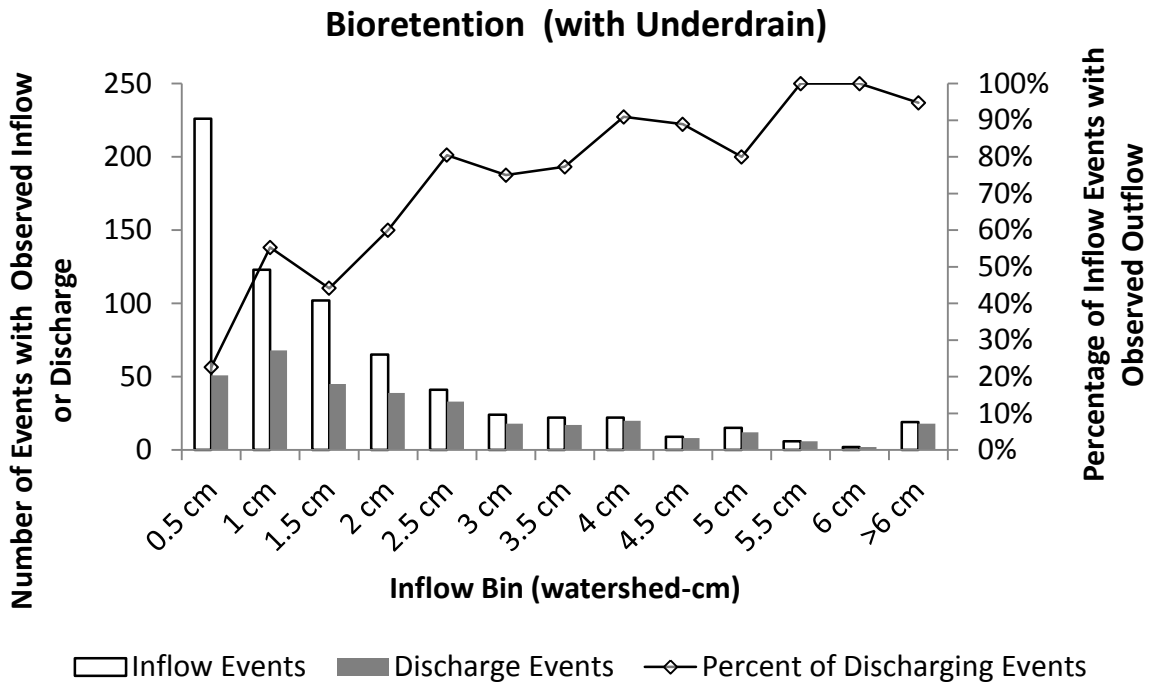


Exhibit 8: Binned presence/absence plots for only sites without underdrains

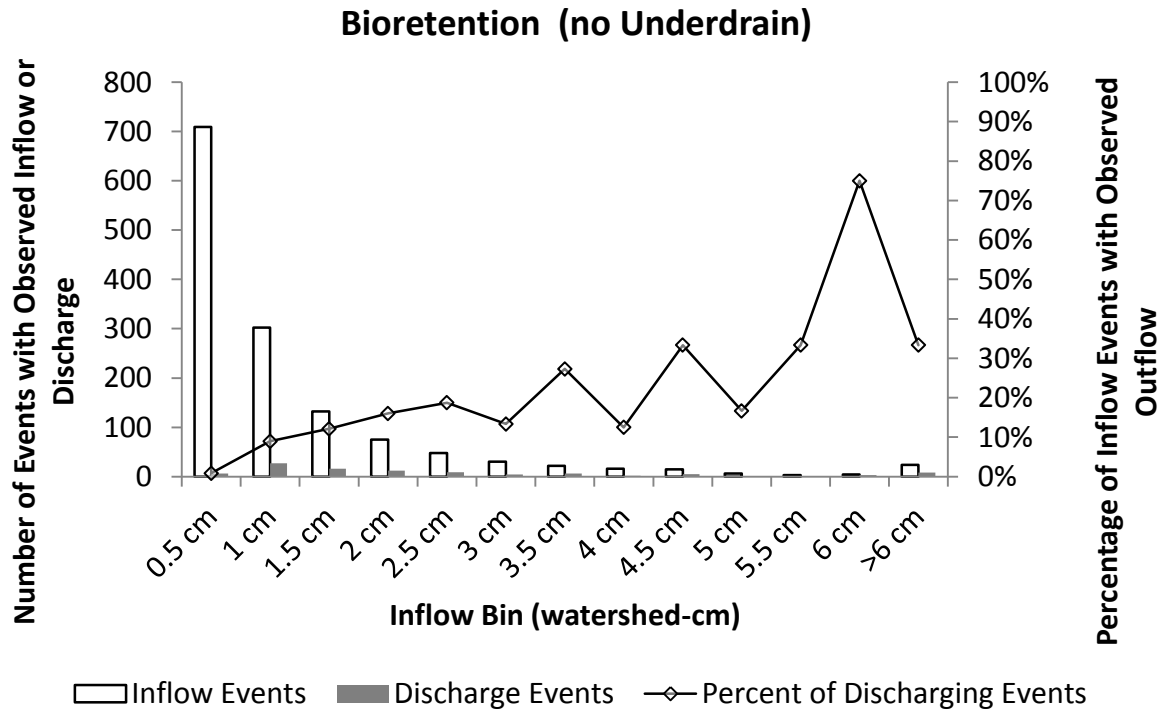


Exhibit 9 reports relative volume reduction statistics for all bioretention studies, and for subsets with and without underdrains. Relative volume reduction is calculated as the fraction of the total study inflow volume that does not discharge. It is calculated by summing total inflow and outflow volumes for all monitored events.

Exhibit 9: Relative volume reduction statistics for bioretention studies

Analysis Group	# Studies	25th Pctl.	Median	75th Pctl.	Avg.
All Studies	20	42%	66%	98%	66%
No Underdrains	6	85%	99%	100%	89%
With Underdrains	14	33%	52%	73%	56%

Exhibit 10 shows binned relative volume reduction plots by event magnitude for all studies. The bars represent the total volume of inflow and outflow within each bin. The lines report the average event inflow and outflow volume within each bin. Exhibit 11 shows the same plot for studies with underdrains, and Exhibit 12 shows the same plot for studies without underdrains

Exhibit 10: Total and average inflow and outflow binned by event size for all studies

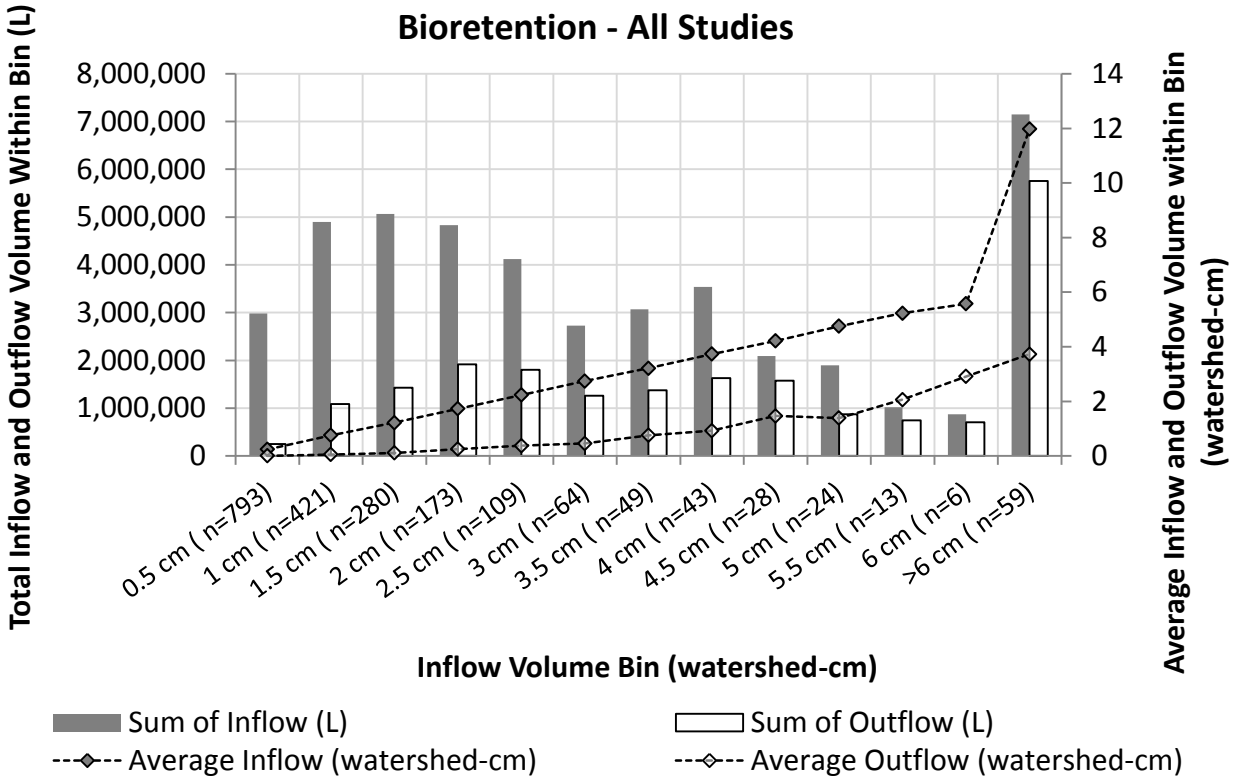


Exhibit 11: Total and average inflow and outflow binned by event size for only sites with underdrains

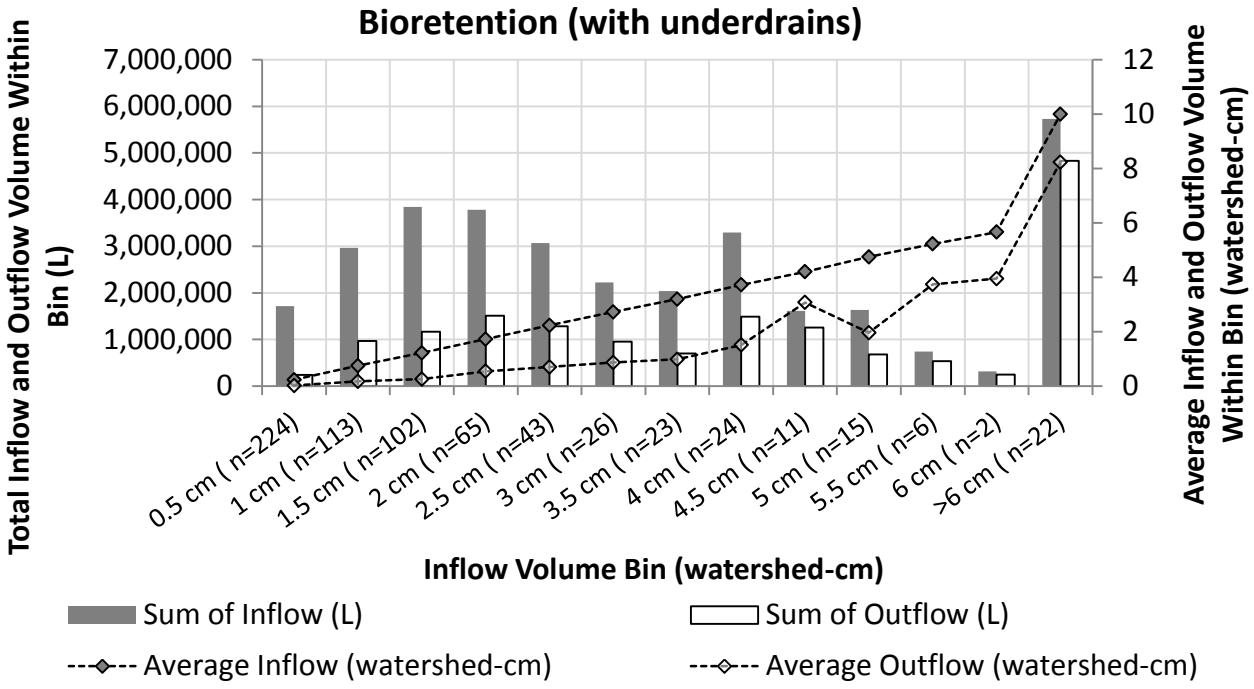
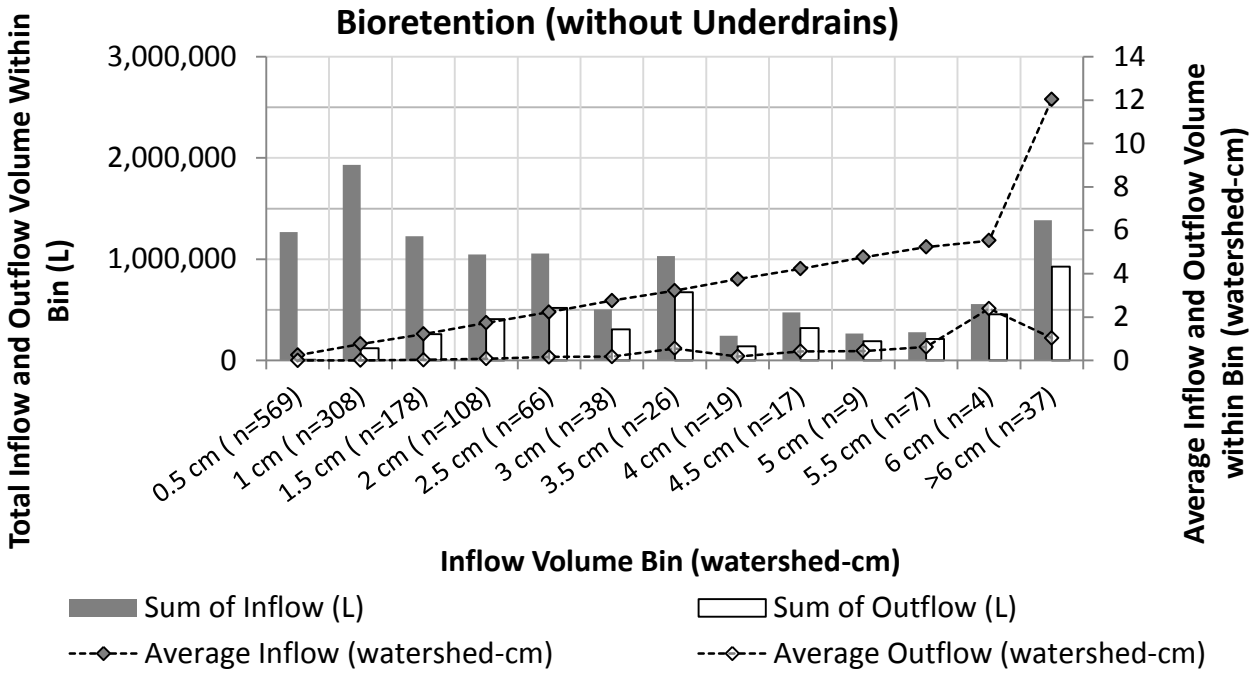


Exhibit 12: Total and average inflow and outflow binned by event size for only sites without underdrains



3.2 Categorical Regression Plots

As described in Section 2.3, BMP category-based regression plots can be useful in understanding relationships between independent and dependent variables. Initial plots have been developed to begin to visualize potential causal relationships between bioretention design parameters and volume reduction performance. Additionally, study attributes presented in Attachment B may be useful for conducting expanded regression analyses. Due to the relatively limited data set analyzed, these analyses should be considered preliminary, but provide examples of analyses that may be further refined in the future as the dataset grows.

