Water Balance of Retrofit, Right-of-way Rain Gardens

THESIS

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Abstract

Increased storm runoff results from urbanization and development. Rain gardens can reduce runoff in a cost-effective manner as compared to expensive infrastructure construction, but more knowledge of their behavior and performance are required to increase their applications. This research demonstrates that rain gardens can reduce storm runoff from developments built without stormwater retention infrastructure to mitigate increases in storm runoff. Retrofit rain gardens were installed in a residential neighborhood in Westerville, Ohio, in July 2010. Between spring of 2011 and 2012, inflow and outflow volumes and soil water content were monitored for 20 simulated rainfall events. The change in water storage within the rain garden was calculated from the initial and final soil water content of 15 cm layers for the 60 cm depth of the rain gardens. A water balance equation was used to estimate the volume of water exfiltrating to the surrounding in situ soil. Overall, the rain gardens provided a 44% volume reduction from inflow to outflow with 15% of the inflow exfiltrating to the surrounding soil. Three inlet designs for right-of-way rain gardens were also evaluated. The original construction allowed for vegetative growth at the inlet, which accumulated debris and inhibited inflow during natural storm events. Replacing the vegetation and soil at the entrance with stones reduced hydrologic performance, but underlining the stones with bentonite clay provided a statistically significant increase in volume reduction during simulated rainfall events.

This study finds that retrofit, right-of-way rain gardens can substantially reduce storm runoff in a residential development despite their proximity to curb underdrains and their small garden to impervious area ratios.

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Introduction

Many landscapes have been transformed from pervious to impervious surfaces through urbanization and commercial development. This change in land use has often occurred without consideration for the increased volume of water flowing from impervious surfaces into waterways. Previous rain garden and bioretention studies have focused primarily on describing the effectiveness of the technology and demonstrated reductions in stormwater runoff from new developments. Preliminary success has also been shown in retrofitting existing developments. While rain gardens and bioretention cells have become increasingly popular as a means of mitigating storm flows for new construction, gaps of knowledge exist related to their performance in existing developments and the amount of water exfiltrating to the surrounding soil. This study increases the knowledge of the complete water balance and the impact of entrance designs on the hydrologic performance of retrofit rain gardens.

During storm events and snowmelt, runoff from developed areas poses many threats to the environment. High volumes of water can cause flooding, property damage, stream bank erosion, and sewer overflows. In addition, these storm surges contain hazardous levels of pollutants such as nutrients and carcinogenic hydrocarbons. In particular, the initial surface runoff of a storm event contains the highest concentration of pollutants because it carries the majority of the contaminants deposited on roadways and rooftops.

Municipalities in Ohio and the United States are spending billions of dollars to manage stormwater runoff through costly infrastructure projects. The City of Columbus Wet Weather Management Plan is a $2.5 billion infrastructure investment to help address high volume stormwater flow through the construction of deep sewer tunnels and increasing wastewater treatment plant capacity (Columbus Department of Public Utilities 2007). Chicagoôs Tunnel and Reservoir Plan (TARP, commonly known as Deep Tunnel) and the Water Pollution Abatement Program of the Milwaukee Metropolitan Sewerage District address the same stormwater issues at costs of $4 billion and $3 billion, respectively (CHS 2005 and MMSD 2010). With further quantification and understanding of their ability to reduce stormwater runoff, retrofit rain gardens can be lower-cost and more sustainable alternatives to complement costly infrastructure projects.

Rain gardens reduce stormwater runoff by increasing infiltration and evapotranspiration (Prince Georgeôs County 1999). Storm runoff ponds on top of and infiltrates into a mulched porous media with flood- and pollution-tolerant vegetation. During installation, the soil is generally amended with sand and/or compost to increase the infiltration rate. Dussaillant et al. (2004) and Atchison et al. (2006) indicate that 10-20% and approximately 15%, respectively, of the impervious surface draining to a rain garden should be used as the area of the bioretention cell. Such a large area for bioretention is not generally feasible in a retrofit situation, but significant rain garden performance has been shown for significantly smaller rain gardens. For instance, a downspout rain garden showed 38% outflow volume reduction despite the garden area being only 3.9% of the rooftop area (Abi Aad et al. 2010). Brown and Hunt (2011) showed that substantially deeper rain gardens (0.9 m) can perform as well or better than gardens with typical depths (0.6 m), which may reduce the areal needs of future gardens.

Previous rain garden studies have found volume reductions in stormwater flows from 33-90% (Barr Engineering 2006; Bedan and Clausen 2009; Hatt et al. 2009; Hunt et al. 2006; Hunt et al. 2008; Yang et al. 2009) and peak outflow reductions from 42-96.5% (Hatt et al. 2009; Muthanna et al. 2008; Yang et al. 2009; Davis 2008; Hunt et al. 2008; Bedan and Clausen 2009). Rain gardens have also been shown to substantially reduce the concentration of pollutants in runoff from impervious surfaces (Brander et al. 2004; DeBusk and Wynn 2011).

The vast majority of rain garden research has involved new construction with little consideration directed toward implementation within existing development. Without further understanding of retrofit rain gardens, cities will continue to overlook rain gardens for costly infrastructure projects to manage storm flows. One study has evaluated the benefits of rain gardens, vegetated swales and pervious pavement in a housing development (Dietz 2007), but it would be difficult or impossible to incorporate all three of these treatment systems into existing developments. A preliminary study by Barr

Engineering (2006) reports a 90% reduction in runoff volume in a Minnesota neighborhood retrofitted with street-side gardens, but the performance and design of these systems is still not well understood or documented.

Road construction often employs an underdrain below the curb to discourage ponding in manicured lawns and remove excess water from the roadbed. Most retrofit right-of-way rain gardens will be built over these pre-existing curb underdrains, and it is essential to understand how this affects their hydrologic performance. Atchison et al. (2006) advocate including an underdrain that can be manipulated for adaptive management purposes. The accessible orifice of many retrofit rain gardens, however, will be a part of the existing sewer system and ineligible for alteration. This study helps determine how the curb underdrain impacts hydrologic performance in retrofit, right-of-way rain gardens.

The focus on overall hydrologic performance in rain garden research overlooks the importance of understanding the water balance of a rain garden. During and following a storm event while evapotranspiration is minimal, the volume of inflow that does not become outflow must either infiltrate into the rain garden soil for storage within the garden or infiltrate to the soil surrounding the rain garden, which is referred to as exfiltration in most rain garden literature. A process model simulation of flow through a bioretention cell indicates that most exfiltration occurs through the bottom of the media (He and Davis 2011), but did not confirm this with experimental data. Previous studies have either assumed that exfiltration to surrounding soil is insignificant (Schlea et al.

2011), assumed that exfiltration accounts for most of the difference between inflow and outflow (Debusk and Wynn 2011; Brown and Hunt 2011) or neglected to describe the destination of the water that does not exit the garden via outflow (Abi Aad et al. 2010; Barr Engineering 2006; Bedan and Clausen 2009; Brander et al. 2004; Carpenter and Hallam 2010; Davis 2008; Hatt et al. 2009; Hunt et al. 2006; Hunt et al. 2008; Muthanna et al. 2008; Yang et al. 2009). This limitation of knowledge is highlighted by the fact that no previous rain garden study has quantified the amount of exfiltration. Estimating this volume will improve both understanding of the function and future designs of rain gardens. Furthermore, rain garden research has predominantly neglected long-term flow processes, such as subsurface flow, in favor of the shorter-term flow processes of infiltration, exfiltration and outflow reduction. Better quantification of the ultimate destination of water that enters rain gardens will greatly benefit the understanding of these systems.

Schlea et al. (2011) established a correlation between the applied water depth in simulated rain events with the volume reduction for these rain gardens when the initial soil moisture was relatively constant (volumetric soil water content 0.49 ï 0.57) in the top 15 centimeters of the soil. In this study we used initial and final water content from greater soil depths to better quantify the hydrologic performance of rain gardens and allow for the calculation of the amount of water exfiltrating out of the rain gardens.

Design and maintenance standards for rain gardens warn that inflow areas can be prone to erosion where overland flow or pipe discharge enters the rain garden (Fairfax County 2009). The inlet area of right-of-way rain gardens, however, is also prone to the accumulation of debris in storm runoff. The accumulation of debris can prevent water from entering the garden during rainfall events. Inflow designs of right-of-way rain gardens must limit the accumulation of debris without compromising hydrologic performance. Inlet design standards exist for roof runoff rain gardens (NEO PIPE 2006) and it is recommended to use sheet flow over grassed areas for other rain garden entrances (Dyke 2009). However, this design is also prone to the accumulation of debris by the grass which can deflect water away from the garden entrance.

Goals

The goals of this study were to (1) quantify the overall hydrologic performance of the rain gardens; (2) quantitatively describe the water balance around the rain gardens including inflow, outflow, exfiltration and change in storage; and (3) quantify the effects of three inlet designs on the hydrologic performance of retrofit, right-of-way rain gardens.

Methods

Site Description

The study site was the Brook Run residential subdivision in Westerville, Ohio (Figure 1). Westerville, Ohio has an average annual precipitation of 39.35 inches (NCDC 2012). In the year of this study from April 2011 to March 2012, the area experienced 55.29 inches of precipitation (NWS 2012). Previously a wooded area, the homes of the Brook Run neighborhood were built from 1988ï 1992 ï before legislation requiring stormwater mitigation. The developmentôs 29 lots average 0.15 hectares. Existing stormwater management included curb and gutter collection flowing into a storm sewer that discharges directly into the Condit and Nichols Ditch through an outfall pipe. The ditch is a second order stream within the Ohio River Watershed.

Figure 1. The rain gardens of the study site are connected to a storm sewer line discharged to Condit & Nichols Ditch. The rain gardens are connected to the storm sewer via pre-existing curb underdrains.