Exhibit 13 shows study average relative percent volume reduction plotted against the ratio of tributary area to BMP surface area. Data for calculating the ratio was available for all 20 sites.

Exhibit 14 shows study average relative percent volume reduction versus BMP ponded volume as a percent of study average event inflow volumes for each site. BMP ponded volume was available or could be estimated for all systems.

It is noted that the independent variables used in Exhibit 13 and 14 are not mutually independent as both are related to total system size.

Exhibit 13: Study average relative percent volume reduction versus the ratio of BMP surface area to tributary area

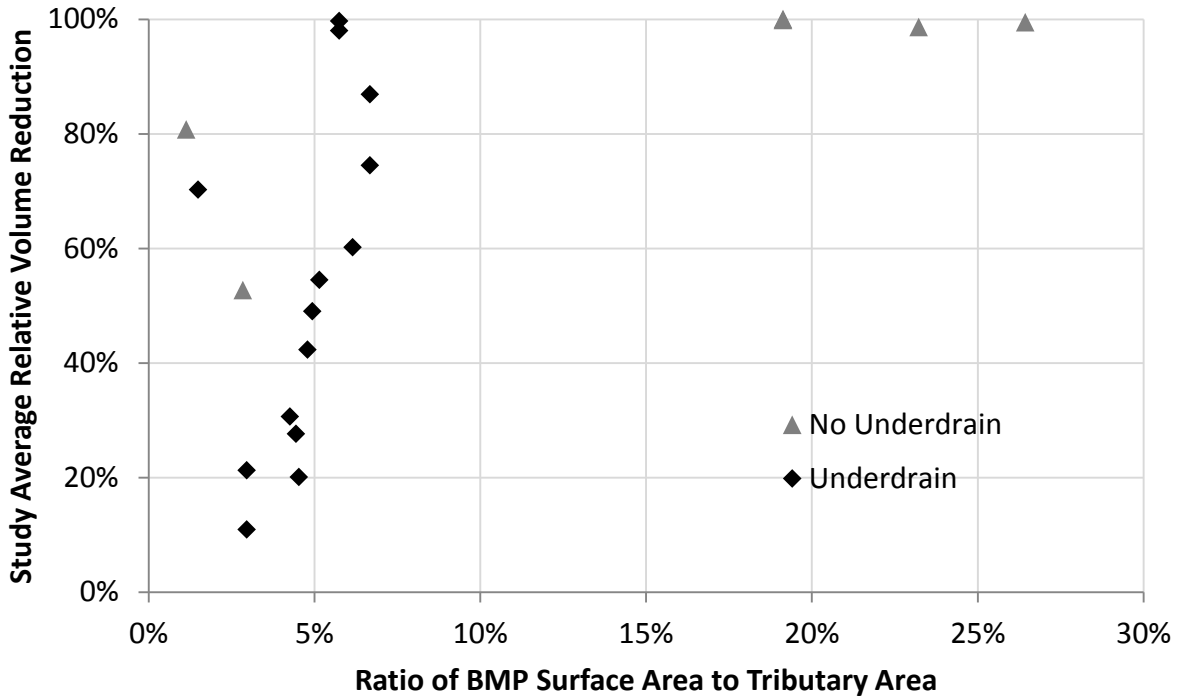


Exhibit 14: Study average relative percent volume reduction versus BMP ponded volume as a percent of study average event inflow volume

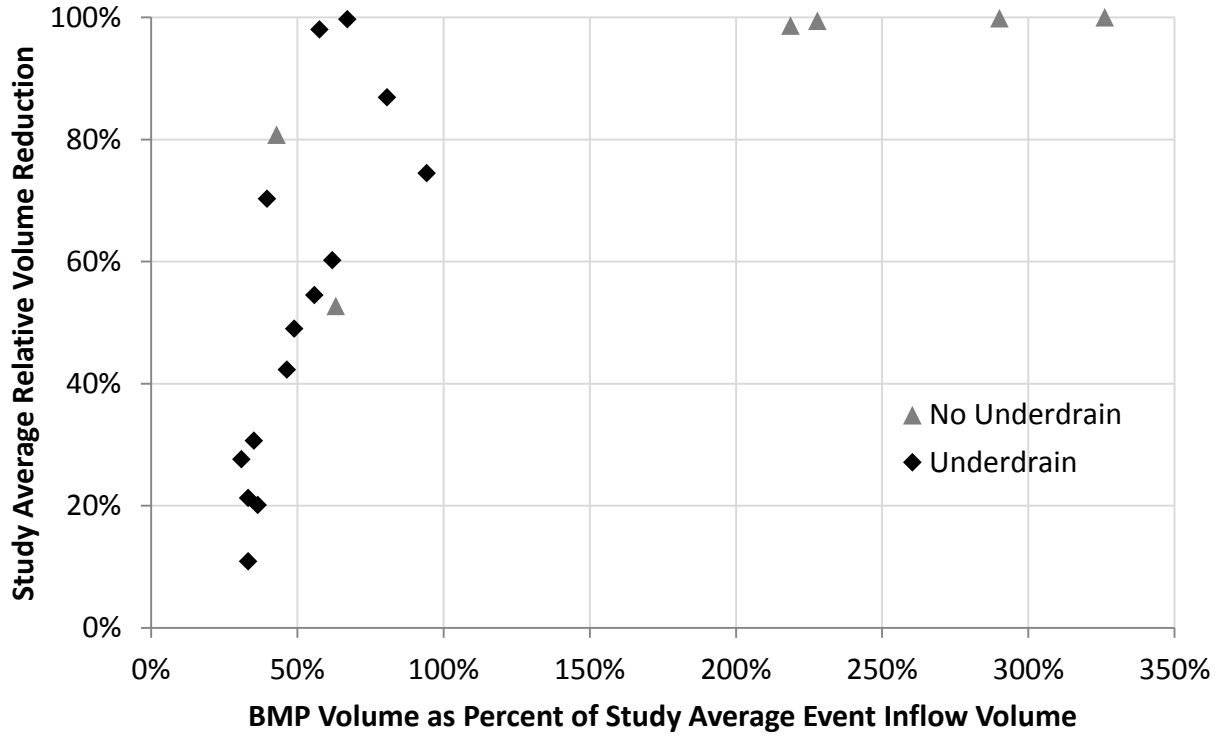


Exhibit 15: Data supporting preliminary regression plots (Exhibit 13 and Exhibit 14)

Study Site	Study Name	Ratio of BMP Surface Area to Tributary Area	BMP Ponded Volume as Percent of Study Average Event Inflow Volume	Study Average Relative Volume Reduction	Underdrain?
Partridgeberry Place	Central Rain Garden	1.1%	43%	81%	No
Villanova Traffic Island	Traffic Island	2.8%	63%	53%	No
Madison Water Pump House	Pump House Rain Garden Turf	23.2%	219%	99%	No
Madison Water Pump House	Pump House Rain Garden Prairie	26.4%	228%	99%	No
Owen Conservation Park	Owen Rain Garden Prairie	19.1%	326%	100%	No
Owen Conservation Park	Owen Rain Garden Turf	19.1%	290%	100%	No
BRC Site A	BRC_A	4.3%	35%	31%	Yes
BRC Site B	BRC_B	4.8%	47%	42%	Yes
Graham H.S. Bioretention Cells	North cell	3.0%	33%	11%	Yes
Graham H.S. Bioretention Cells	South cell	3.0%	33%	21%	Yes
Greensboro bioretention-G1	G1	4.9%	49%	49%	Yes
Greensboro bioretention-G2	G2	5.1%	56%	55%	Yes
Hal Marshall Bioretention Cell	Hal Marshall Bioretention Cell	6.2%	62%	60%	Yes
Louisburg bioretention-L1	L1	4.4%	31%	28%	Yes
Louisburg bioretention-L2	L2	4.5%	37%	20%	Yes
Rocky Mount Grassed Cell_Year 1 (deeper IWS zone)	Rocky Mount Grassed Bioretention Cell 1	6.7%	81%	87%	Yes
Rocky Mount Grassed Cell_Year 2 (Shallower IWS Zone)	Rocky Mount Grassed Bioretention Cell 2	6.7%	94%	74%	Yes
Rocky Mount Mulch/Shrub Cell_Year 1 (deeper IWS zone)	Rocky Mount Mulch/Shrub Bioretention Cell 1	5.8%	58%	98%	Yes
Rocky Mount Mulch/Shrub Cell_Year 2 (shallower IWS zone)	Rocky Mount Mulch/Shrub Bioretention Cell 2	5.8%	67%	100%	Yes
Charlottesville HS Biofilter	CHS_BioFilter	1.5%	40%	70%	Yes

3.3 Individual Study Plots and Statistics

Attachment A provides the results of study level analyses. For each study, the following standardized plots and tables have been generated:

Exhibit A: Binned Presence-Absence Plots by Inflow Event Magnitude

Exhibit B: Binned Relative Volume Reduction Plots by Inflow Event Magnitude

Exhibit C: Scatter Plots of Inflow versus Outflow Volume

Exhibit D: Study Average Relative Volume Reduction Table

Note that the number of events for each study varies considerably, therefore the significance of these analyses varies.

Attachment B provides a condensed table of study attributes. These attributes have been consolidated from the original table of study attributes contained in the Database. The attributes presented in Attachment B were selected based on the following criteria: (1) attributes that are uniformly and consistently reported, or can be derived from available data without significant interpretation required, and (2) attributes that are considered to have a significant potential influence on volume reduction results.

4 DISCUSSION AND FINDINGS

A variety of methods have been used to visualize and quantify volume reduction performance of bioretention BMPs at the category level, sub-category level, and study level. While the purpose of this Addendum is primarily to report analysis results and not to interpret data, the following observations have been made:

- Volume-related data for bioretention BMPs in the BMP Database show that bioretention can be an effective approach for reducing runoff frequencies, peak flow rates and volumes during frequently occurring storm events. Performance at individual sites will depend on a variety of site-specific factors, as well as BMP design, installation and maintenance.
- The bioretention dataset appears to be well-suited to volume reduction analyses. Visualizations show reasonable magnitudes. Additionally, trends are generally consistent with theoretical expectations.
- The analyses reported in this Addendum are considered reliable to provide an indication of the expected variability and the range of volume reduction performance that may potentially be expected from bioretention BMPs. The general limitations of categorical analysis discussed in the Technical Summary still apply.
- While the bioretention category has grown considerably since the 2011 Technical Summary, the reliability of categorical analysis results is still limited by the number of available studies. Many of the studies have been concentrated in a few areas of the country (mid-Atlantic/eastern seaboard). Additionally, while there are a wide range of bioretention designs and site conditions represented, some studies are understood to have been conducted on systems with somewhat atypical design conditions (i.e., very large footprints; very high infiltration rates). Because of design and site conditions are believed to have substantial influence on volume reduction performance, design parameters should be considered when extrapolating result of categorical and study-level analyses to other bioretention installations.
- Initial regression plots suggest that relationships may exist between volume reduction performance and bioretention design attributes. Additionally, relationships may exist, though were not evaluated, between volume reduction performance and site attributes such as soil infiltration rate below the BMP location (infiltration into native soils). These relationships indicate that the volume reduction performance of bioretention BMPs can potentially be described by causal relationships, and suggest that attention should be given to these causal relationships when extrapolating study results to expected volume reduction. For example, Davis et al. (2012) have proposed several metrics to explain causal relationships in bioretention hydrologic performance.

- The relatively wide scatter in regression plots based on selected independent variables indicates that other variables also influence volume reduction performance. For example, within a range of footprint ratios from approximately 4% to 6%, the relative volume reduction ranges from 20% to 100%.
- The bioretention volume dataset would potentially provide a sound starting point for further analysis of causal relationships, including potential to develop more robust multi-variate regressions and/or to develop calibrated models for volume reduction and associated pollutant load reduction. As new studies are added to the BMP Database, the benefit of these studies will be the greatest when facility design and watershed characteristics are included with the data submission.

5 REFERENCES

BMP Database Reports for Further Information:

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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 EPA, WERF, FHWA and EWRI/ASCE. (accessible at www.bmpdatabase.org)

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Brown, R.A. and W.F. Hunt. 2011. Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads. Journal of Environmental Engineering. 137(11):1082-1091.

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Li, H., L.J. Sharkey, W.F. Hunt, and A.P. Davis. 2009. Mitigation of impervious surface hydrology using bioretention in North Carolina and Maryland. Journal of Hydrologic Engineering, 14(4): 407-415.

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Selbig, W.R. and Balster, N., 2010. Evaluation of turf grass and prairie vegetated rain gardens in a sand and clay soil: Madison, Wisconsin, water years 2004 – 08: U.S. Geological Survey, Scientific Investigations Report 2010-5077, 75 p.

Thomas Jefferson Planning District Commission. 2011. Charlottesville High School Biofilter Performance Study Final Report, March 31, 2011. Prepared for Rivanna River Basin Commission. Research conducted by Dr. Teresa Culver, Dr. Joanna Curran and Dr. Janet Herman University of Virginia.