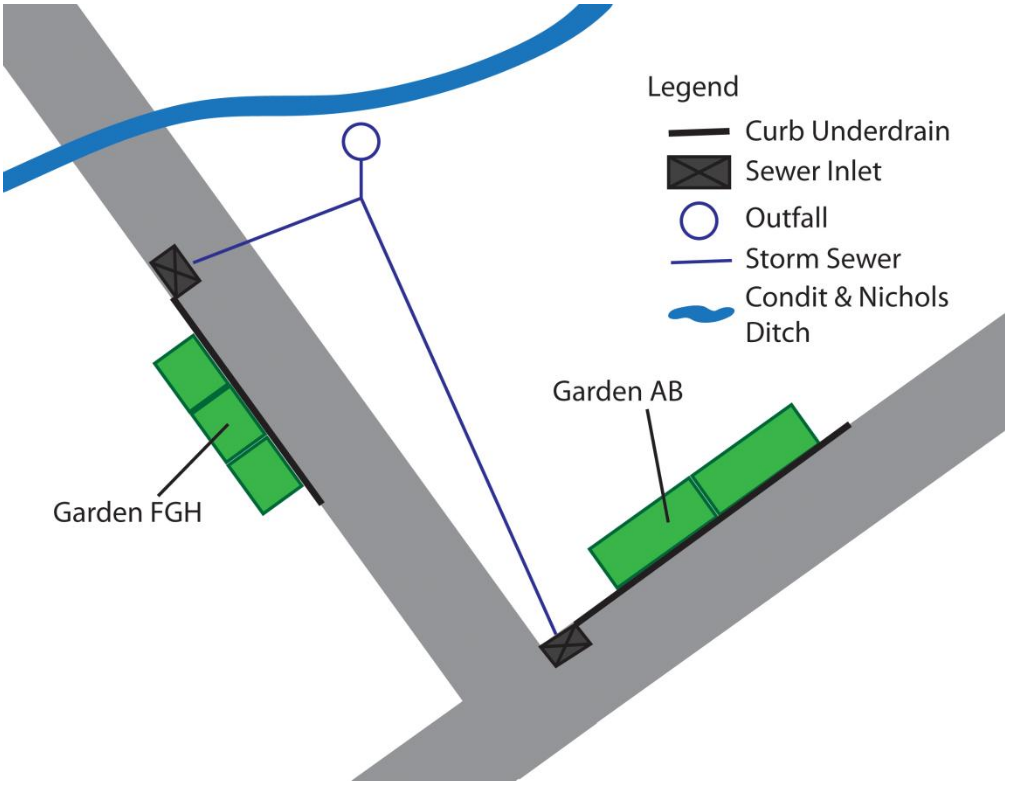
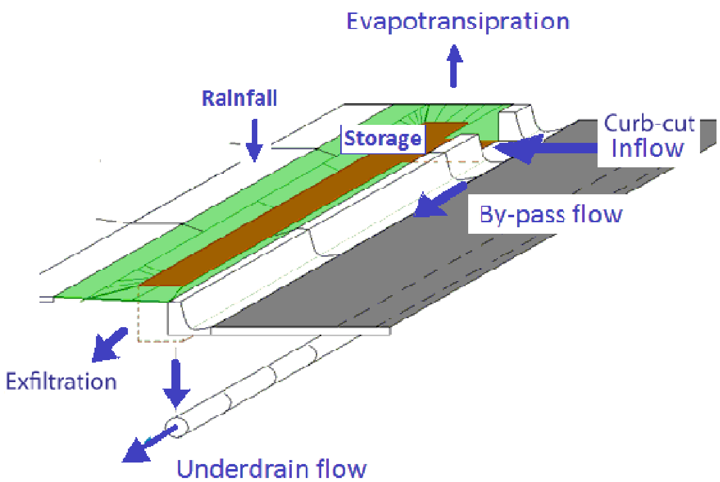


Figure 2. Runoff moves down the curb as indicated by the direction of the bypass flow and enters the garden at the curb cut. When the rain garden is ponded to the height of the inlet, flow continues along the curb to the storm sewer according to pre-existing stormwater management design.



Each garden is a combination of multiple, terraced cells. Cells were divided by a 0.5 m berm. 0.6 m curb cuts were made along the curb on the upstream end of each rain garden cell to provide an entry for stormwater runoff. This created a terracing effect of consecutive rain garden cells of lower elevation separated by berms so that when a cell becomes full, the flow bypasses the full cell and flows along the curb to the adjacent, lower cell. When all cells are full, the water bypasses to continue flowing along the curb to the storm sewer inlet (Figure 2). This study focused on the two sets of rain gardens displayed in Figure 1 due to their different watershed sizes and their proximity to the storm sewer outfall and a hydrant for simulated rainfall events.

Rain Garden Design

In July 2010, retrofit, right-of-way rain gardens were installed in the Brook Run neighborhood by Watershed Organic and the City of Westerville Service Department with assistance from neighborhood residents to intercept street-side stormwater runoff in the Brook Run neighborhood. Plants were selected based on their aesthetics, nativity to the central Ohio area, and ability to thrive in fluctuating hydrologic conditions typical of rain gardens. A complete listing of plants can be found in Schlea (2011). The in situ clay soil was excavated and backfilled to a depth of 60 cm with a sandy loam soil mix comprised of 70% sand, 19% silt and 11% clay as determined by the hydrometer method and the USDA Soil Textural Triangle (SSSA 2002). The average soil water content at the conclusion of the simulated rainfall events for each depth of the gardens is presented with the bulk density (Table 1). Final soil water content is only available for 6 simulated rainfall events, and so the average final soil water contents from these 6 events were used for all tests to calculate the final volume of water present in the gardens. The low standard deviations of the final volumetric water contents indicated that the outflow ceased at consistent water content within the gardens. The bulk density was used to calculate the initial and final volume of water present in the rain garden from the gravimetric soil water contents.

Table 1. The bulk densities and volumetric soil water contents when the underdrain completed draining for different depths of the gardens were used to compute the storage potential for simulated rainfall events. Bulk density and gravimetric soil water content were determined via the core method. Gravimetric soil water content was converted to volumetric via the bulk density. Standard deviations are listed in parentheses.

	Dry Bulk Density (g/cm^3)					Average Final Volumetric Water Content (cm^3/cm^3)				
Depth (cm)	A	B	F	G	H	A	B	F	G	H
0-15	0.92 (0.02)	0.91 (0.03)	0.91 (0.09)	0.93 (0.12)	0.88 (0.06)	0.46 (0.01)	0.48 (0.02)	0.52 (0.06)	0.44 (0.01)	0.41 (0.01)
15-30	0.90 (0.02)	0.92 (0.01)	0.93 (0.05)	0.93 (0.08)	0.90 (0.02)	0.46 (0.03)	0.55 (0.04)	0.55 (0.08)	0.50 (0.04)	0.50 (0.03)
30-45	1.06 (0.06)	1.02 (0.04)	0.94 (0.06)	0.95 (0.09)	0.98 (0.04)	0.65 (0.01)	0.53 (0.07)	0.56 (0.04)	0.61 (0.05)	0.65 (0.01)
45-60	1.16 (0.08)	1.01 (0.07)	1.03 (0.17)	1.02 (0.14)	1.00 (0.01)	0.65 (0.02)	0.60 (0.11)	0.61 (0.06)	0.60 (0.11)	0.61 (0.02)

The right-of-way area was approximately 2 meters from the curb to the sidewalk. While recommendations generally say that the garden area should be approximately equal to 15% of the impervious area of the watershed area (Dussaillant et al. 2004), the small right-of-way size did not allow this garden to impervious watershed area ratio. Rain gardens AB and FGH have garden to impervious watershed surface area ratios of 2.2% and 2.7%, respectively (Table 2).

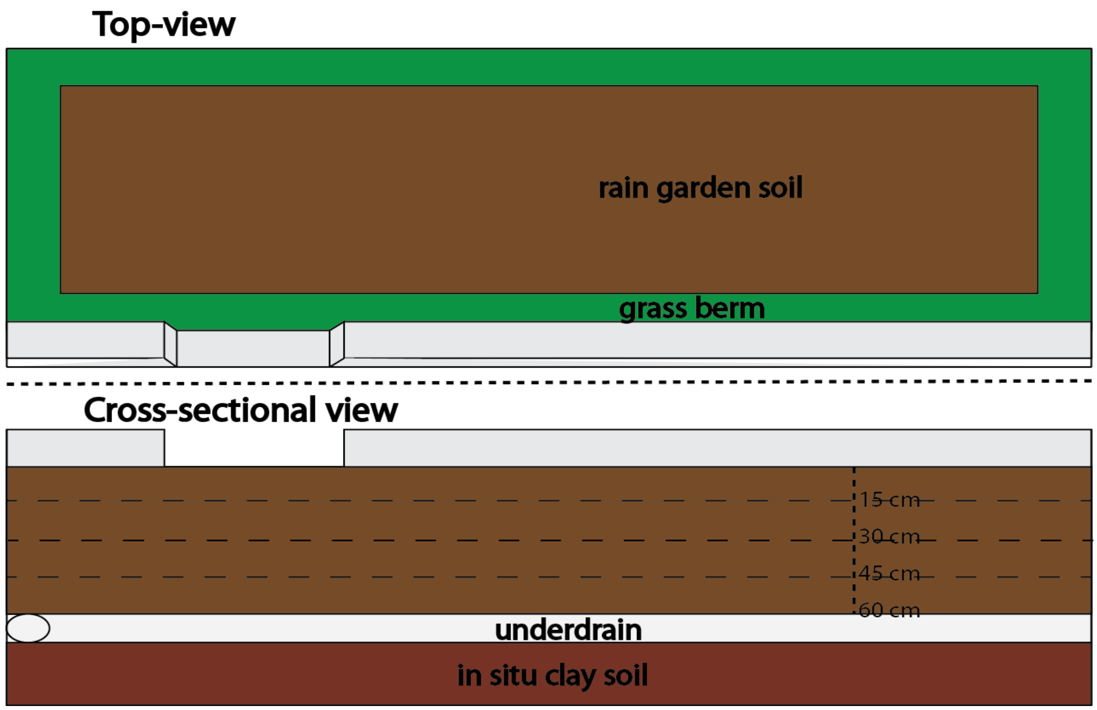
Table 2. The garden area to its watershedös impervious surface area ratio is important for predicting the gardenös hydrologic performance.