ATTACHMENT A: STUDY-LEVEL EXHIBITS

Study Level Analysis - BRC Site A

Exhibit A: Presence-absence of discharge by event magnitude

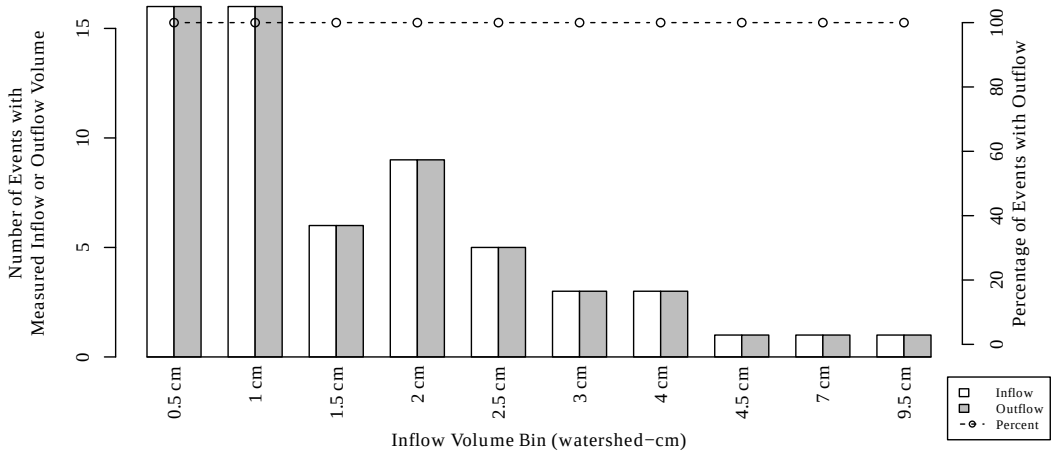

Exhibit B: Inflow vs. outflow by event magnitude

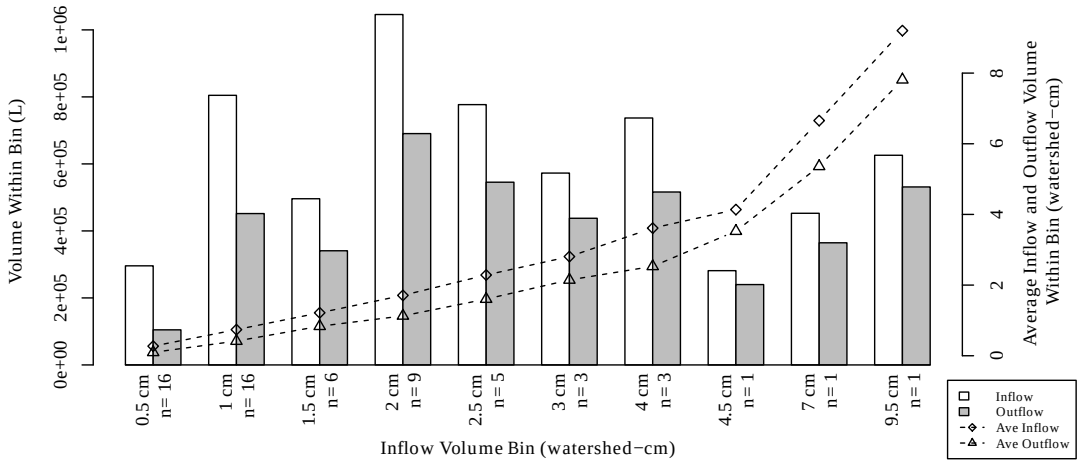

Exhibit C: Scatter plot of inflow and outflow volume

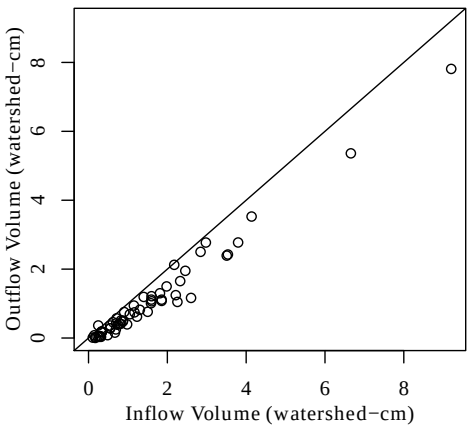

Exhibit D: Relative volume reduction by event

Event Statistics BRC Site A	
Count of Events	61
25th Percentile Event Volume Reduction	27%
Median Event Volume Reduction	42%
75th Percentile Event Volume Reduction	50%
Average Event Volume Reduction	43%
Study Cumulative Volume Reduction[a]	31%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - BRC Site B

Exhibit A: Presence-absence of discharge by event magnitude

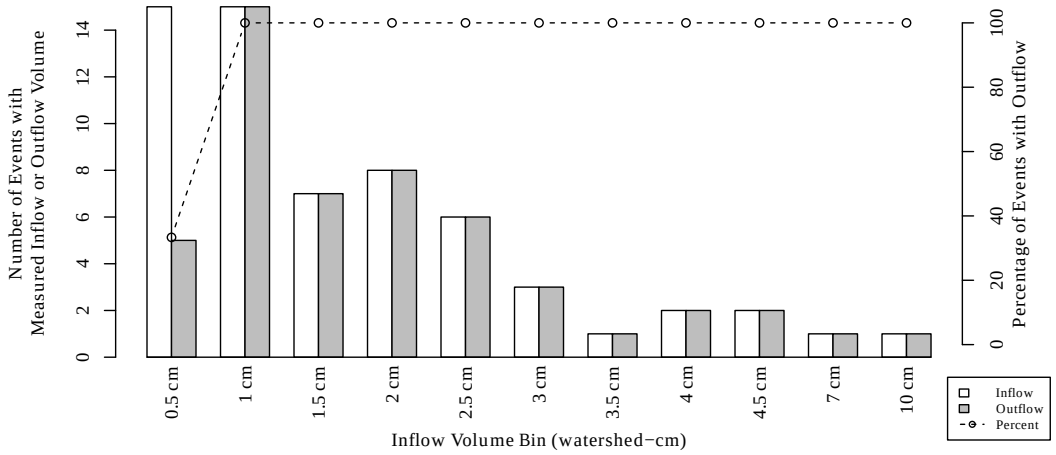

Exhibit B: Inflow vs. outflow by event magnitude

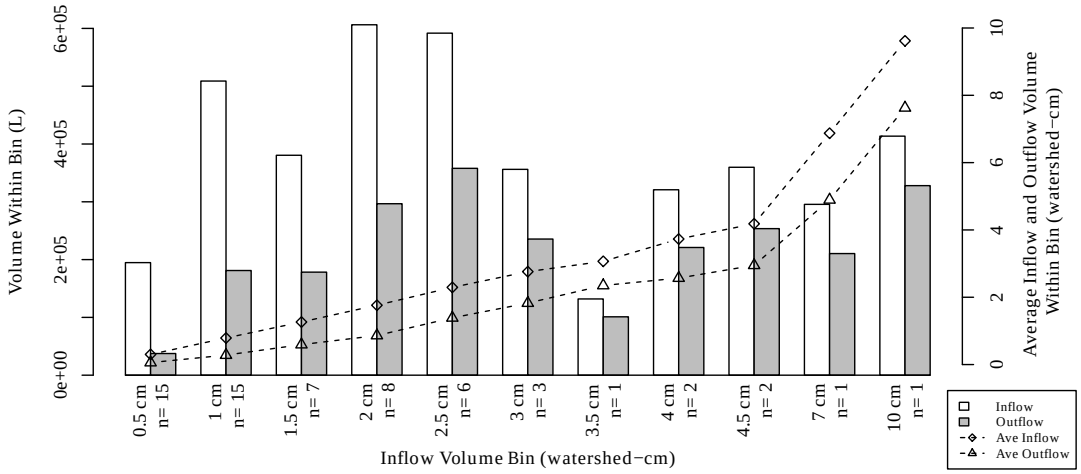

Exhibit C: Scatter plot of inflow and outflow volume

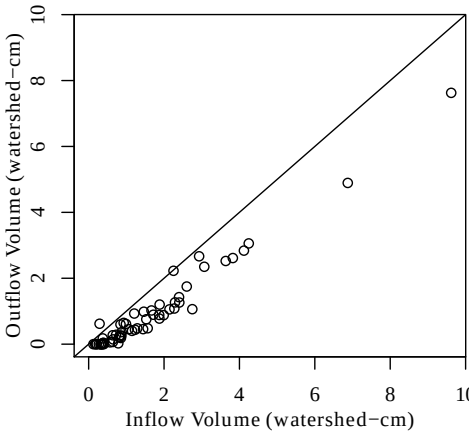

Exhibit D: Relative volume reduction by event

Event Statistics BRC Site B	
Count of Events	61
25th Percentile Event Volume Reduction	36%
Median Event Volume Reduction	58%
75th Percentile Event Volume Reduction	90%
Average Event Volume Reduction	58%
Study Cumulative Volume Reduction[a]	42%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Charlottesville HS Biofilter

Exhibit A: Presence-absence of discharge by event magnitude

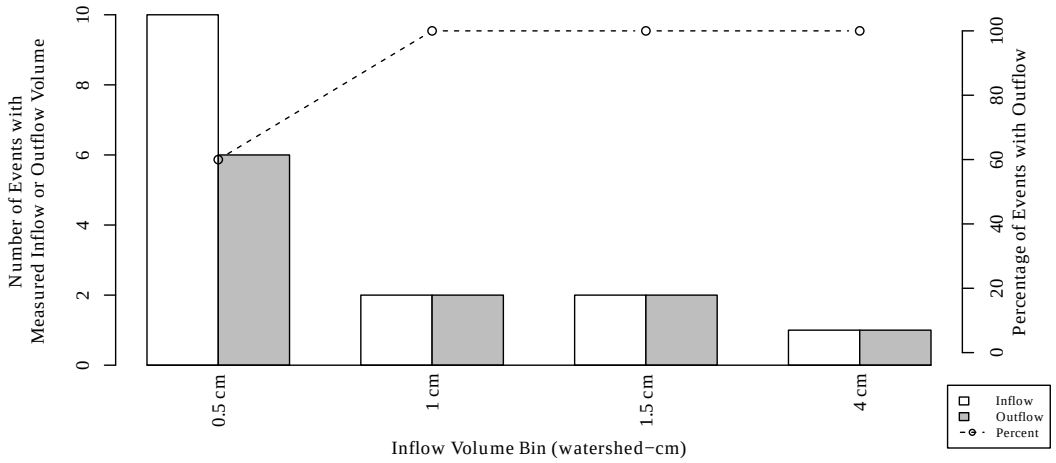

Exhibit B: Inflow vs. outflow by event magnitude

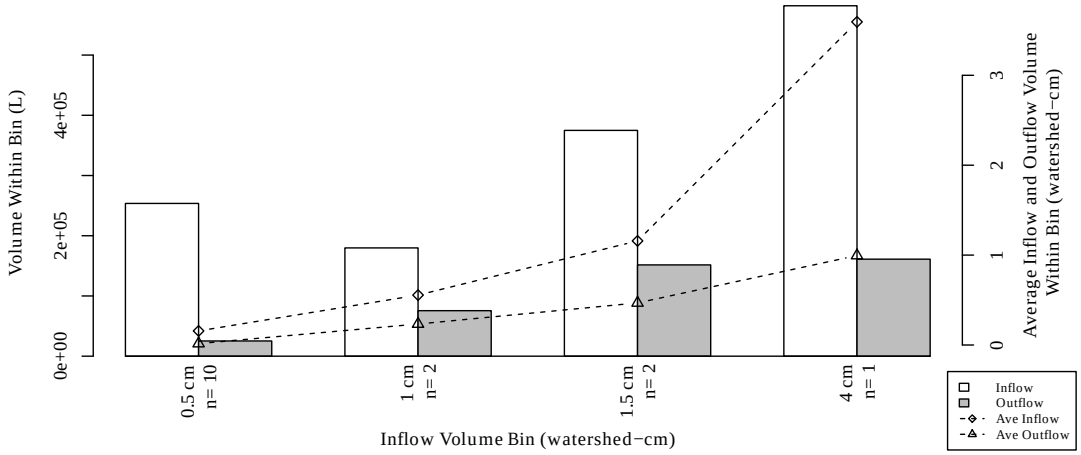

Exhibit C: Scatter plot of inflow and outflow volume

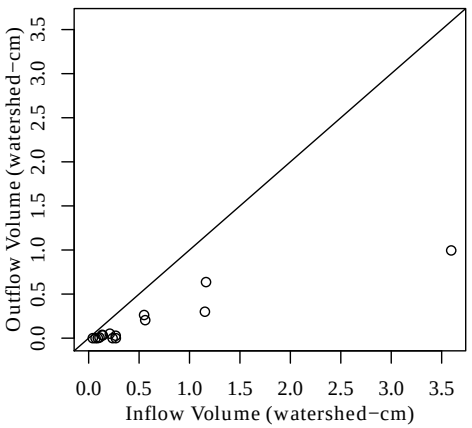

Exhibit D: Relative volume reduction by event

Event Statistics Charlottesville HS Biofilter	
Count of Events	15
25th Percentile Event Volume Reduction	72%
Median Event Volume Reduction	78%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	81%
Study Cumulative Volume Reduction[a]	70%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Graham H.S. Bioretention Cells (North)

Exhibit A: Presence-absence of discharge by event magnitude

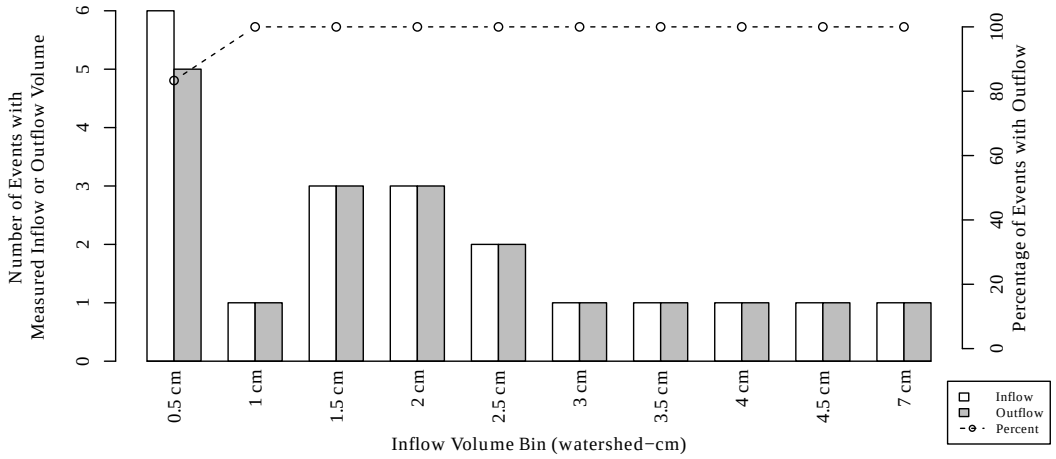

Exhibit B: Inflow vs. outflow by event magnitude

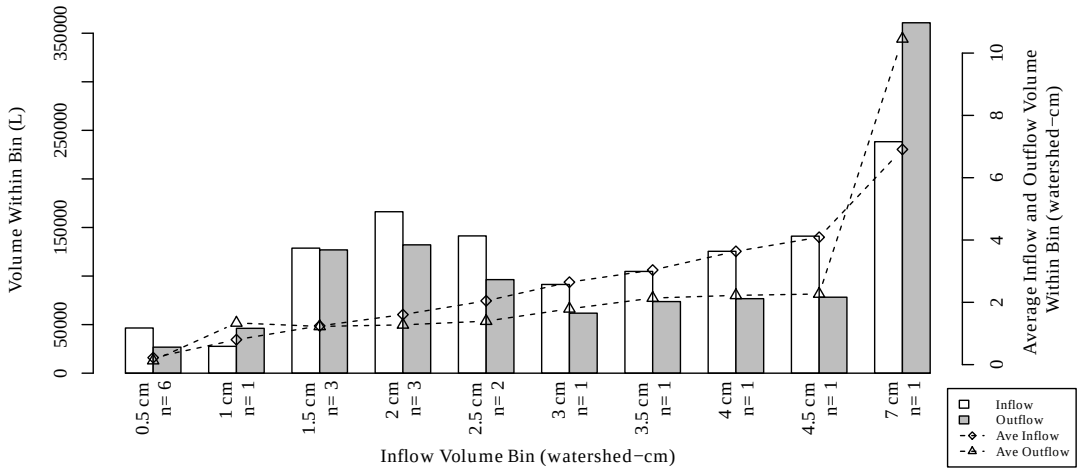

Exhibit C: Scatter plot of inflow and outflow volume

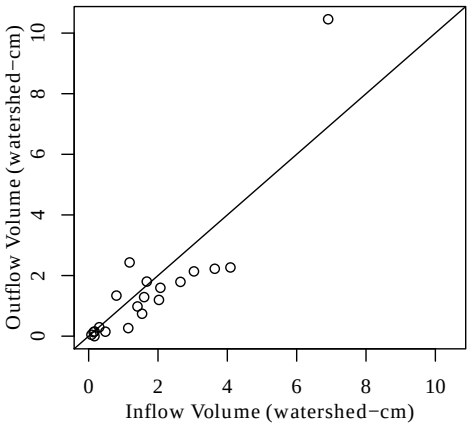

Exhibit D: Relative volume reduction by event

Event Statistics Graham H.S. Bioretention Cells (North)	
Count of Events	20
25th Percentile Event Volume Reduction	7%
Median Event Volume Reduction	30%
75th Percentile Event Volume Reduction	43%
Average Event Volume Reduction	19%
Study Cumulative Volume Reduction[a]	11%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Graham H.S. Bioretention Cells (South)

Exhibit A: Presence-absence of discharge by event magnitude

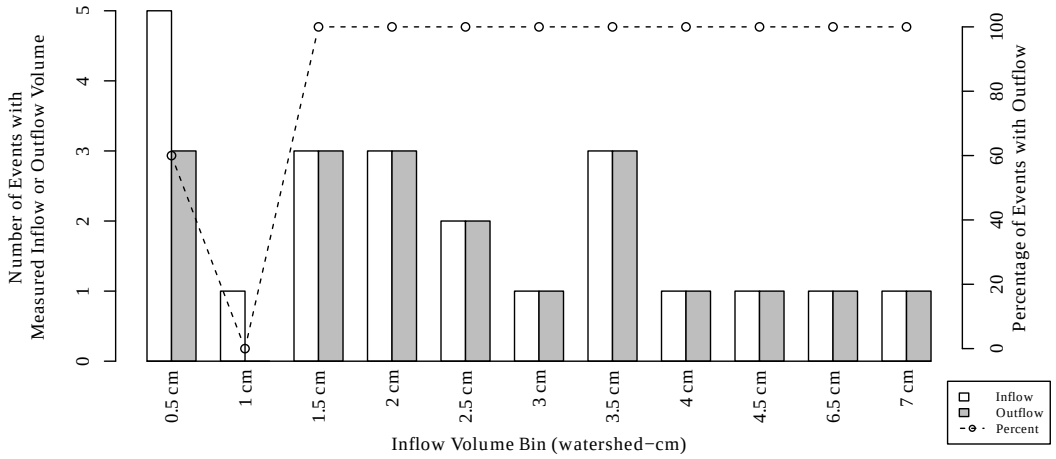

Exhibit B: Inflow vs. outflow by event magnitude

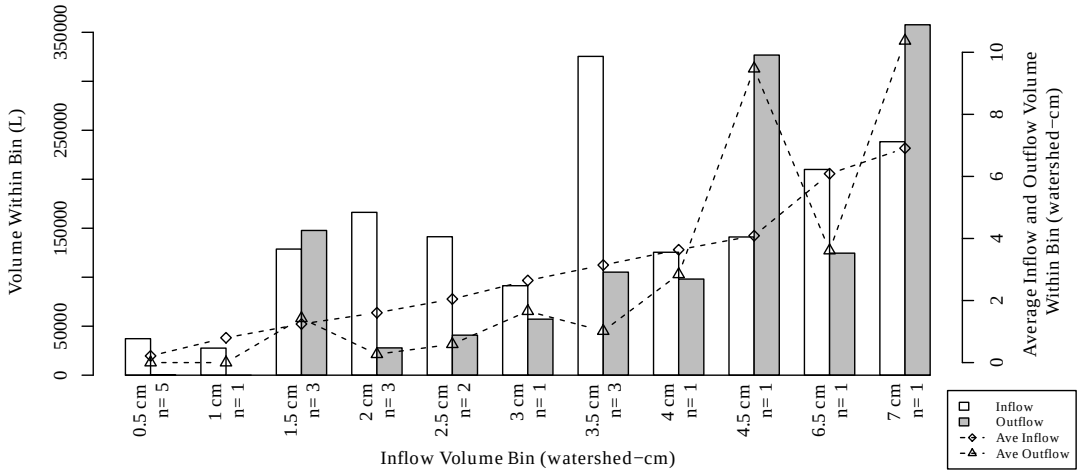

Exhibit C: Scatter plot of inflow and outflow volume

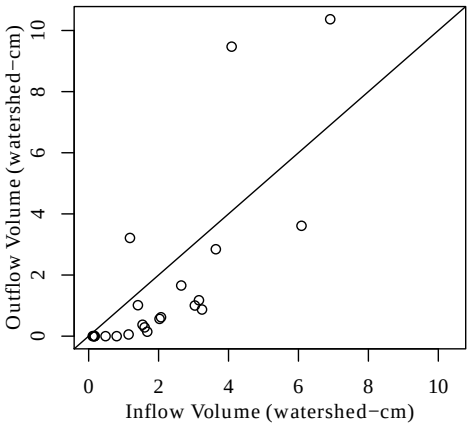

Exhibit D: Relative volume reduction by event

Event Statistics Graham H.S. Bioretention Cells (South)	
Count of Events	22
25th Percentile Event Volume Reduction	38%
Median Event Volume Reduction	73%
75th Percentile Event Volume Reduction	97%
Average Event Volume Reduction	48%
Study Cumulative Volume Reduction[a]	21%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Greensboro Bioretention G1

Exhibit A: Presence-absence of discharge by event magnitude

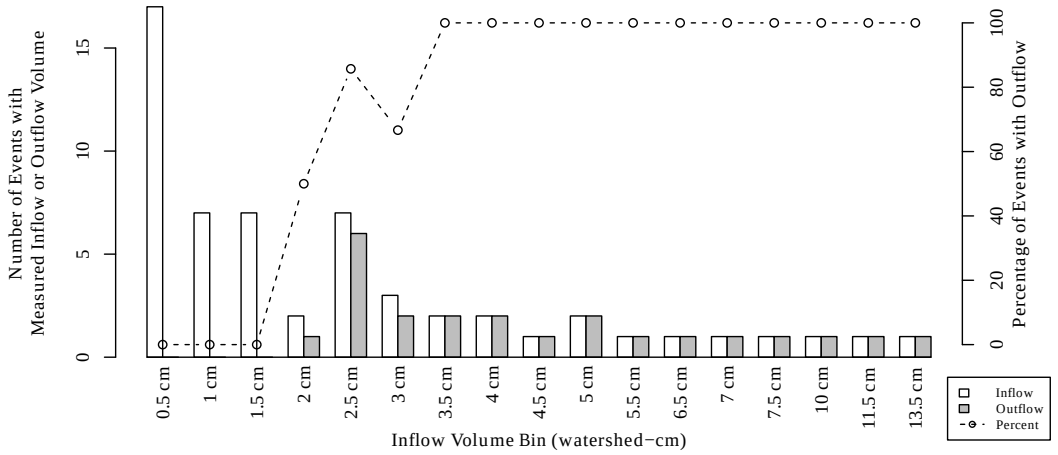

Exhibit B: Inflow vs. outflow by event magnitude

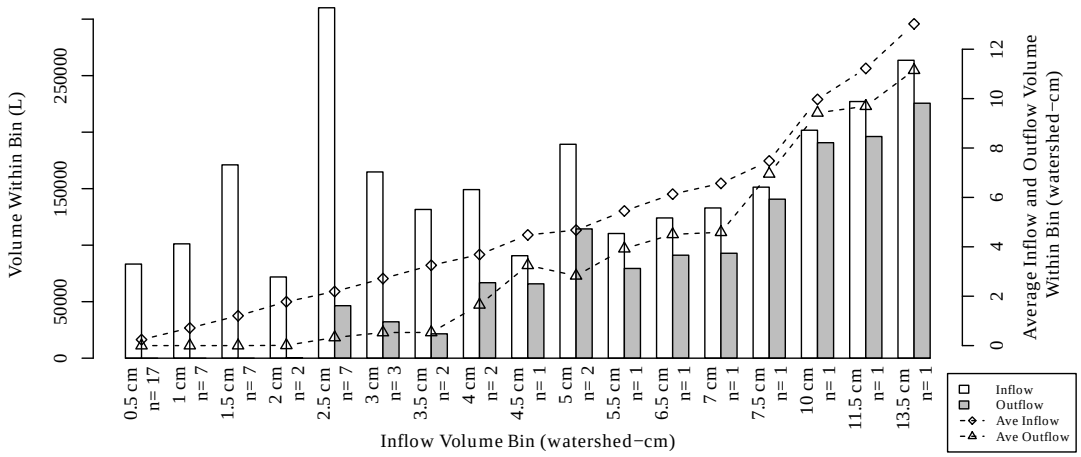

Exhibit C: Scatter plot of inflow and outflow volume

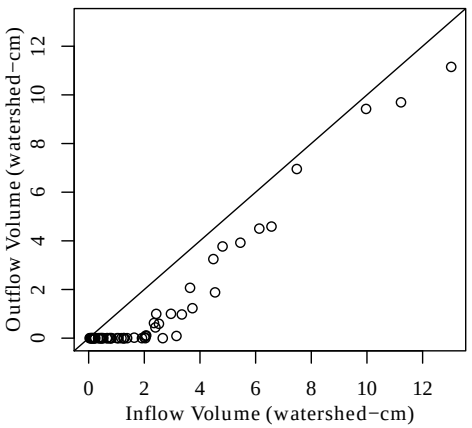

Exhibit D: Relative volume reduction by event

Event Statistics Greensboro Bioretention G1	
Count of Events	57
25th Percentile Event Volume Reduction	71%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	82%
Study Cumulative Volume Reduction[a]	49%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Greensboro Bioretention G2

Exhibit A: Presence-absence of discharge by event magnitude

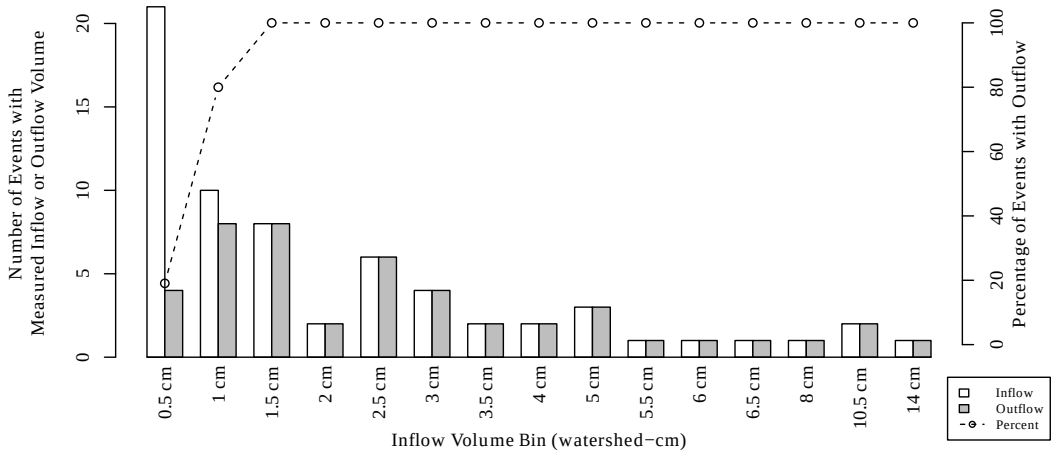

Exhibit B: Inflow vs. outflow by event magnitude

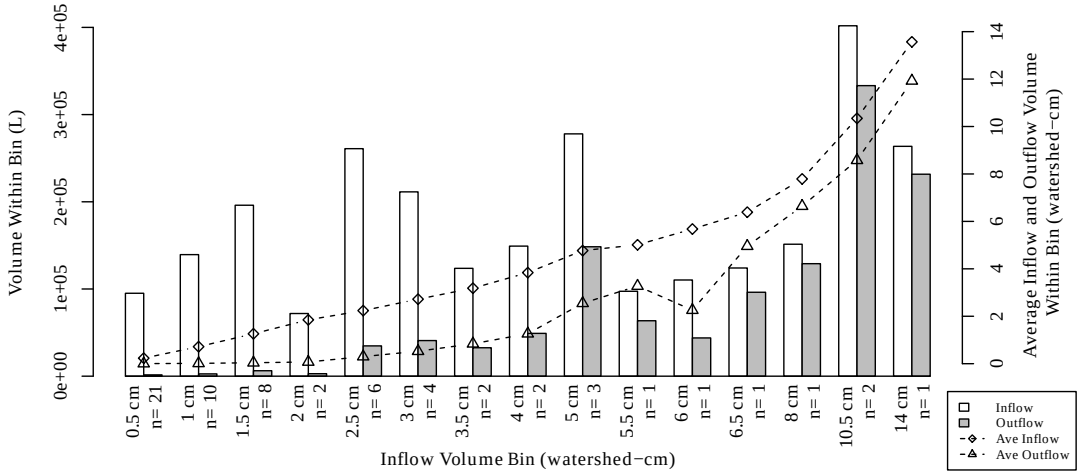

Exhibit C: Scatter plot of inflow and outflow volume

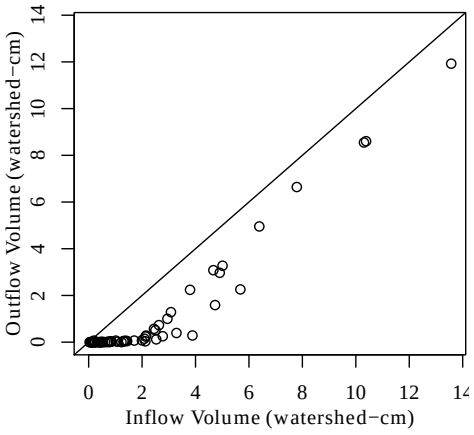

Exhibit D: Relative volume reduction by event

Event Statistics Greensboro Bioretention G2	
Count of Events	65
25th Percentile Event Volume Reduction	80%
Median Event Volume Reduction	97%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	84%
Study Cumulative Volume Reduction[a]	55%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Hal Marshall Bioretention Cell