Garden Name	Garden Surface Area (m^2)	Watershed Area (m^2)	Impervious (Pavement + Roofs) Watershed Area (m^2)	Pervious Watershed Area (Manicured Lawns) (m^2)	Garden to Impervious Surface Area Ratio
AB	26.5	2,894	1,215	1,679	2.2%
FGH	18.5	869	687	182	2.7%

Underdrains are used in rain gardens to prevent excessive ponding (Roy-Poirier et al. 2010) and can be placed approximately 0.3 m above the bottom of the bioretention cell to promote denitrification between storm events (DeBusk and Wynn 2011). A pre-existing perforated pipe under the curb intended for draining water from under the road into the storm sewer served as an underdrain for the right-of-way gardens. The underdrain was located below the curb at the interface between the bottom of the rain garden soil and the in situ clay soil 0.6 m from the top of the bioretention cell (Figure 3Figure 2).

The initial construction featured grass at the curb-cut entrance of the garden as recommended in rain garden design standards (Dyke 2009). This was altered during July 2011 (Table 3) to prevent blocking the entrance of the garden with debris by replacing the grass at the entrance in a 1.0 m by 0.8 m area to a depth of 0.2 m with stones approximately 7 cm in diameter (Figure 3).

Figure 3. Top view (top) and cross-sectional view (bottom) of rain garden illustrating the dimensions of the area excavated and filled with stones for inlet designs 2 and 3.



Results from the second inlet design showed that the volume reduction in simulated rainfall events decreased considerably following this change. In the fall of 2011, the entrances to the rain gardens were altered again to improve the volume reduction of the garden while deterring the accumulation of debris by adding a layer of bentonite clay below the 0.2 m of stones at the inlet. This study analyzed the 3 inlet designs to determine their effectiveness in reducing stormwater runoff.

Table 3. The original inlet design accumulated debris at the inlet, and needed to be frequently cleaned to facilitate the flow of water to the gardens during storm events. Inlet design 2 improved the inlet performance by allowing water to flow in freely, but simulated rainfall events showed reduced hydrologic performance. Inlet design 3 maintained inflow and hydrologic performance of the rain garden.

Inlet Design	Date of Alteration	Description
1	8/2010	Soil with grass at the curb-cut inlet. Grass and accumulating debris prevented water from entering the gardens.
2	7/21/2011	Soil and grass excavated from inlet in an area 1.0 m by 0.8 meters to a depth of 20 cm. Elimination of vegetation from the inlet increases volume of water entering gardens during storms, but simulated rainfall events show decreased performance.
3	11/17/2011	Layer of bentonite clay added between soil and rocks at inlets. Simulated rainfall events indicate improved stormwater flow reduction.

Simulated Rainfall Events

Simulated rainfall events were used to quantify the hydrologic performance of the rain gardens by simplifying the variables of the water budget. The simulated rainfall events utilized either a municipal water source or water pumped from the ditch to which the outflow was discharged. The size of the simulated rainfall events were chosen to approximate the runoff of each gardenǿs watershed for storms of small (0.6 cm) and moderate (1.1 cm) size. Inflow rates varied from 75-100 liters per minute during the 20 events. A large number of 1.1 cm storms were performed on garden FGH in cooperation with a water quality study. The quantity of water introduced to the rain gardens was measured, which eliminated the error inherent in runoff quantity estimation methods and field flow meters. Inflow bypassed the inlet and entered directly into the garden. By performing the experiments on days in which there was no precipitation and the storm sewer was dry, the volume of water that exited the storm sewer outfall was measured and attributed to the water introduced to the rain garden. The quantity of water retained by the rain garden was calculated. Exfiltration (E) was estimated as the volume of water unaccounted for by the known variables: inflow (I), outflow (O) and the change in storage within the garden substrate (φS) (Equation 1). Inflow and outflow were measured and the change in storage was calculated from the difference between the initial soil water content and average final water content for the depths of the soil profile. Equation 1 defines exfiltration ï or infiltration to the in situ soil surrounding the rain garden ï as all water unaccounted for in measured variables of the water balance. A key assumption made in using Equation 1 was that evapotranspiration is negligible during the 60 to 90 minute duration of the tests.

$$E = I - O - \Delta S \qquad \text{(Equation 1)}$$

Dry bulk density and gravimetric soil water content were determined by analyzing soil cores with the gravimetric method (SSSA 2002). 2.5-cm cores were placed in airtight plastic bags immediately upon removal, and the maximum amount of time before drying was 5 hours. Cores were sampled at 15 cm intervals along the 60 cm depth of the rain garden before inflow began and after underdrain outflow ceased for simulated rainfall events to determine the initial and final water contents. Field capacity for each layer of soil was determined by a pressure plate apparatus at a suction of 0.33 bar (Richards 1947). The post-drainage cores had higher water contents than the laboratory measurement of field capacity. Measured gravimetric soil water content was converted to volumetric water content using dry bulk density. Recharge/storage capacity was the difference between the volume of water that the soil held before and after a simulated rainfall event (Table 4). Soil chemical analyses were completed by Ohio Stateôs Service Testing and Research Laboratory in Wooster, Ohio (Schlea 2011). The inflow volume was represented as an applied water depth ï inflow volume divided by surface area of rain garden ï to normalize hydrologic performance to rain gardens of different surface and watershed areas (Table 4). Volume reduction was used to quantify hydrologic performance of the rain gardens during simulated rainfall events. Each cell has a piezometer to a depth of approximately 70 cm with an Onset HOBO Model U20 pressure transducer recording pressure at 3 minute intervals. An additional pressure transducer recorded barometric pressure to determine water levels within each cell. The temperature of the top layer of the soil profile was measured using Rapitest 1618 soil thermometers.

Data Analyses

Inflow rates were measured every 3-5 minutes and outflow rates were measured every 1-2 minutes during the simulated rainfall events. Cumulative flows were calculated according to the trapezoidal rule for numerical integration (Atkinson 1989) for tests that did not utilize a tank for measuring the volume of water. The summation of the change in storage of all soil layers is equal to the change in storage of water in the rain garden (Figure 4). The 68% confidence intervals for exfiltration were determined by calculating the values using +/- 1 standard deviation of the average final water content. Volume reduction percentage was calculated as the difference between the inflow and outflow volumes divided by the inflow volume. Statistical tests to determine significant differences between inlet designs were performed with an alpha-value of 0.01.

Results & Discussion

Overall Hydrologic Performance

Across all 20 simulated rainfall events, the rain gardens provided 44% volume reduction. By removing the tests with soil temperature initially below 0°C, the overall volume reduction increased to 47%. While these results suggest that rain garden performance may decrease when the top soil layer temperature is below 0°C, more tests are needed to explore rain garden function during cold temperatures. Garden AB provided 52% volume reduction while garden FGH provided 34% volume reduction over 7 and 13 simulated rainfall events, respectively. ABȇs 52% volume reduction is similar to average results for previous rain garden literature (Bedan and Clausen 2009; Hunt et al. 2006; Yang et al. 2009). The 34% volume reduction from FGH fits within the lower end of the spectrum for published rain garden results (Hatt et al. 2009). DeBusk and Wynn (2011) showed similar results and suggest that deeper rain gardens be used in retrofit scenarios with spatial constraints to maximize outflow volume reductions. Retrofit, right-of-way rain gardens perform in the range of other results despite their lower garden area to impervious area ratios. ABȇs better hydrologic performance compared to FGH can be attributed to exfiltration, increased size and patterns of preferential flow. AB exhibited more exfiltration, which may have been aided by its increased surface area contact between the rain garden and surrounding soils due to its larger size. The water balance equation estimated that 25% of the total inflow to AB became exfiltration compared to 9% for FGH, which accounts for the difference in volume reduction between the gardens (52% and 34% volume reduction). Additionally, the efficacy of paths of preferential flow to the underdrain was unaffected by inlet design 2 in AB but was increased in FGH, as will be described more fully in the discussion of inlet design. This impact of inlet design likely further decreased the performance of FGH relative to garden AB. Future right-of-way rain garden design with underdrains at 0.6 m should consider deeper construction (0.9 m) to improve hydrologic function (Brown and Hunt 2011) as well as allowing for 0.3 m of saturation zone to promote denitrification between storm events (Debusk and Wynn 2011).

Table 4. Inflow is represented as a volume, equivalent rainfall depth according to the USDA SCS curve number estimation method and the applied water depth of irrigation.