Exhibit A: Presence-absence of discharge by event magnitude

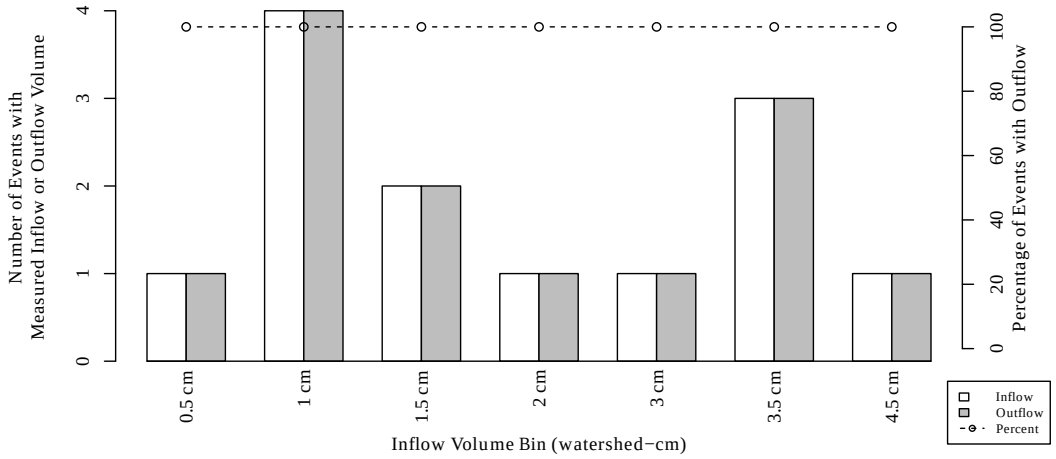

Exhibit B: Inflow vs. outflow by event magnitude

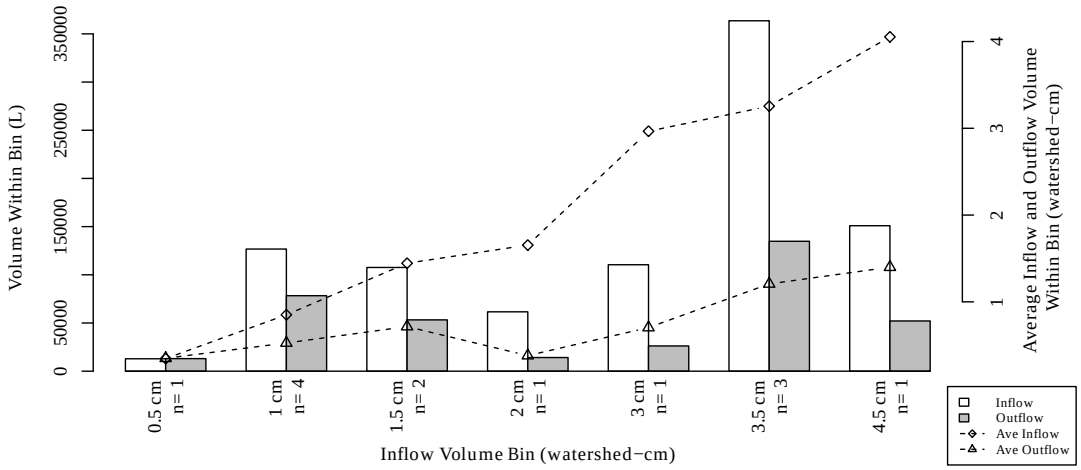

Exhibit C: Scatter plot of inflow and outflow volume

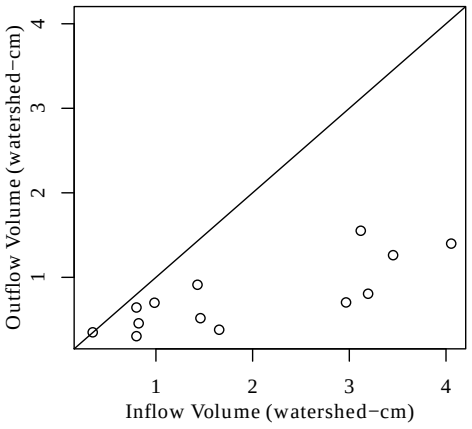

Exhibit D: Relative volume reduction by event

Event Statistics Hal Marshall Bioretention Cell	
Count of Events	13
25th Percentile Event Volume Reduction	36%
Median Event Volume Reduction	62%
75th Percentile Event Volume Reduction	65%
Average Event Volume Reduction	51%
Study Cumulative Volume Reduction[a]	60%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Louisburg Bioretention L1

Exhibit A: Presence-absence of discharge by event magnitude

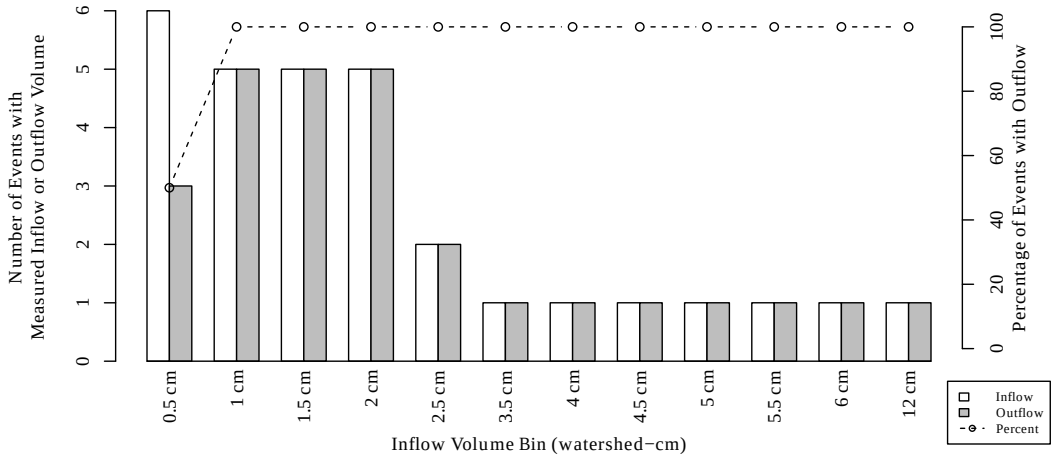

Exhibit B: Inflow vs. outflow by event magnitude

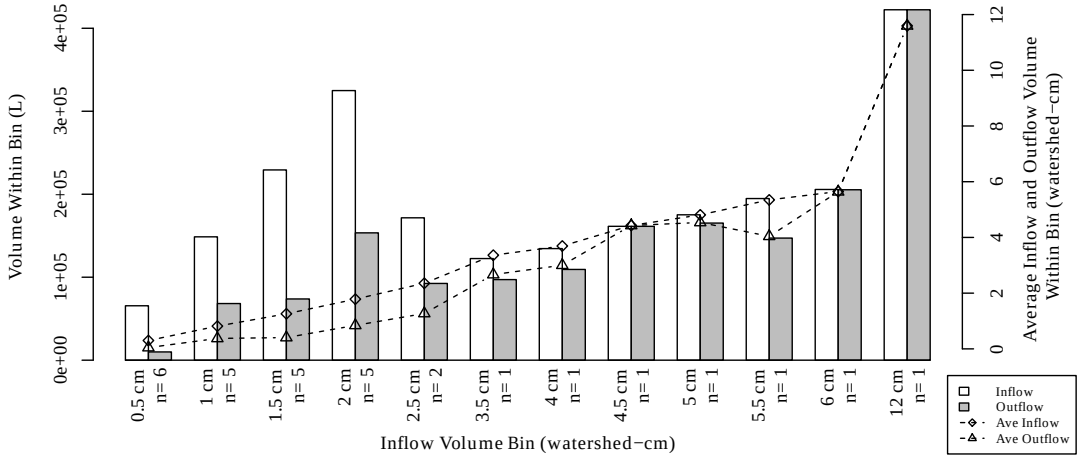

Exhibit C: Scatter plot of inflow and outflow volume

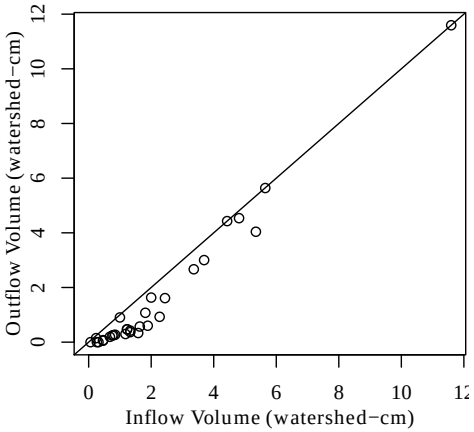

Exhibit D: Relative volume reduction by event

Event Statistics Louisburg Bioretention L1	
Count of Events	30
25th Percentile Event Volume Reduction	22%
Median Event Volume Reduction	64%
75th Percentile Event Volume Reduction	72%
Average Event Volume Reduction	52%
Study Cumulative Volume Reduction[a]	28%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Louisburg Bioretention L2

Exhibit A: Presence-absence of discharge by event magnitude

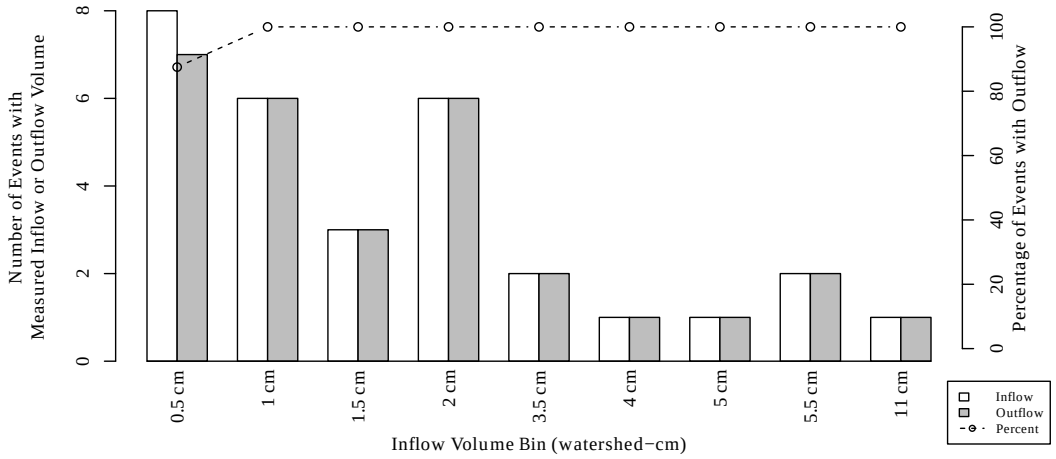

Exhibit B: Inflow vs. outflow by event magnitude

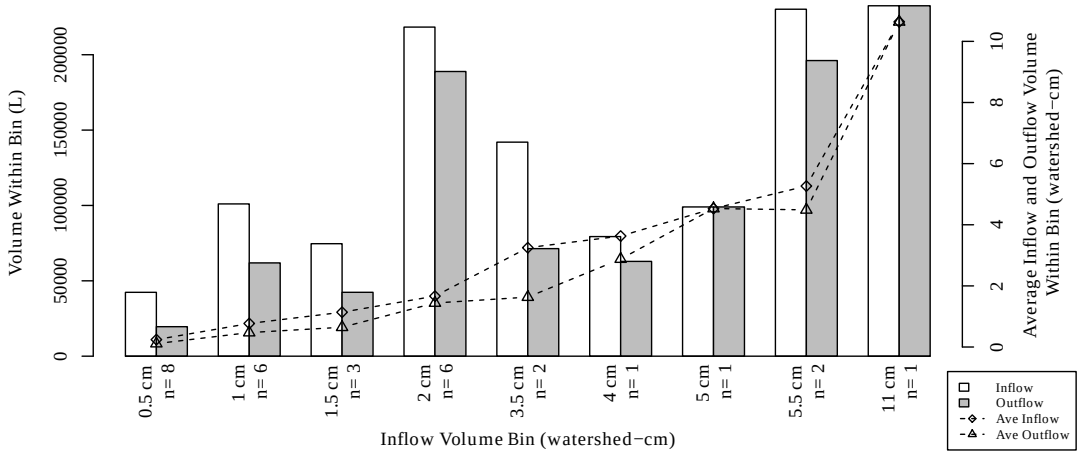

Exhibit C: Scatter plot of inflow and outflow volume

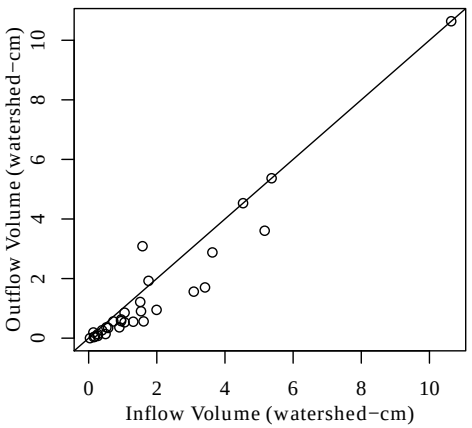

Exhibit D: Relative volume reduction by event

Event Statistics Louisburg Bioretention L2	
Count of Events	30
25th Percentile Event Volume Reduction	20%
Median Event Volume Reduction	40%
75th Percentile Event Volume Reduction	56%
Average Event Volume Reduction	34%
Study Cumulative Volume Reduction[a]	20%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Madison Water Pump House (Prairie)

Exhibit A: Presence-absence of discharge by event magnitude

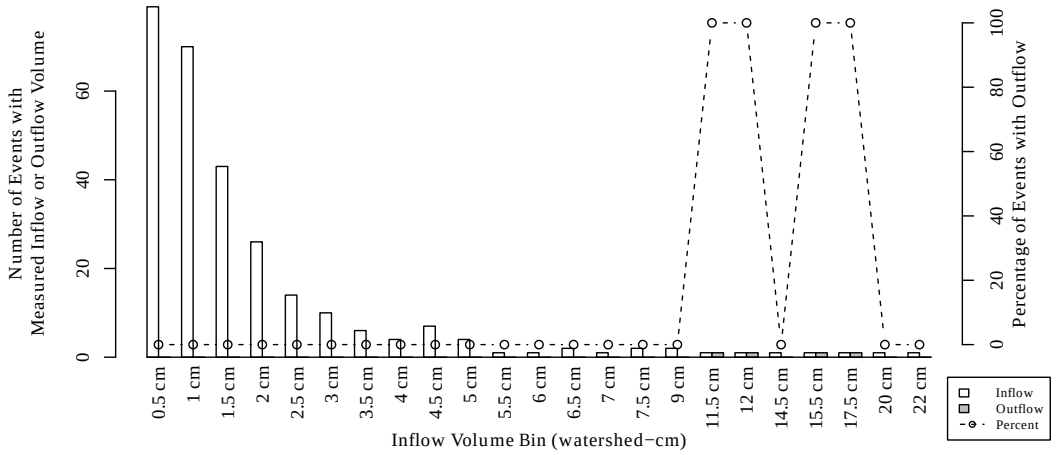

Exhibit B: Inflow vs. outflow by event magnitude

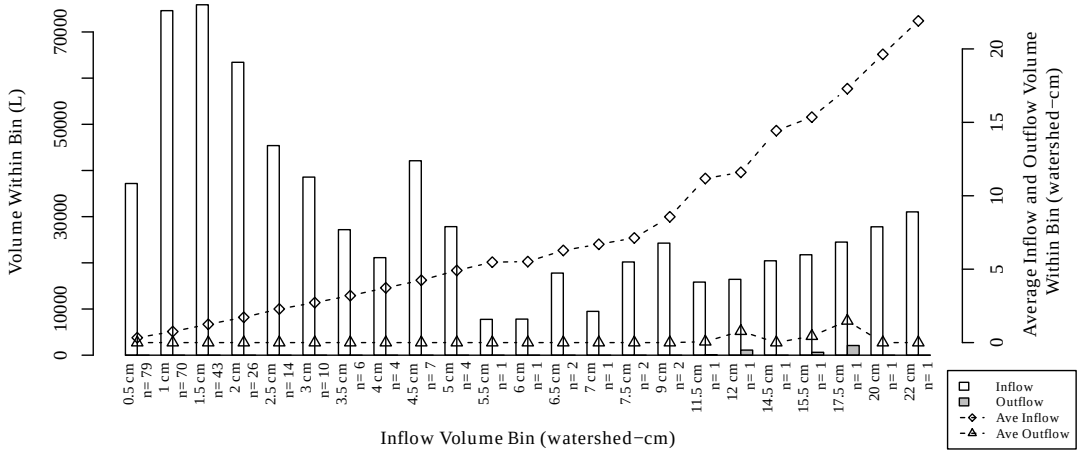

Exhibit C: Scatter plot of inflow and outflow volume

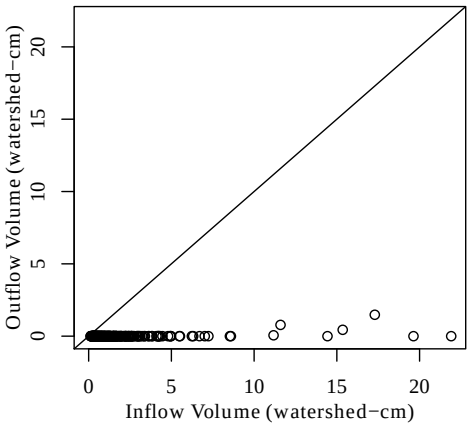

Exhibit D: Relative volume reduction by event

Event Statistics Madison Water Pump House (Prairie)	
Count of Events	279
25th Percentile Event Volume Reduction	100%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	100%
Study Cumulative Volume Reduction[a]	99%
Underdrain	No