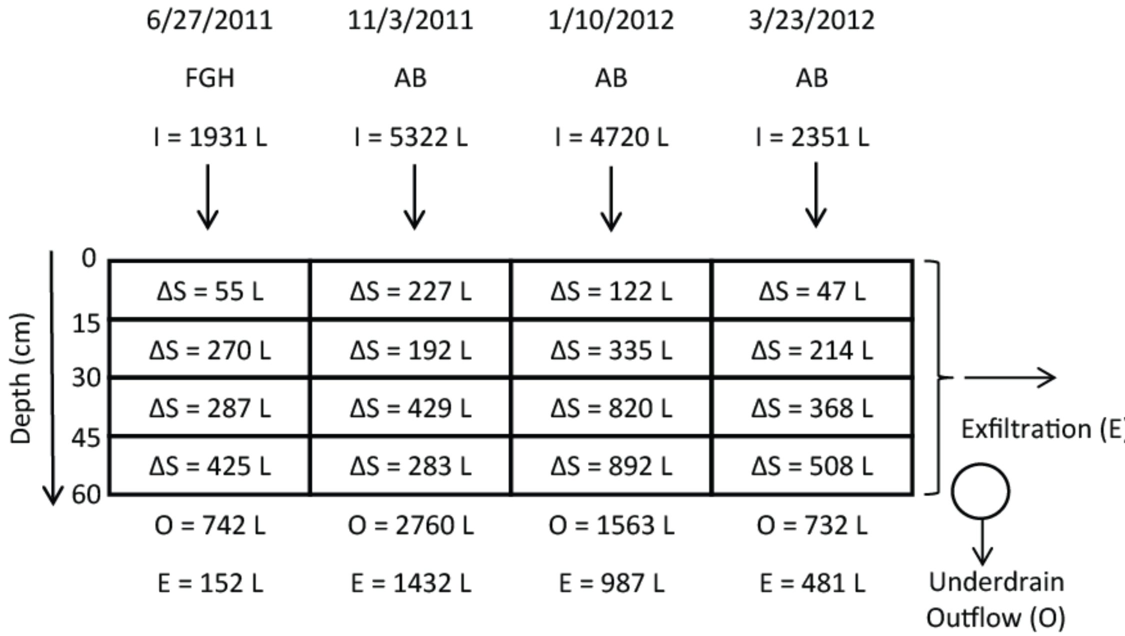
					Inflow		Outflow		Storage			Exfiltration	
Test	Date	Site	Inlet	Storage Potential (L)	Vol. (L)	Applied H_2O Depth (cm)	Vol. (L)	% Inflow	Vol. (L)	% Storage Potential	% Inflow	Vol. (L)	% Inflow
1	10/25/11	AB	2	380	5250	19.8	3437	65%	380	100%	7%	1434	27%
2	11/3/11	AB	2	1131	5322	20.1	2760	52%	1131	100%	21%	1432	27%
3	12/13/11	AB	3	1229	5368	20.3	1787	33%	1229	100%	23%	2352	44%
4	1/10/12	AB	3	2170	4720	17.8	1563	33%	2170	100%	46%	987	21%
5	*1/24/12	AB	3	654	5148	19.4	4013	78%	654	100%	13%	482	9%
6	3/23/12	AB	3	1137	2351	8.9	732	31%	1137	100%	48%	481	20%
7	3/29/12	AB	3	1368	2510	9.5	529	21%	1368	100%	54%	613	24%
8	6/27/11	FGH	1	1037	1931	10.4	742	38%	1037	100%	54%	152	8%
9	7/11/11	FGH	1	1462	1931	10.4	1120	58%	810	55%	42%	0	0%
10	7/26/11	FGH	2	849	1931	10.4	1541	80%	390	46%	20%	0	0%
11	8/4/11	FGH	2	477	1931	10.4	1518	79%	413	87%	21%	0	0%
12	8/23/11	FGH	2	1385	1931	10.4	1363	71%	568	41%	29%	0	0%
13	9/13/11	FGH	2	321	1931	10.4	1586	82%	321	100%	17%	24	1%
14	9/16/11	FGH	2	739	1931	10.4	1571	81%	360	49%	19%	0	0%
15	9/20/11	FGH	2	628	1931	10.4	1571	81%	360	57%	19%	0	0%
16	*2/7/12	FGH	3	759	2199	11.9	1563	71%	636	84%	29%	0	0%
17	2/13/12	FGH	3	781	1734	9.4	617	36%	781	100%	45%	336	19%
18	2/28/12	FGH	3	1102	1919	10.4	837	44%	1083	98%	56%	0	0%
19	*3/6/12	FGH	3	514	840	4.5	583	69%	257	50%	31%	0	0%
20	3/23/12	FGH	3	792	737	4.0	581	79%	156	20%	21%	0	0%

*Top soil layer below 0°C

Water Budget

Using Equation 1, exfiltration to surrounding soil during simulated rainfall events was estimated as the water unaccounted for by the measured values of the water balance (Figure 4). All seven events in garden AB produced exfiltration to surrounding soil (Table 4), accounting for 25% (68% confidence interval: 16-40%) of the inflow to garden AB. Only 2% (68% confidence interval: 0-12%) of inflow exfiltrated in the thirteen simulated rainfall events for garden FGH. For the three events in garden FGH with exfiltration, 9% of the inflow exfiltrated to the soil surrounding the rain garden. For the ten tests resulting in exfiltration across both gardens, 23% of the inflow became exfiltration to the surrounding soil. Across all twenty tests, 15% (68% confidence interval: 7-29%) of the total inflow exited the garden via exfiltration to the surrounding soil. AB was 8 square meters larger than FGH, which created 14 square meters, or 30%, more surface area contact between the rain garden and surrounding soils. Greater exfiltration in AB can be attributed to its larger surface area compared to FGH. Additionally, events with low volume reductions exhibited low volumes of exfiltration. For these events, it is likely that most of the water was retained by the soil of the rain garden. FGHǿs hydrologic performance was significantly decreased by inlet design 2. ABǿs greater surface area and FGHǿs poor performance in inlet design 2 resulted in higher exfiltration for garden AB.

Figure 4. Using equation 1, water balance variables were calculated for all 20 events, of which 4 examples are displayed. The difference between the final and initial volumes of water present in the garden was the change in storage (φS) within layers of the rain garden. The water that enters the surrounding soil via exfiltration (E) was estimated by subtracting the curb underdrain outflow (O) and change in soil water storage (φS) from the inflow (I). Detailed figures of individual tests including initial and final moisture contents for each cell at each depth are available in Appendix A.



The initial and final soil water contents of the 15-cm layers of soil were compared to determine the storage potential of the garden for each simulated rainfall event. The final soil water content was defined as the average water content for that depth across all tests for which this data are available. Laboratory determinations of field capacity were lower than the average soil water contents (Table 5).

Table 5. Laboratory field capacity determinations yielded lower volumetric water contents than was present in the garden at the cessation of underdrain flow for simulated rainfall events. Less data were available for the field capacity determinations due to laboratory constraints so the average across all gardens for each depth was used. Standard deviations are listed in parentheses.

Depth (cm)	Laboratory Field Capacity (cm^3/cm^3)	Average Final Volumetric Water Content (cm^3/cm^3)
0-15	0.39 (0.03)	0.46 (0.03)
15-30	0.35 (0.10)	0.48 (0.03)
30-45	0.45 (0.01)	0.57 (0.02)
45-60	0.46 (0.05)	0.52 (0.04)

Exfiltration that occurred prior to the cessation of underdrain discharge of the simulated rainfall events was estimated by using the average final water contents rather than laboratory field capacity data. Evapotranspiration can be assumed to be negligible during the short duration of a simulated rainfall event and its drainage time, but would need to be estimated during the approximately 2 days (Lal and Shukla 2004) required for the soil to reach its field capacity soil moisture. Exfiltration was estimated at 15% of inflow at the cessation of underdrain discharge across all tests using the average water contents from the cessation of underdrain discharge to determine the change in storage within the garden. Using field capacity, exfiltration was estimated as 43% of total inflow assuming that there was no evapotranspiration. A lack of both evapotranspiration and further exfiltration is unlikely in wet conditions, so the true value of total exfiltration was likely in the range of 15-43% of inflow. Estimating the change in soil water storage with the soil water content from the cessation of underdrain outflow rather than field capacity resulted in a larger calculated volume of storage and, therefore, a more conservative estimate of exfiltration.

Plots of the pressure transducer data indicate that the water table is still near its peak within the rain gardens at the cessation of underdrain outflow, and the water table continues to drop for hours after the simulated rainfall event (Figure 5). This shows that the change in storage within the gardens calculated by this study was temporary storage. This indicates that much of the estimated change in soil water content ultimately left the garden as exfiltration or evapotranspiration. A hypothetical soil water depth profile (Figure 6) illustrates the quantity of water that would leave the gardenôs storage if allowed to release all of its drainable porosity before the next rainfall event. The ultimate destination of this water was unknown in this study, but there are two likely possibilities: exfiltration to the surrounding soil, and evapotranspiration. Given these rain gardensô close proximity to a waterway, it is also likely that a portion of the rain gardensô exfiltration eventually entered the stream via subsurface flow. Future studies can monitor stream flow or use tracer studies to better estimate the amount of storm water that ultimately reaches surface water bodies.

Figure 5. Pressure transducer data during and after the 2/7/2012 (A) and 12/13/2011 (B) simulated rainfall events in FGH & AB, respectively. The fact that the water table depth continued to decrease for many hours after the cessation of underdrain outflow indicated that a substantial amount of water remaining in the garden at the cessation of underdrain outflow eventually exited through exfiltration or evapotranspiration. A natural rainfall event occurred on 12/14/2011, raising the water level.