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Madison Water Pump House (Turf)

Exhibit A: Presence-absence of discharge by event magnitude

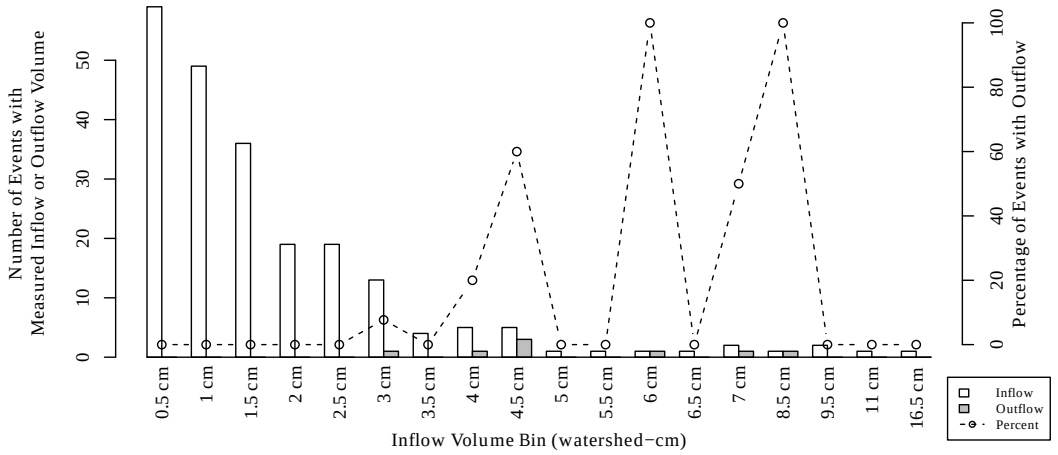

Exhibit B: Inflow vs. outflow by event magnitude

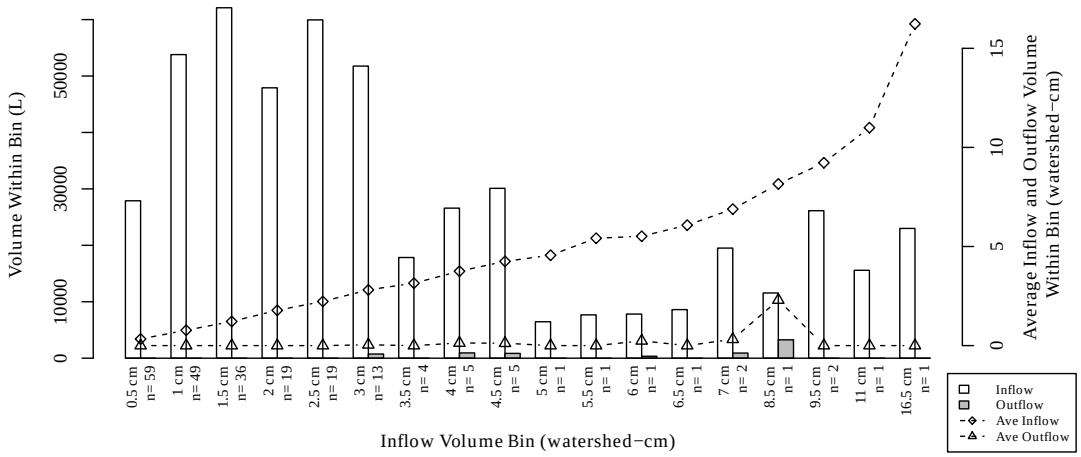

Exhibit C: Scatter plot of inflow and outflow volume

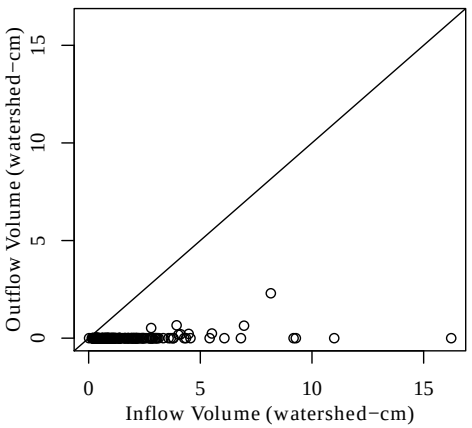

Exhibit D: Relative volume reduction by event

Event Statistics Madison Water Pump House (Turf)	
Count of Events	220
25th Percentile Event Volume Reduction	100%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	100%
Study Cumulative Volume Reduction[a]	99%
Underdrain	No

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Owen Conservation Park (Prairie)

Exhibit A: Presence-absence of discharge by event magnitude

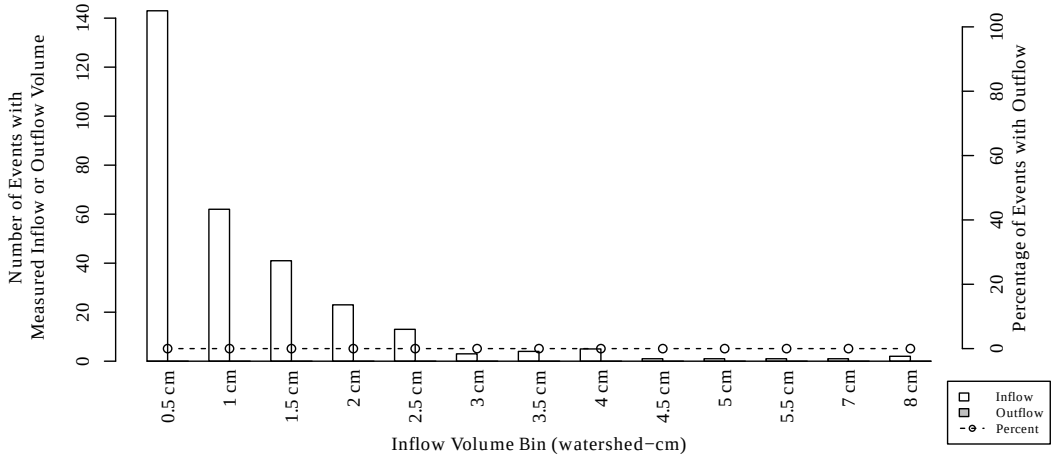

Exhibit B: Inflow vs. outflow by event magnitude

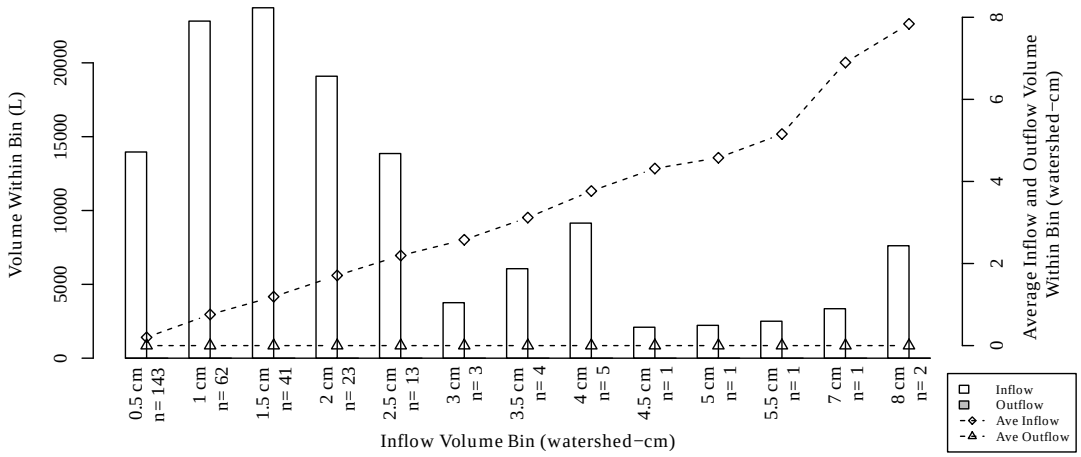

Exhibit C: Scatter plot of inflow and outflow volume

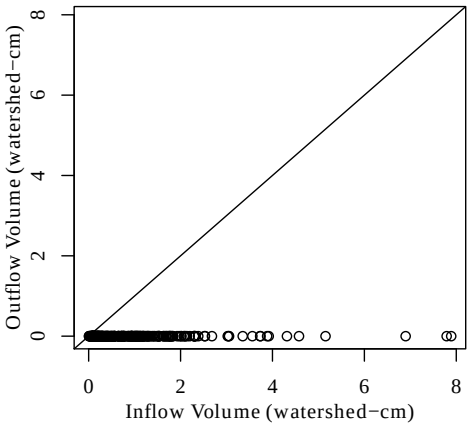

Exhibit D: Relative volume reduction by event

Event Statistics Owen Conservation Park (Prairie)	
Count of Events	300
25th Percentile Event Volume Reduction	100%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	100%
Study Cumulative Volume Reduction[a]	100%
Underdrain	No

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Owen Conservation Park (Turf)

Exhibit A: Presence-absence of discharge by event magnitude

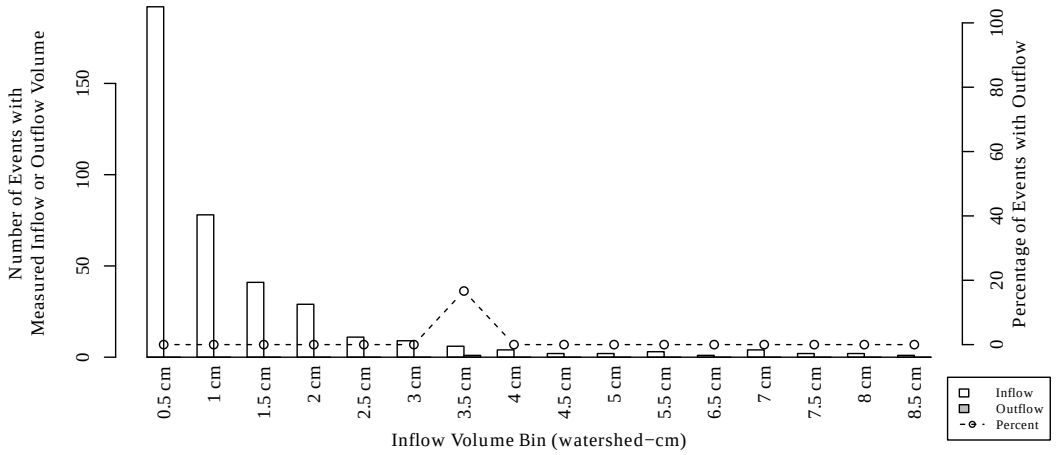

Exhibit B: Inflow vs. outflow by event magnitude

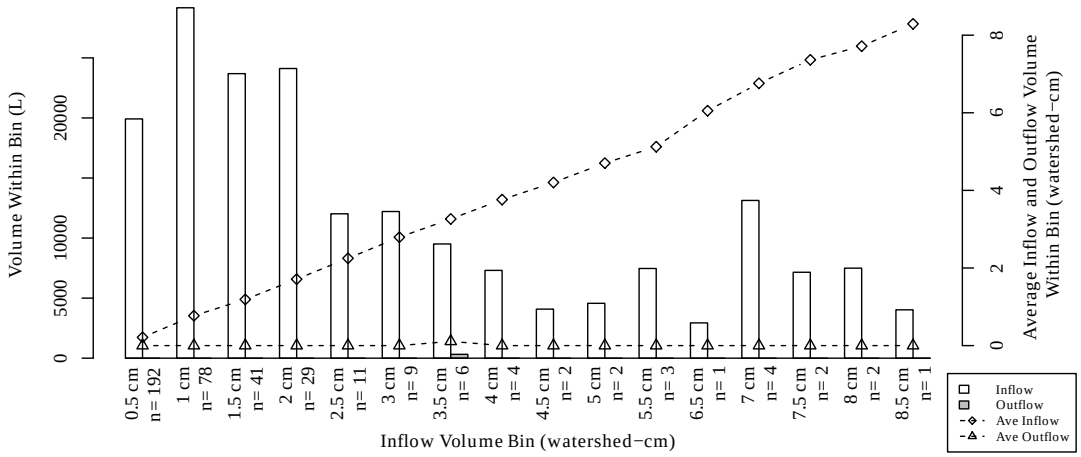

Exhibit C: Scatter plot of inflow and outflow volume

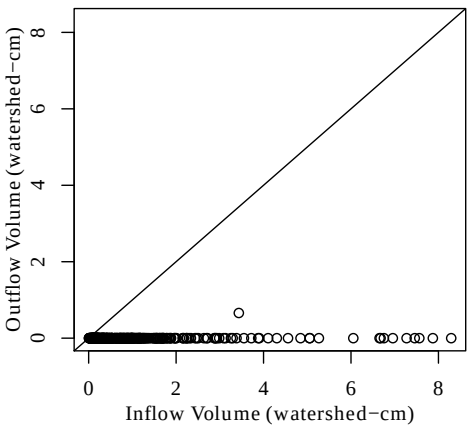

Exhibit D: Relative volume reduction by event

Event Statistics Owen Conservation Park (Turf)	
Count of Events	387
25th Percentile Event Volume Reduction	100%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	100%
Study Cumulative Volume Reduction[a]	100%
Underdrain	No