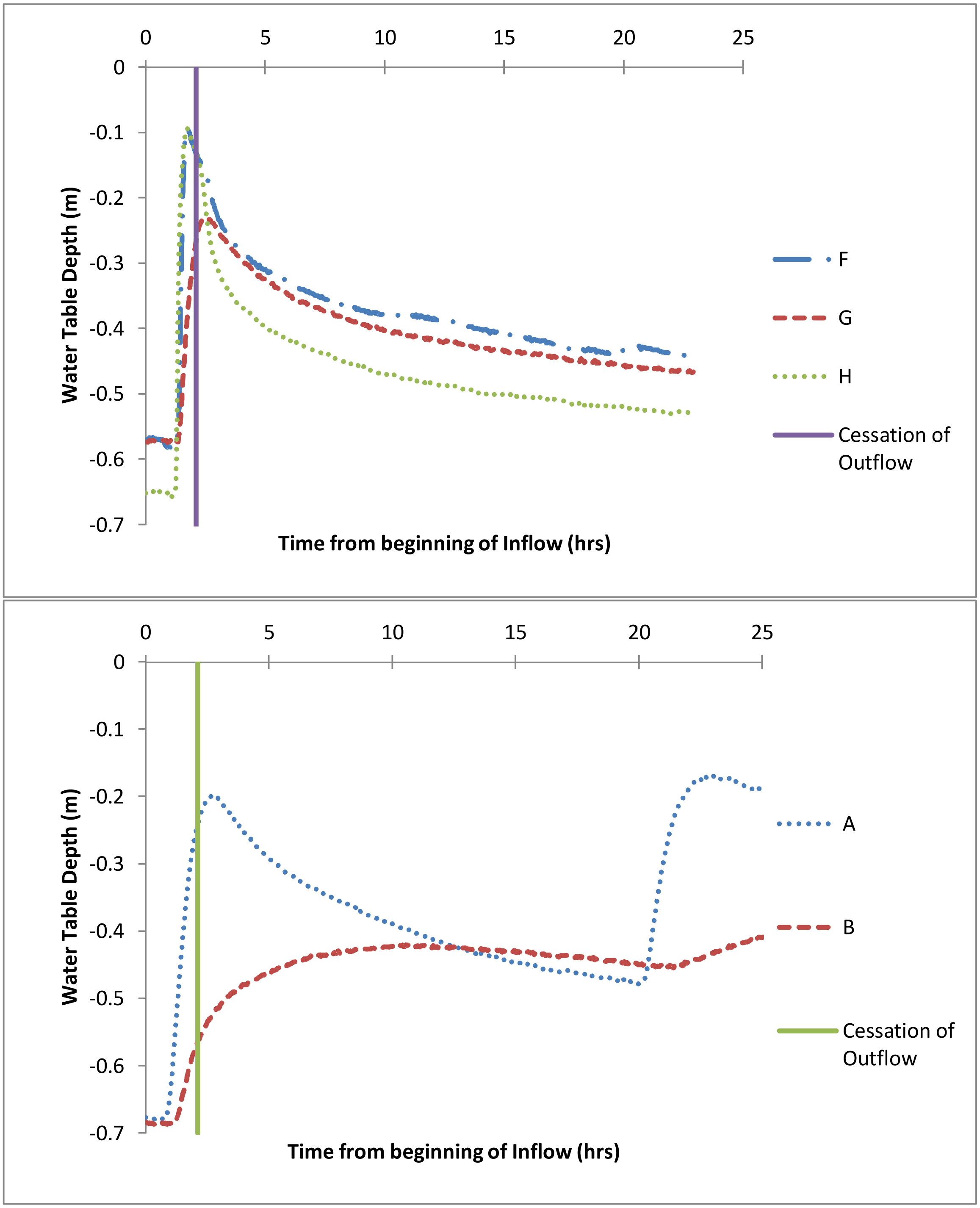
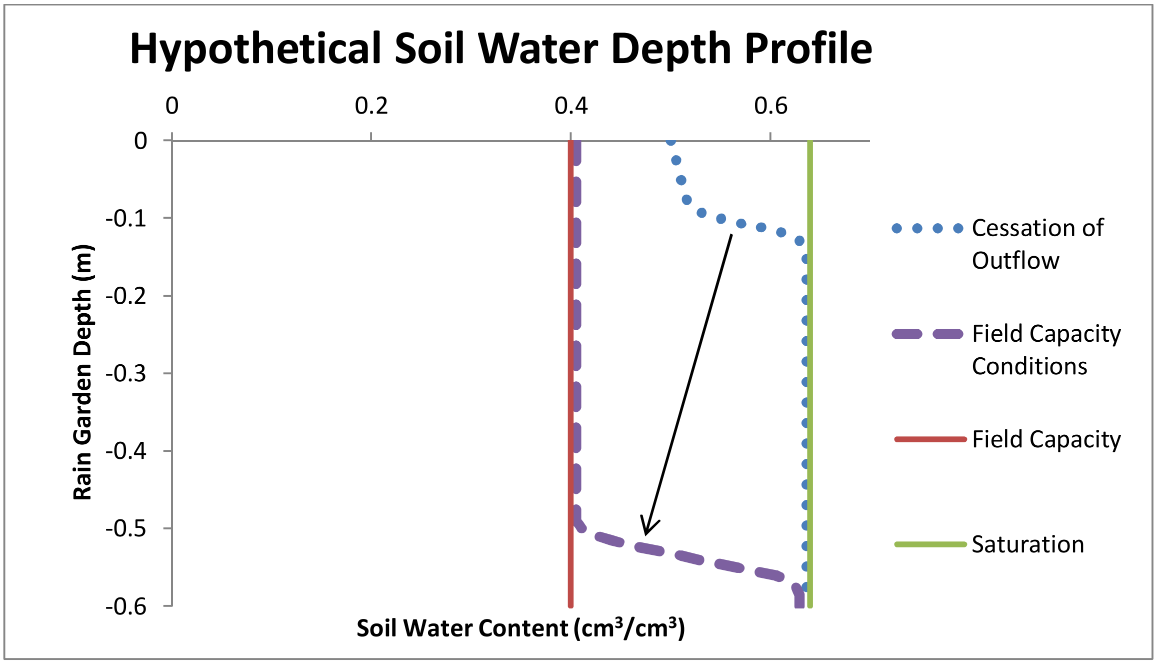


Figure 6. A hypothetical soil water depth profile comparing the soil water content just after the cessation of outflow and near field capacity conditions some time later indicate that more water would leave the garden, illustrating that the volume of water represented between these two curves was only stored temporarily in the rain garden soil. This volume of water lost from the rain garden during this time likely exits through exfiltration or evapotranspiration.



These results demonstrate that exfiltration to surrounding soil accounts for a substantial proportion of the water balance for retrofit, right-of-way rain gardens (estimated between 15% and 43% in this study). The predominant indicator of hydrologic performance in rain garden studies is the volume reduction from inflow to outflow. The authors of this study hope that future rain garden research will further the understanding of flow processes within the garden to more fully explain the mechanisms resulting in volume reduction. Significant stormwater mitigation can be achieved within relatively smaller rain gardens, particularly if exfiltration is a considerable component to the water balance.

Water movement between the soils of the rain garden and the surrounding area may be improved by enhancing the connectivity between the rain gardens and the surrounding soil through scarification of the underlying soil during construction (Dyke 2009). Future research investigating methods to promote exfiltration could improve the performance of rain gardens. The rain gardens of this study are also a relatively shallow 0.6 m deep. Deeper rain garden designs will increase the surface area between the rain garden and the surrounding soil, which should encourage more exfiltration to surrounding soil.

Inlet Design

Hydrologic performance decreased significantly for inlet design 2 when compared to the performance of inlet design 3 for AB (Figure 7). Similarly, inlet design 2 yielded significantly lower volume reductions in gardens FGH (Figure 8). No complete water balance data were available for tests on Garden AB with inlet design 1, but the average outflow reduction data were available from Schlea (2011).

Figure 7. Storage potential and volume reduction for simulated rainfall events of ~20 cm applied water depth in garden AB. At the Ŭ= 0.01 level, there was a significant difference in volume reduction between inlet designs 2 & 3. No significant difference was exhibited between inlet designs 1 & 2 or inlet designs 1 & 3. Tests with top soil layer temperature below 0°C were excluded from this statistical analysis. No storage potential data are available for inlet design 1, but 4 tests performed from 3/25/2011 to 4/21/2011 (Schlea 2011) were used for statistical analysis. Test numbers have been included to cross-reference with Table 4.

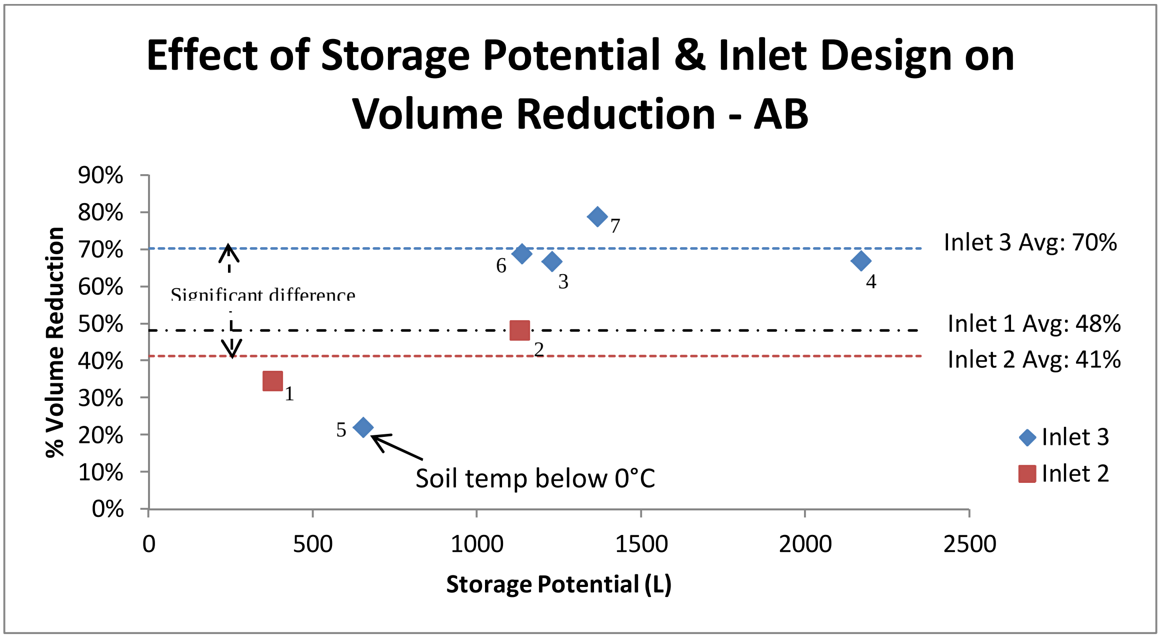
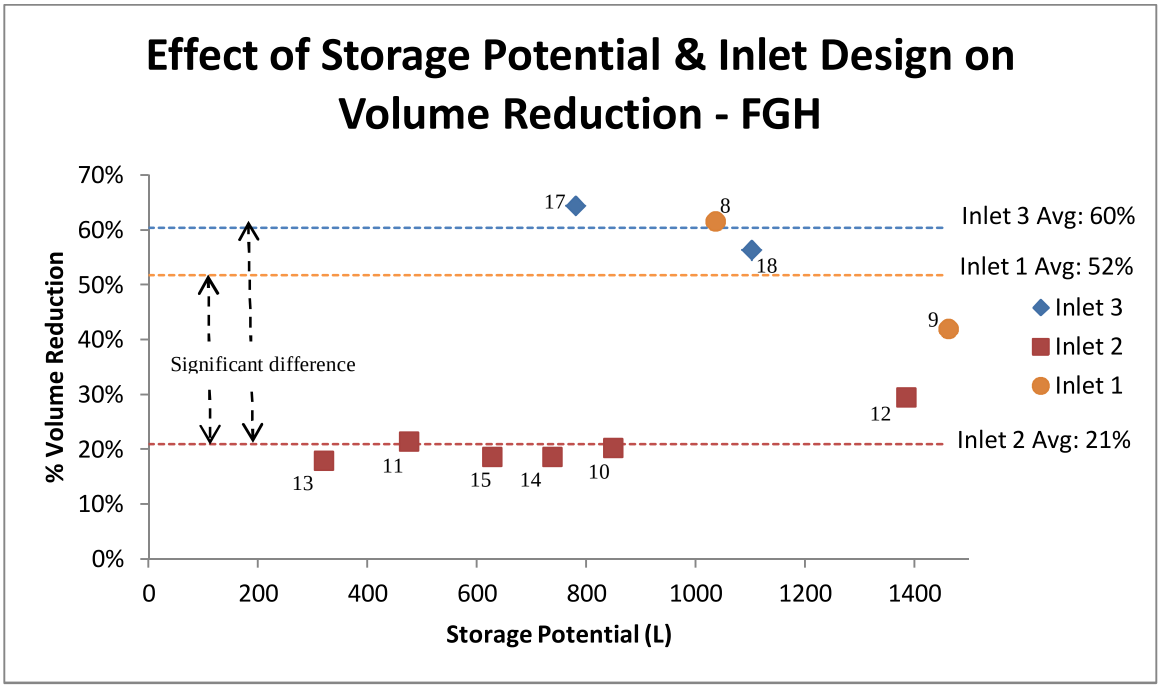