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Partridgeberry Place

Exhibit A: Presence-absence of discharge by event magnitude

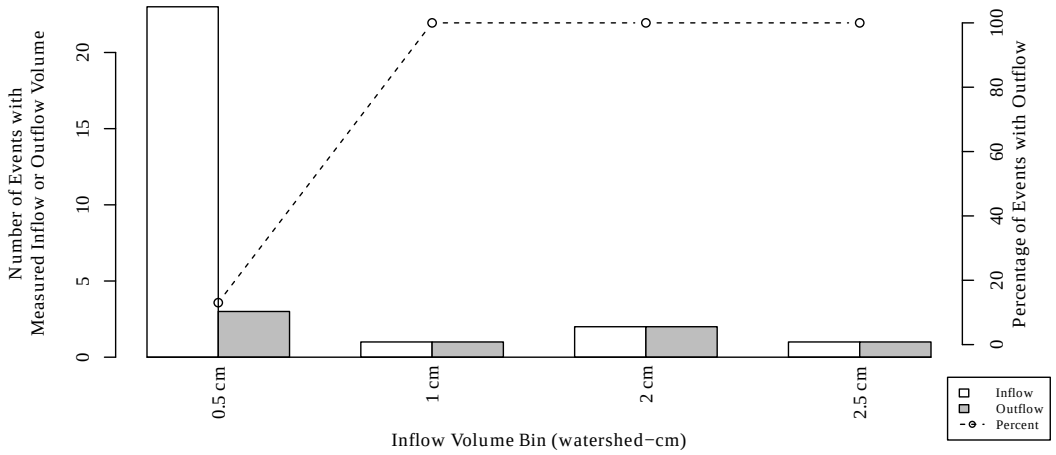

Exhibit B: Inflow vs. outflow by event magnitude

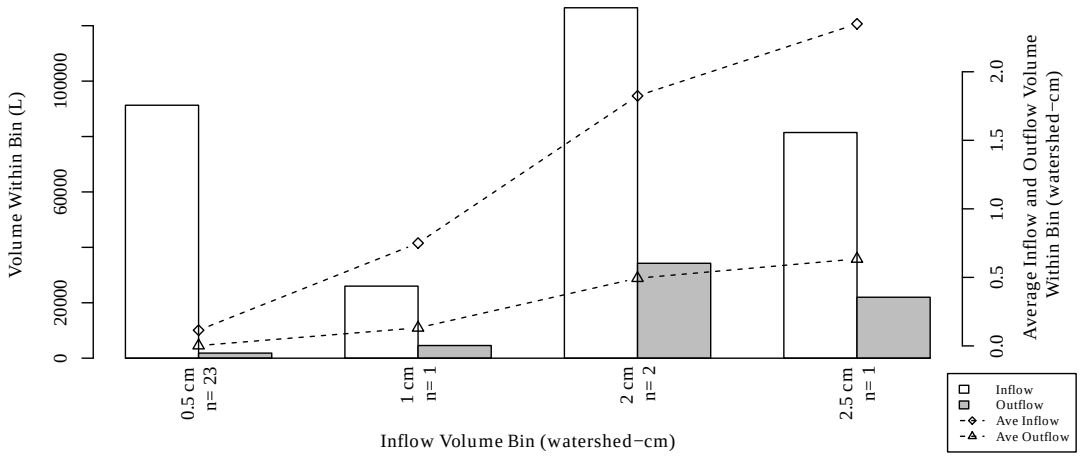

Exhibit C: Scatter plot of inflow and outflow volume

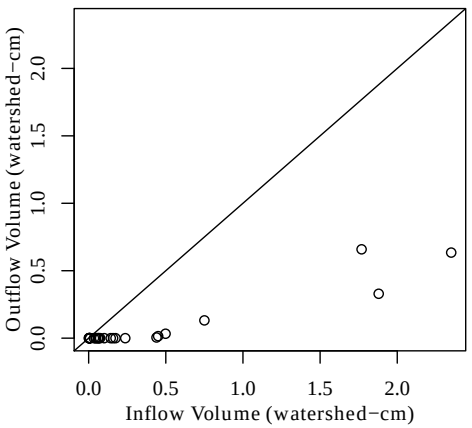

Exhibit D: Relative volume reduction by event

Event Statistics Partridgeberry Place	
Count of Events	27
25th Percentile Event Volume Reduction	99%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	96%
Study Cumulative Volume Reduction[a]	81%
Underdrain	No

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Rocky Mount Grassed Cell Year 1 (deeper IWS zone)

Exhibit A: Presence-absence of discharge by event magnitude

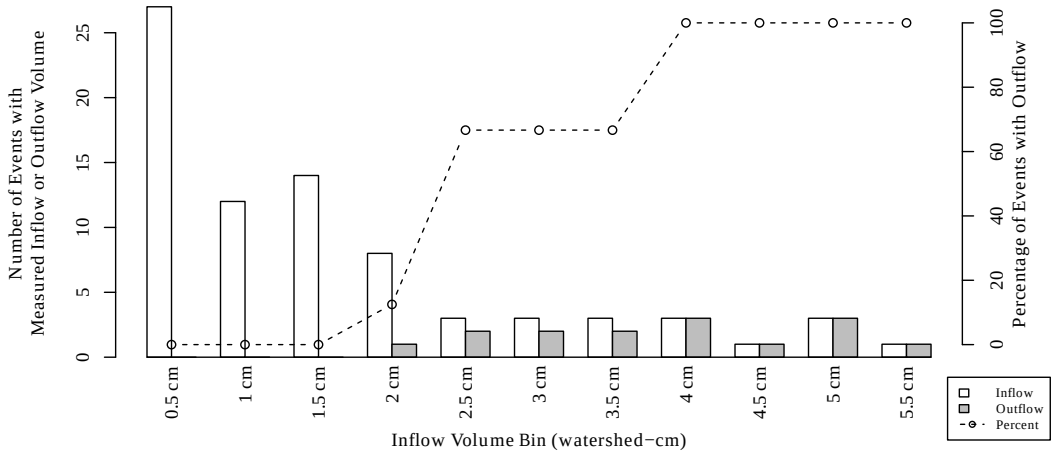

Exhibit B: Inflow vs. outflow by event magnitude

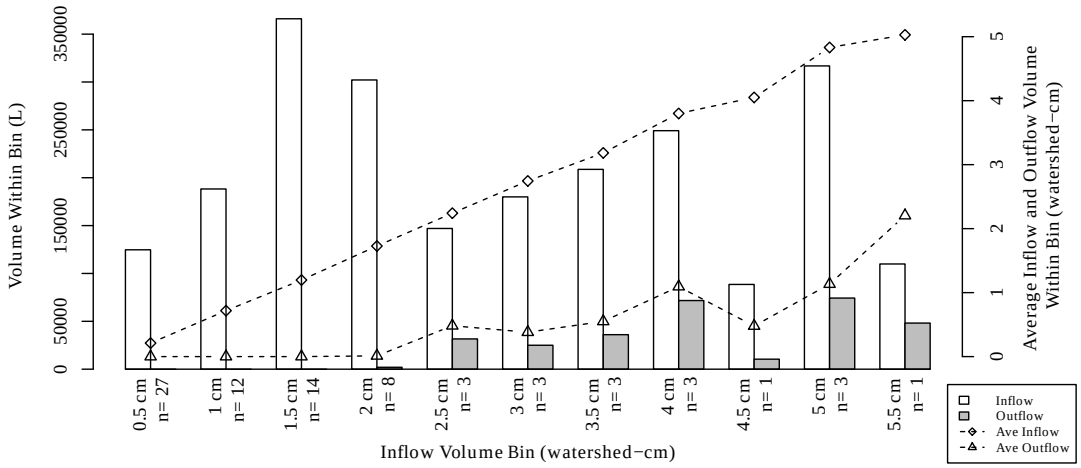

Exhibit C: Scatter plot of inflow and outflow volume

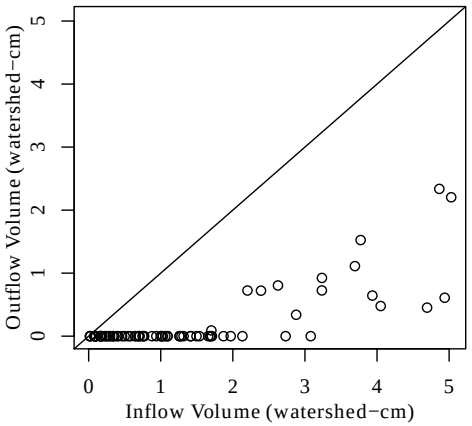

Exhibit D: Relative volume reduction by event

Event Statistics Rocky Mount Grassed Cell Year 1 (deeper IWS zone)	
Count of Events	78
25th Percentile Event Volume Reduction	100%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	95%
Study Cumulative Volume Reduction[a]	87%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Rocky Mount Grassed Cell Year 2 (Shallower IWS Zone)

Exhibit A: Presence-absence of discharge by event magnitude

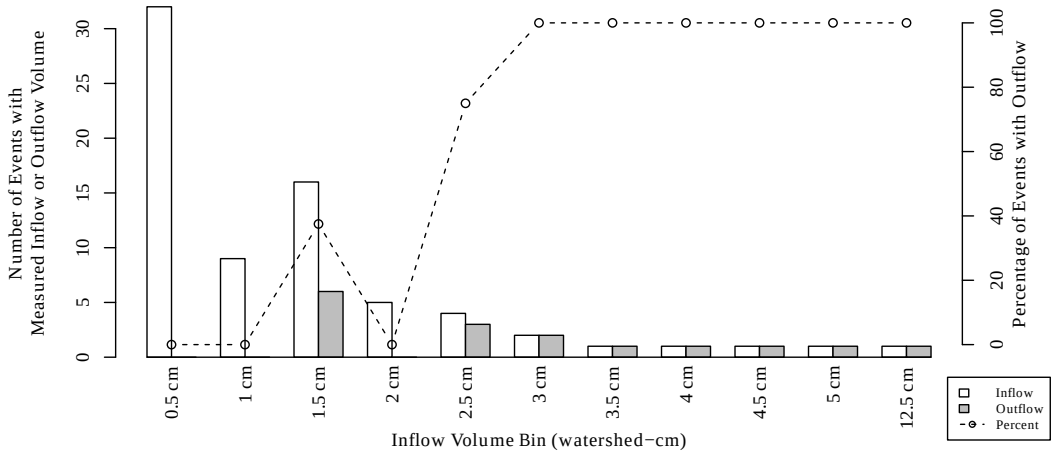

Exhibit B: Inflow vs. outflow by event magnitude

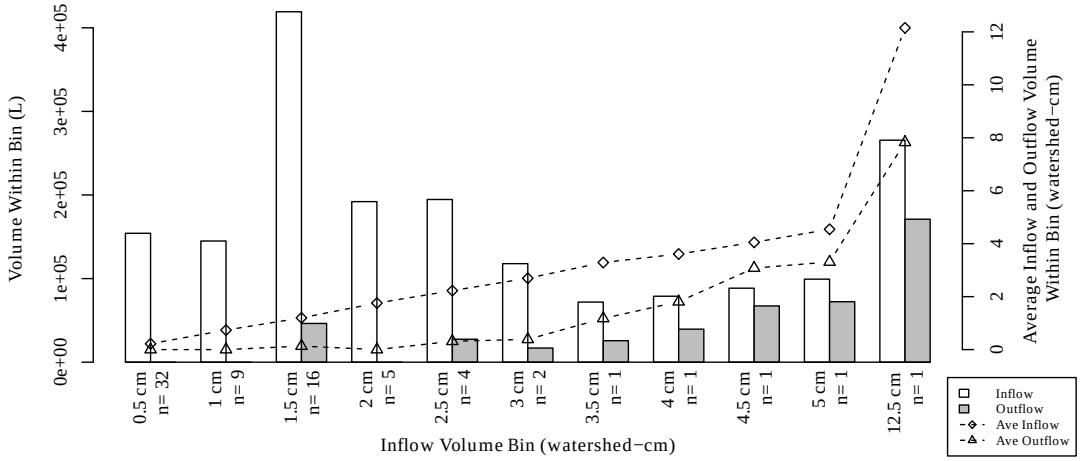

Exhibit C: Scatter plot of inflow and outflow volume

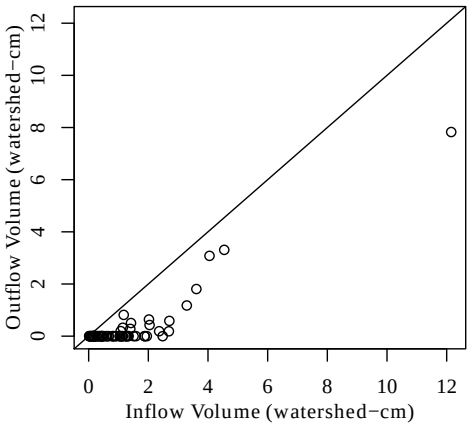

Exhibit D: Relative volume reduction by event

Event Statistics Rocky Mount Grassed Cell Year 2 (Shallower IWS Zone)	
Count of Events	73
25th Percentile Event Volume Reduction	100%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	92%
Study Cumulative Volume Reduction[a]	74%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Rocky Mount Mulch/Shrub Cell Year 1 (deeper IWS zone)

Exhibit A: Presence-absence of discharge by event magnitude

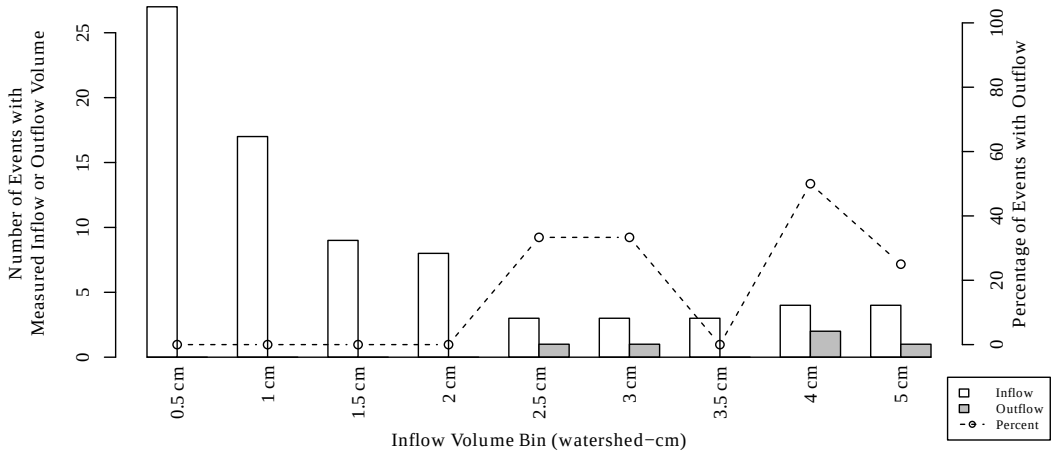

Exhibit B: Inflow vs. outflow by event magnitude

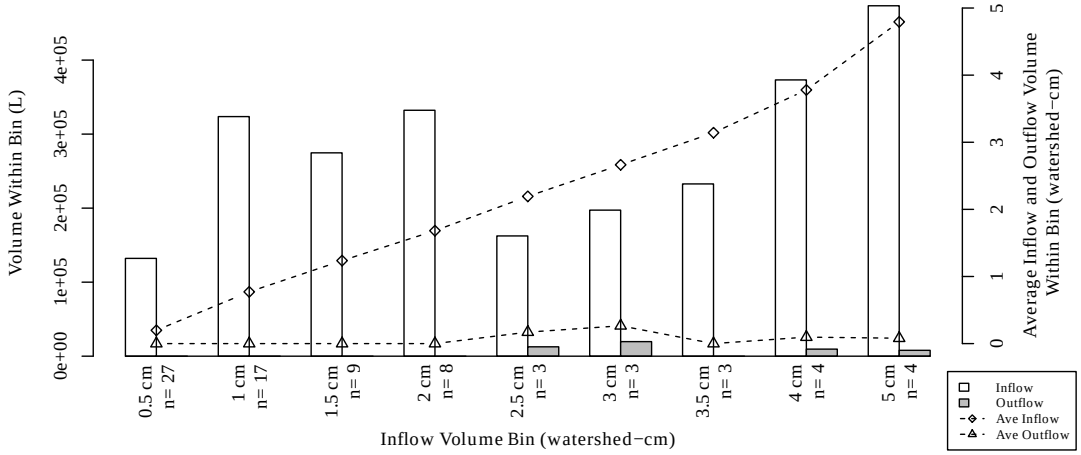

Exhibit C: Scatter plot of inflow and outflow volume

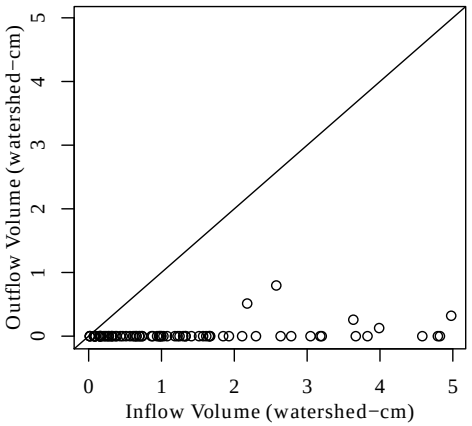

Exhibit D: Relative volume reduction by event

Event Statistics Rocky Mount Mulch/Shrub Cell Year 1 (deeper IWS zone)	
Count of Events	78
25th Percentile Event Volume Reduction	100%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	99%
Study Cumulative Volume Reduction[a]	98%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Rocky Mount Mulch/Shrub Cell Year 2 (shallower IWS zone)