Figure 8. Storage potential and volume reduction for simulated rainfall events of ~10.5 cm applied water depth in garden FGH. At the Ŭ= 0.01 level, a significant difference was found between inlet designs 1 & 2 and inlet designs 2 & 3. No significant difference was exhibited between inlet designs 1 & 3. Test numbers have been included to cross-reference with Table 4.



The hydrologic performance decreased significantly in FGH from inlet design 1 (52%) to 2 (21%) and increased significantly from 2 (21%) to 3 (60%). The unusually high volume reduction (29%) in inlet design 2 for Garden FGH on 8/23/2011 (Table 4) occurred during unusually dry conditions when the storage potential was approximately double the average for all other tests. In AB, no significant change was observed in volume reduction from inlet design 1 (48%) to 2 (41%), but volume reduction increased significantly from 2 (41%) to 3 (70%). This may illustrate the origins of the paths of preferential flow to the curb underdrain within these gardens. A water table response study on these gardens by Schlea (2011) indicated that paths of preferential flow originated from the top of the garden in AB and from within the soil matrix in FGH.

ABôs lack of a significant change from inlet design 1 to 2 indicated that preferential flow paths were mostly undisturbed by soil excavation in the top of garden AB. This agreed with Schleaôs hypothesis that paths of preferential flow originated in the top of garden AB. Excavating soil from the top of garden FGH for inlet design 2, however, significantly lowered volume reduction, which indicated that paths of preferential flow originated in the middle of FGHôs soil matrix. Excavation of the top layer of soil opened a more direct line of access to these flow paths. Restricting access to these paths of preferential flow with a layer of bentonite clay in inlet design 3 resulted in a significant increase of performance from 21% to 60% volume reduction in garden FGH. A new path of preferential flow was also created at the beginning and end of each simulated rainfall event through the removal of a 2.5-cm core for water content analysis. While it appears that the study was not compromised by the creation of these paths of preferential flow through data collection, future studies should minimize this destructive sampling technique.

Removing events with inlet design 2, the outflow volume reduction improves for both garden AB and FGH to 57% and 46%, respectively, across the remaining 12 simulated rainfall events. Each of the three events in garden FGH with exfiltration occurred in a different inlet design, with inlet 2ôs single exfiltration value an almost negligible 24 liters or 1% of inflow. Volume reduction and exfiltration are lower in garden FGH than AB. These findings indicate that greater reductions of storm runoff occurred with reduced preferential flow and greater exfiltration.

Garden FGH showed a significant increase in performance from inlet design 1 to 3, which indicates that the layer of bentonite clay at the inlet of the rain garden provided better protection against preferential flow to the underdrain compared to the grass and soil inlet. Garden AB did not show a significant difference between inlet designs 1 and 3, but there is a notable difference between these inlet designs regarding their practical performance. All data for this study were from simulated rainfall events in which the inflow was placed directly inside the garden, bypassing the inlet. Inlet design 3 ï replacing the top of the soil matrix with rocks at the inlet to prevent the accumulation of debris and including a lining of bentonite clay ï limited the accumulation of debris at the inlet and allowed for more stormwater runoff to enter the garden during natural storm events. Future rain garden design should mimic inlet design 3 by maintaining high hydrologic performance while minimizing maintenance issues and paths of preferential flow.

Summary & Conclusions

The hydrologic performance of these bioinfiltration systems shows that retrofit, right-of-way rain gardens with lower than recommended garden to impervious watershed area ratios and relatively shallow depths can achieve substantial reductions of stormwater runoff. Results also demonstrate that exfiltration is an important part of the water balance of rain gardens. Future rain garden studies should strive for a more complete understanding of the water balance of these systems. Not only is it important to determine short-term volume reductions via discharge pipes, but it is also important to determine the eventual flow paths of water temporarily stored in the gardens. Improved understanding of these longer-term flow processes will likely improve the design and function of future rain gardens. This study showed that 15% of the inflow had exfiltrated to the surrounding soil at the cessation of underdrain outflow within approximately 2 hours of 20 simulated rainfall events. Because of the methods employed in this study, this is likely a conservative estimate of exfiltration, and total exfiltration was likely between 15% and 43% of total inflow. Greater reductions of storm runoff occurred within the garden exhibiting greater exfiltration and lesser preferential flow to the underdrain. The performance of rain gardens can be increased with deeper rain gardens and other practices to encourage exfiltration to surrounding soil while discouraging preferential flow to the underdrain. Future research should examine methods to promote exfiltration including deeper rain gardens and scarification.

Inlet design must be considered carefully to ensure that retrofit rain gardens receive runoff during natural storm events. Replacing the soil and vegetation with stones at the inlet of the rain gardens increased the amount of flow that could enter during storm events. Simulated rainfall events showed that hydrologic performance increased significantly by lining the bottom of excavated inlet with a layer of bentonite clay. The hydrologic performance of the gardens with different inlet designs indicates impacts of paths of preferential flow to the curb underdrain. Reductions in exfiltration to the surrounding soil with inlets that encouraged short-circuiting highlighted the need for proper inlet design.