Exhibit A: Presence-absence of discharge by event magnitude

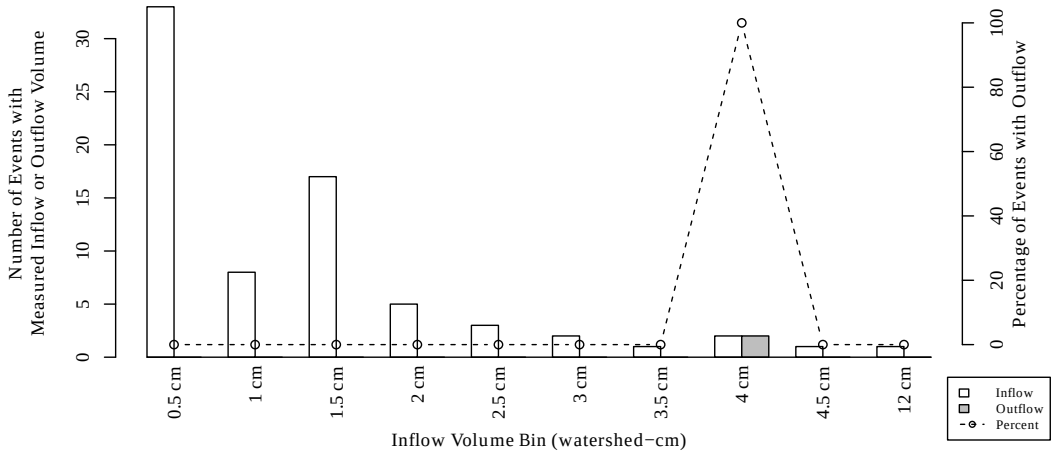

Exhibit B: Inflow vs. outflow by event magnitude

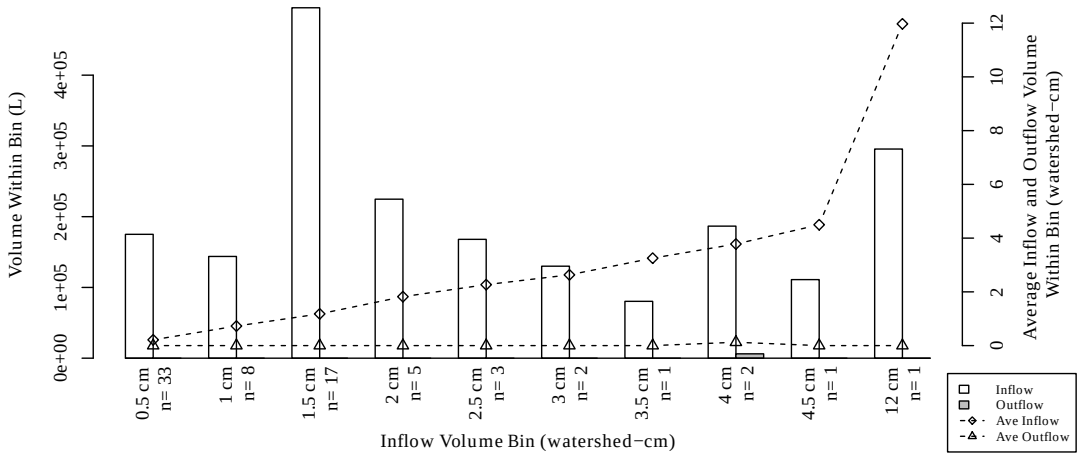

Exhibit C: Scatter plot of inflow and outflow volume

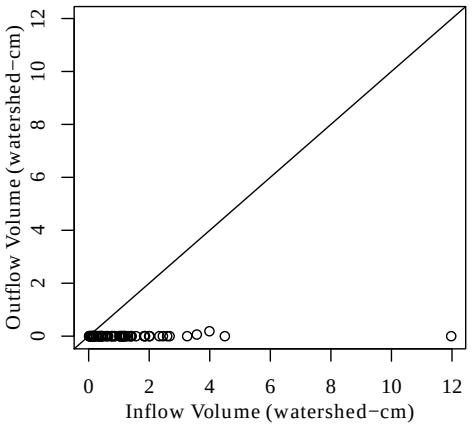

Exhibit D: Relative volume reduction by event

Event Statistics Rocky Mount Mulch/Shrub Cell Year 2 (shallower IWS zone)	
Count of Events	73
25th Percentile Event Volume Reduction	100%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	100%
Study Cumulative Volume Reduction[a]	100%
Underdrain	Yes

[a]Based on Study Total Inflow and Outflow Values

Study Level Analysis - Villanova Traffic Island

Exhibit A: Presence-absence of discharge by event magnitude

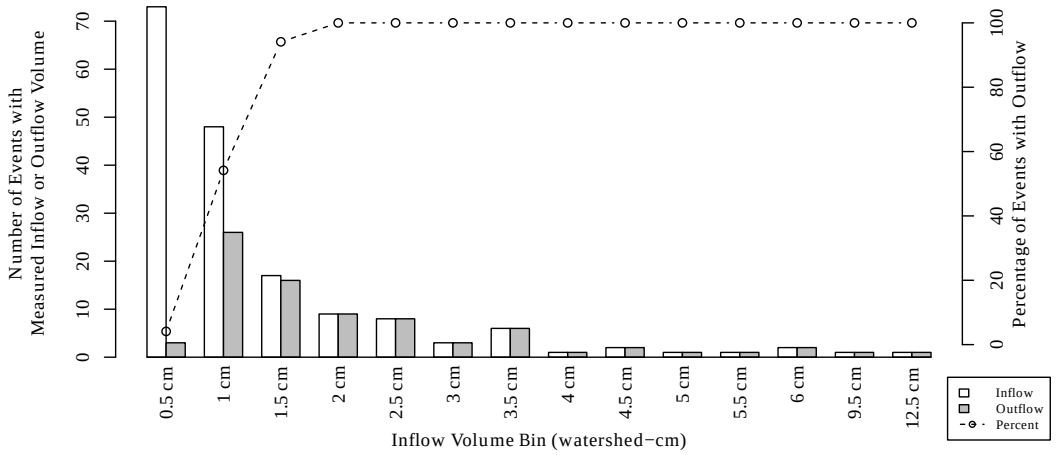

Exhibit B: Inflow vs. outflow by event magnitude

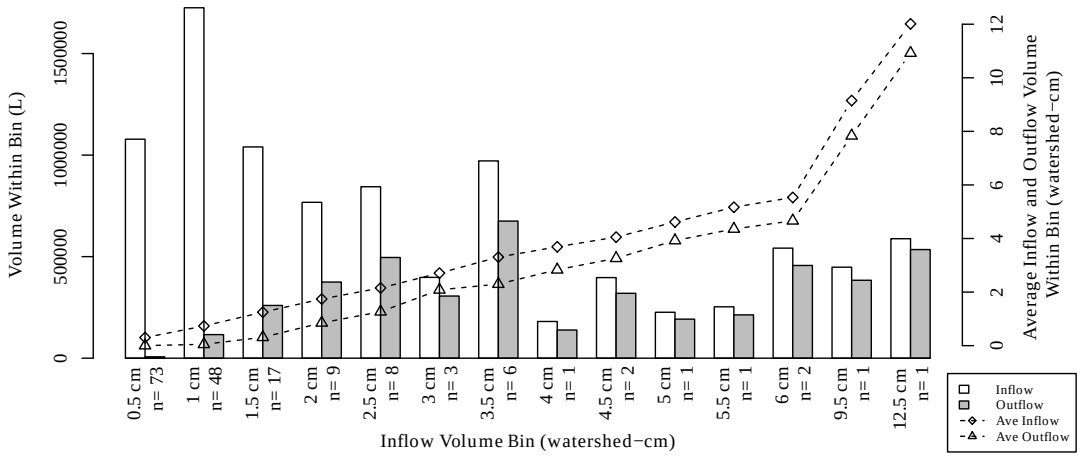

Exhibit C: Scatter plot of inflow and outflow volume

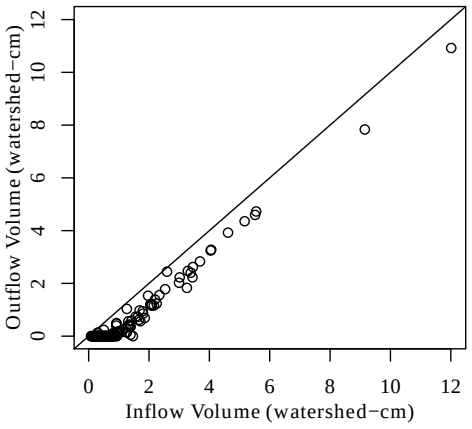

Exhibit D: Relative volume reduction by event

Event Statistics Villanova Traffic Island	
Count of Events	173
25th Percentile Event Volume Reduction	67%
Median Event Volume Reduction	100%
75th Percentile Event Volume Reduction	100%
Average Event Volume Reduction	82%
Study Cumulative Volume Reduction[a]	53%
Underdrain	No

[a]Based on Study Total Inflow and Outflow Values

ATTACHMENT B: CONSOLIDATED STUDY ATTRIBUTES TABLE

Attachment B - Consolidated Bioretention BMP Study Attributes

Test Site Name	BMP Name	State	Date Facility Placed in Service	Tributary Watershed Area (m^2)	Bioretention Surface Area (m^2)	Ratio of Tributary Area to Bioretention Surface Area[1]	Study Average Event Precipitation depth (cm)	Average Ponding Depth above Bioretention Media Surface (cm)	Ponding Volume above Bioretention Media Surface (L)	Bioretention Media Depth (m)	Number of Underdrains Provided	Is "Internal Water Storage Zone" Created?[*E]	Is a Hydraulic Restriction Layer (Liner) Provided?
BRC Site A	BRC_A	NC	11/1/2005	6,800	289.9	4.3%	1.61	13	35,113	0.6	1	No	No[*F]
BRC Site B	BRC_B	NC	11/1/2005	4,300	206.2	4.8%	1.61	15	31,715	0.9	1	No	No
Charlottesville HS Biofilter	CHS_BioFilter	VA	4/1/2010	16,187	241.5	1.5%	1.89	15	36,812	0.914	2	No	No
Graham H.S. Bioretention Cells	North cell	NC	6/1/2005	3,450[*A]	102.2	3.0%	2.37	23[*A]	23,500[*C]	0.75	1	Yes	No[*A]
Graham H.S. Bioretention Cells	South cell	NC	6/1/2005	3,450[*A]	102.2	3.0%	2.37	23[*A]	23,500[*C]	1.05	1	Yes	No[*A]
Greensboro bioretention-G1	G1	NC	7/1/2003	2,023	100.0	4.9%	2.63	23	23,000	1.2	2	Yes	No
Greensboro bioretention-G2	G2	NC	7/1/2003	1,942	100.0	5.1%	2.30	23	23,000	1.2	2	No	No
Hal Marshall Bioretention Cell	Hal Marshall Bioretention Cell	NC	12/1/2003	3,723	229.0	6.2%	1.67	18[*B]	41,000	1.2	1	No[*A]	No
Louisburg bioretention-L1	L1	NC	5/30/2004	3,642	162.0	4.4%	2.40	15	24,300	0.6	2	No	No
Louisburg bioretention-L2	L2	NC	5/30/2004	2,185	99.0	4.5%	2.40	15	14,850	0.6	2	No	Yes
Madison Water Pump House	PumpHouseRainGardenPrairie	WI	6/1/2003	142	37.4	26.4%	1.50	15	5,706[*C]	NA	0	NA	No
Madison Water Pump House	PumpHouseRainGardenTurf	WI	6/1/2003	142	32.9	23.2%	1.54	15	5,012[*C]	NA	0	NA	No
Owen Conservation Park	OwenRainGardenPrairie	WI	6/1/2003	48.5[*A,D]	9.3	19.2%	1.32	15	1,416[*C]	NA	0	NA	No
Owen Conservation Park	OwenRainGardenTurf	WI	6/1/2003	48.5[*A,D]	9.3	19.2%	1.36	15	1,416[*C]	NA	0	NA	No
Partridgeberry Place	Central Raingarden	MA	6/29/2005	3,466	39.3	1.1%	1.48	46	5,182	NA	0	NA	No[*A]
Rocky Mount Grassed Cell_Year 1 (deeper IWS zone)	Rocky Mount Grassed Bioretention Cell 1	NC	11/1/2005	2,185	146.0	6.7%	1.64	16	23,600	1.1	2	Yes	No[*A]
Rocky Mount Grassed Cell_Year 2 (Shallower IWS Zone)	Rocky Mount Grassed Bioretention Cell 2	NC	11/1/2005	2,185	146.0	6.7%	1.41	16	23,600	1.1	2	Yes	No[*A]
Rocky Mount Mulch/Shrub Cell_Year 1 (deeper IWS zone)	Rocky Mount Mulch/Shrub Bioretention Cell 1	NC	11/1/2005	2,469	142.0	5.8%	1.64	13	18,500	0.96	2	Yes	No[*A]
Rocky Mount Mulch/Shrub Cell_Year 2 (shallower IWS zone)	Rocky Mount Mulch/Shrub Bioretention Cell 2	NC	11/1/2005	2,469	142.0	5.8%	1.41	13	18,500	0.96	2	Yes	No[*A]
Villanova Traffic Island	Traffic Island	PA	8/1/2001	4,897	139.5	2.8%	2.75	25[*B]	34,547	1.2	0	NA	No[*A]

1 - Calculated based on ratio of user provided tributary area and BMP area

[*A] Not originally provided or different from original provided; added/modified from review of original study literature

[*B] Estimated as (Total Ponding Volume)/(Bioretention Surface Area)

[*C] Estimated as (Bioretention Surface Area) × (Ponding Depth)

[*D] Does not include the BMP surface area in tributary area total; other studies may or may not include bioretention area in total tributary area

[*E] Internal water storage zone is not precisely defined in terms of a specific depth or volume of IWS. As reported by researcher. Not applicable for systems without underdrains.

[*F] Data on liner not provided; however is believed that a impermeable liners is not present at this site.