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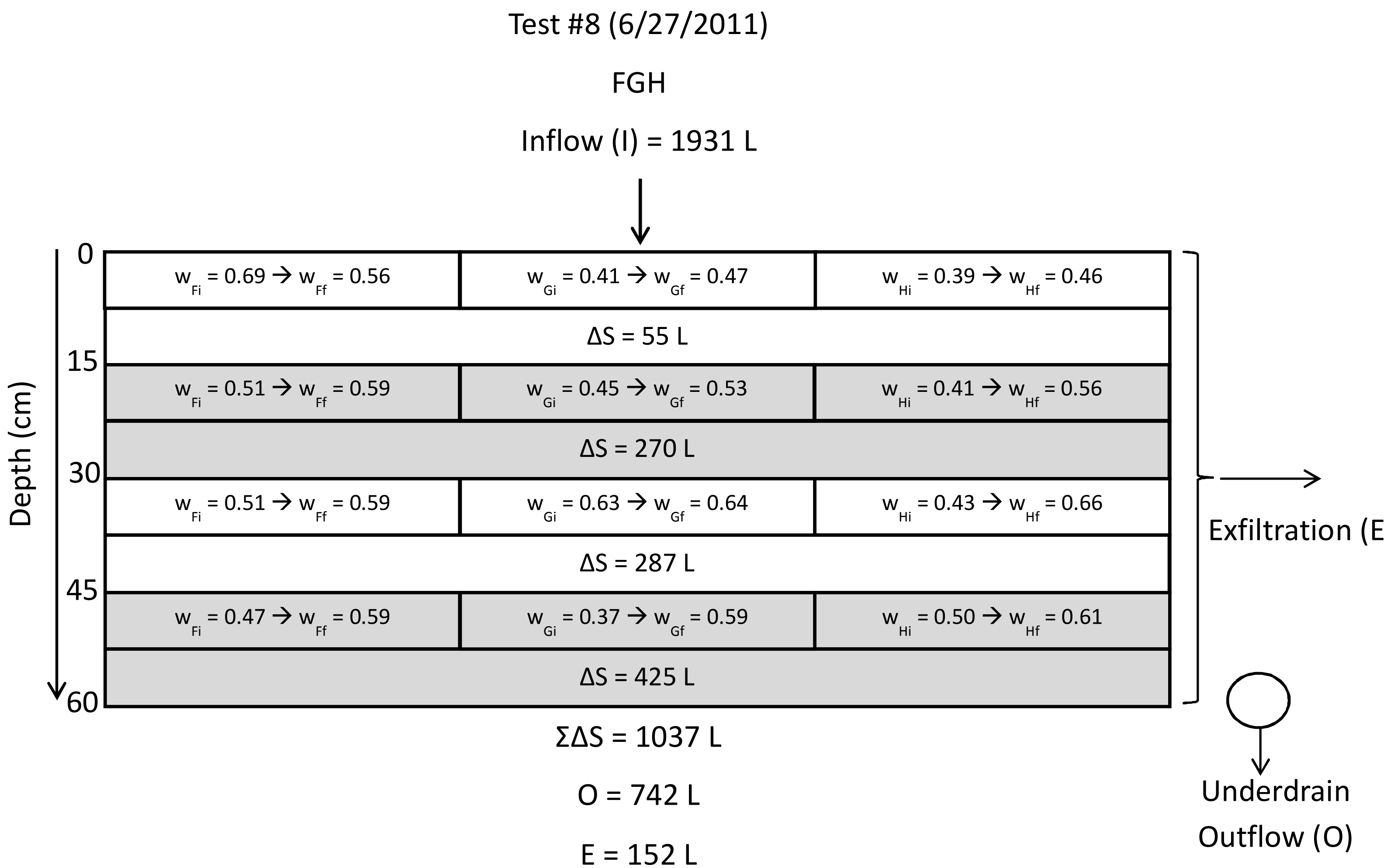
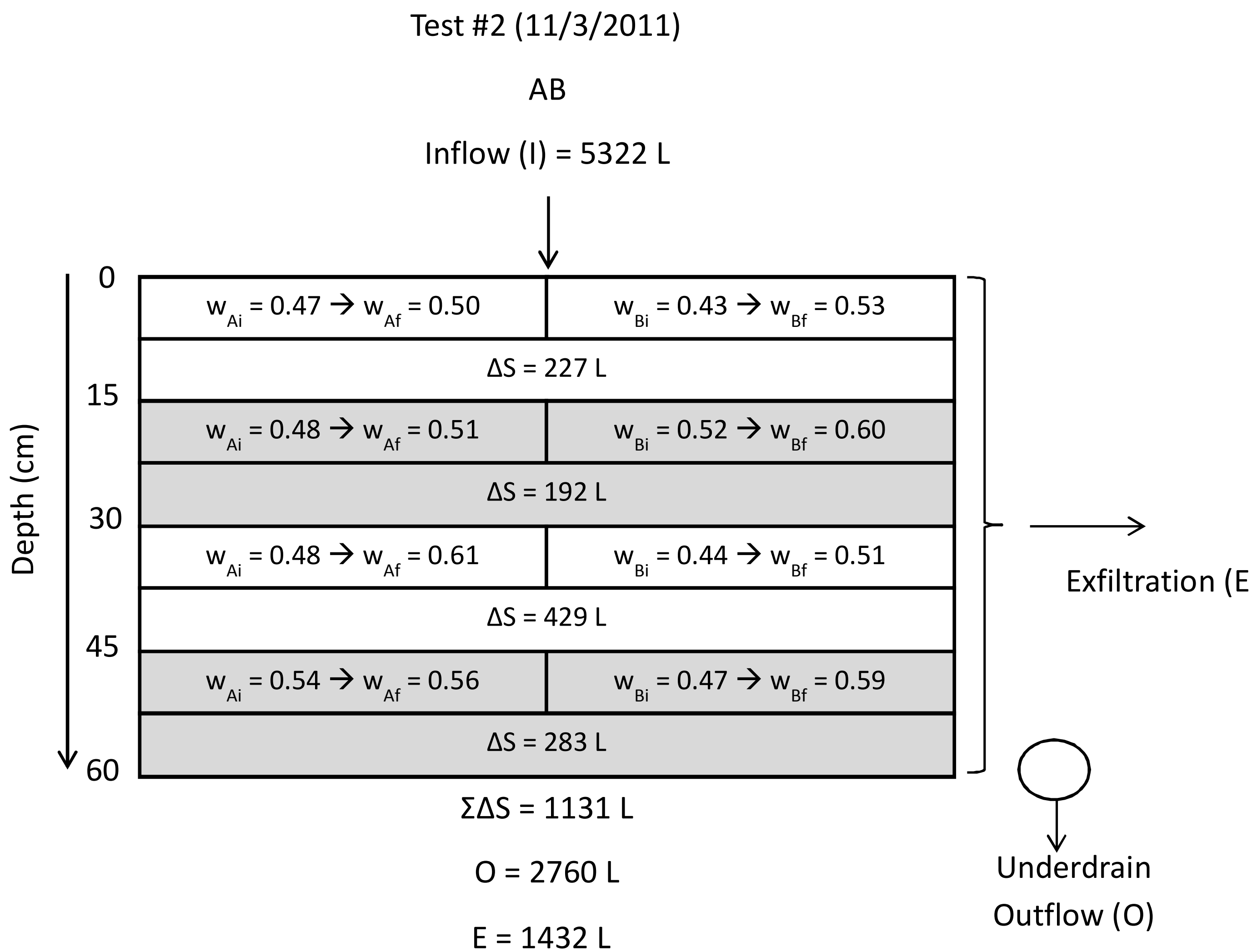
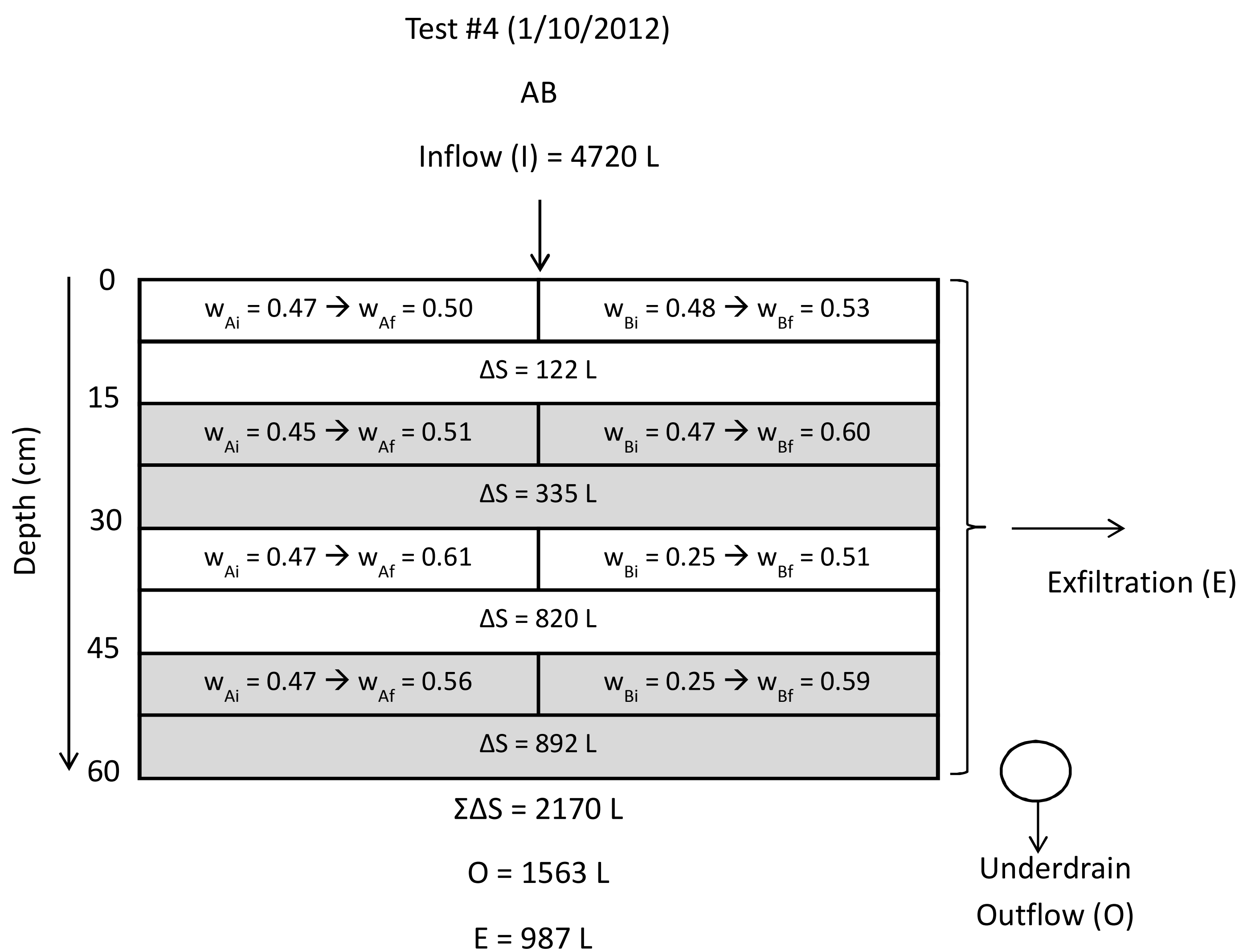
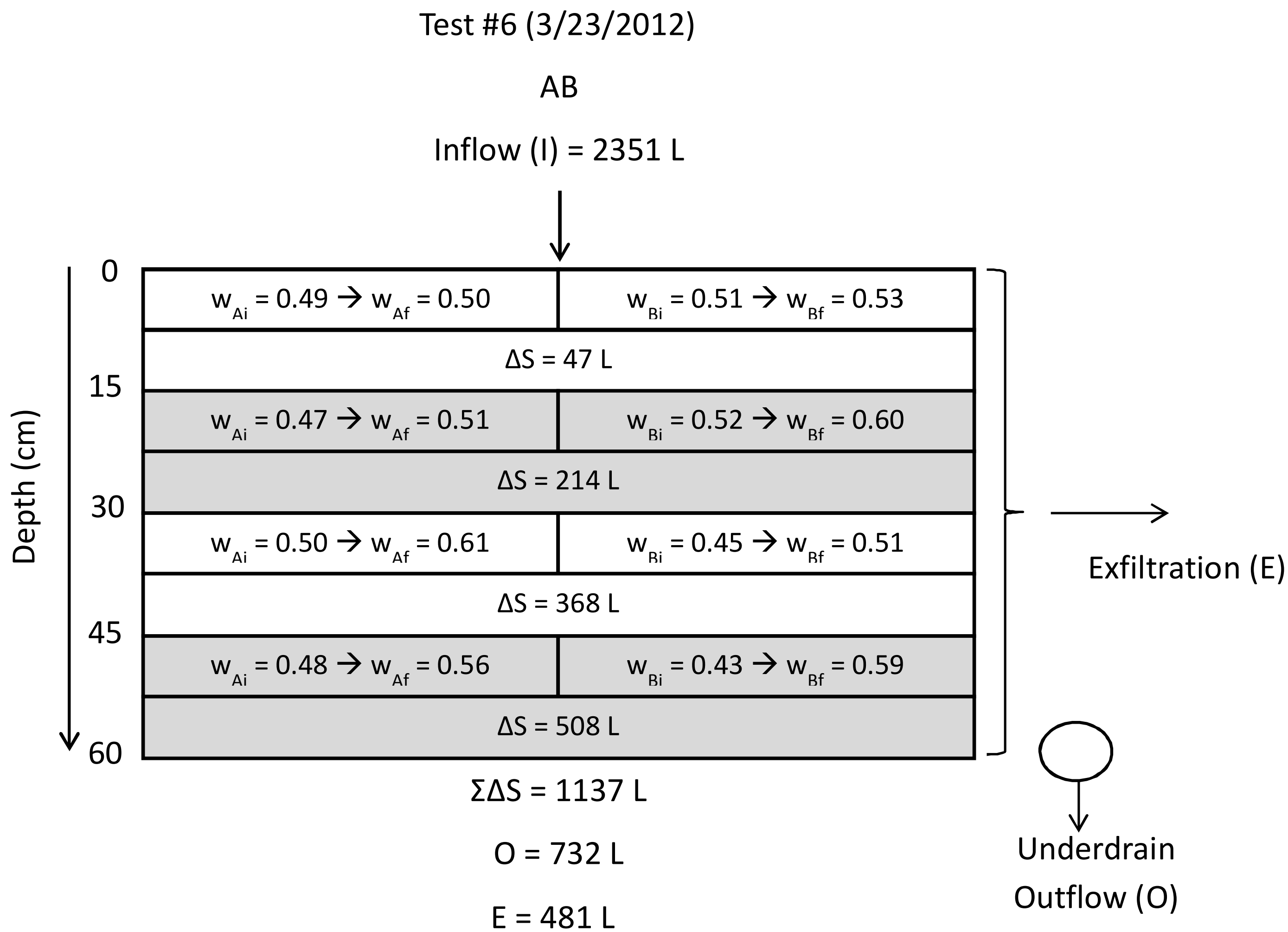
Appendix A: Detailed water balances of 5 simulated rainfall events




Test #2 (11/3/2011)
AB
Inflow (I) = 5322 L
Depth (cm)
0
15
30
45
60
w_{Ai} = 0.47 → w_{Af} = 0.50
w_{Bi} = 0.43 → w_{Bf} = 0.53
ΔS = 227 L
w_{Ai} = 0.48 → w_{Af} = 0.51
w_{Bi} = 0.52 → w_{Bf} = 0.60
ΔS = 192 L
w_{Ai} = 0.48 → w_{Af} = 0.61
w_{Bi} = 0.44 → w_{Bf} = 0.51
ΔS = 429 L
w_{Ai} = 0.54 → w_{Af} = 0.56
w_{Bi} = 0.47 → w_{Bf} = 0.59
ΔS = 283 L
ΣΔS = 1131 L
O = 2760 L
E = 1432 L
Exfiltration (E)
Underdrain
Outflow (O)

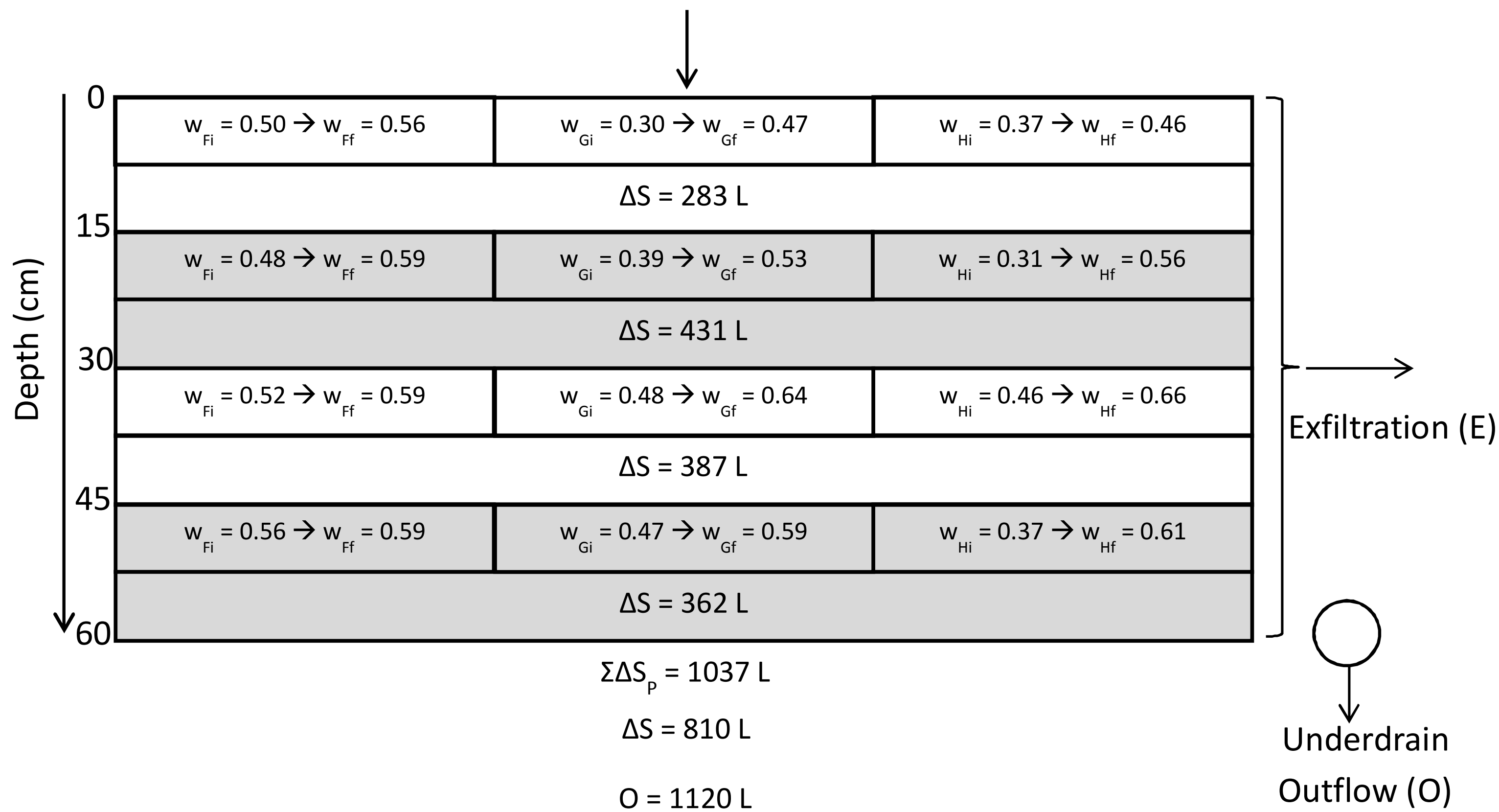

Test #4 (1/10/2012)
AB
Inflow (I) = 4720 L
Depth (cm)
0
15
30
45
60
w_{Ai} = 0.47 → w_{Af} = 0.50
w_{Bi} = 0.48 → w_{Bf} = 0.53
ΔS = 122 L
w_{Ai} = 0.45 → w_{Af} = 0.51
w_{Bi} = 0.47 → w_{Bf} = 0.60
ΔS = 335 L
w_{Ai} = 0.47 → w_{Af} = 0.61
w_{Bi} = 0.25 → w_{Bf} = 0.51
ΔS = 820 L
w_{Ai} = 0.47 → w_{Af} = 0.56
w_{Bi} = 0.25 → w_{Bf} = 0.59
ΔS = 892 L
ΣΔS = 2170 L
O = 1563 L
E = 987 L
Exfiltration (E)
Underdrain
Outflow (O)


Test #6 (3/23/2012)
AB
Inflow (I) = 2351 L
Depth (cm)
0
15
30
45
60
$w_{Ai} = 0.49 \rightarrow w_{Af} = 0.50$
$w_{Bi} = 0.51 \rightarrow w_{Bf} = 0.53$
$\Delta S = 47$ L
$w_{Ai} = 0.47 \rightarrow w_{Af} = 0.51$
$w_{Bi} = 0.52 \rightarrow w_{Bf} = 0.60$
$\Delta S = 214$ L
$w_{Ai} = 0.50 \rightarrow w_{Af} = 0.61$
$w_{Bi} = 0.45 \rightarrow w_{Bf} = 0.51$
$\Delta S = 368$ L
$w_{Ai} = 0.48 \rightarrow w_{Af} = 0.56$
$w_{Bi} = 0.43 \rightarrow w_{Bf} = 0.59$
$\Delta S = 508$ L
$\Sigma\Delta S = 1137$ L
O = 732 L
E = 481 L
Exfiltration (E)
Underdrain
Outflow (O)

Test #9 (7/11/2011)

FGH

Inflow (I) = 1931 L



$\Sigma\Delta S_P$ = 1037 L

ΔS = 810 L

O = 1120 L

E = 0 L