Evaluation of Seasonal and Large Storm Runoff Volume Capture of an Infiltration Green Infrastructure System

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Abstract: Green infrastructure, including stormwater control measures (SCMs), meant to reduce runoff volumes are typically designed for smaller, frequently occurring events (e.g., 2.5 cm or the 2-year, 24 h event), and their performance are not always considered for larger, more infrequent extreme event management. However, even during larger rainfall events, a SCM is still capturing at least the design rainfall and reducing runoff volume. Further, if a SCM relies on infiltration as its primary volume reduction strategy, infiltration continues throughout the rainfall event indicating that SCMs can be considered in flood mitigation strategies. This phenomenon of greater than designed runoff volume removal has been noted in several infiltrating SCMs, and the present work uses the Villanova green infrastructure site comprising an infiltration trench with pretreatment (i.e., linear vegetated SCMs) designed for the 2.5 cm rainfall event as a basis for discussion. The analysis focuses on the infiltration trench volume capture and includes the effect of storm volume, duration, intensity, and antecedent dry time. Seasonally, infiltration rates within the infiltration trench were shown to vary with temperature in the lower ponding depths. While there was some decrease in infiltration rates in the lowest depth increment (0–0.3 m) in the systems' third winter and spring seasons, there was a general increase in infiltration rates over the course of the study period demonstrating the infiltrating SCMs' ability to be a reliable stormwater management solution. With regards to large storm event performance, the results from 2 years of monitoring the infiltration SCM system have been quite impressive. The system has consistently met the volume reduction design goals and usually exceeded them by significantly contributing to storm runoff mitigation during large extreme events. The infiltration SCM system captured and removed at least 59% of the volume of every storm event analyzed from July 2012 through June 2014, with an average of 93% capture for events greater than the design volume of 2.5 cm. Furthermore, there were 159 storm events totaling 259 cm of rainfall during the study period. Given the drainage area loading, approximately 2,365 m^3 of rainfall entered the linear vegetated component, with approximately 420 m^3 (18%) reaching the infiltration trench and only 103 m^3 (4%) of rainfall determined to overflow from the system. These performance results demonstrate that infiltration SCMs can reduce significant volumes of runoff during larger events and that new design strategies are needed to account for their performance. **DOI:** **10.1061/(ASCE)HE.1943-5584.0001257.**

Introduction

Green infrastructure, such as infiltration stormwater control measures (SCMs), are being increasingly used to mitigate the stresses that development places on urban watersheds. Agencies around the United States are developing and implementing SCMs to better reduce stormwater runoff volumes, peak flows, and pollutant loads to receiving water bodies [National Research Council (NRC) 2009; Water Environment Federation (WEF) 2012]. For example, Philadelphia is implementing a long-term control plan to primarily use SCMs to manage stormwater volume and reduce combined sewer overflows [Philadelphia Water Department (PWD) 2011]. As part of any municipal-wide or watershed-wide stormwater management plan, optimal system performance while minimizing cost is desired. Roadblocks to extensive SCM implementation are uncertainty of benefits during large, extreme events, which creates low benefit to cost relationships (Weiss et al. 2005).

The shift to SCMs as a stormwater management technique was in response to the understanding that small, frequent storms can cause environmental damage and that large events were not the only event that should be managed (Prince George's County 1999). Stormwater control measures are designed, generally, to control smaller storms—typically less than 2.5–3.8 cm of rainfall over a drainage area (NRC 2009). With the focus on smaller events, the usefulness of SCMs is commonly thought to be inconsequential for larger and extreme events (EPA 2014). However, the results of the present research indicate that the benefits of SCMs can be substantial during large events and annually, which has also been seen in other infiltrating SCMs. Lord et al. (2013) showed that a bioinfiltration system removed 50% of the runoff volume for storms that exceeded the design rainfall from over a decade of monitoring data; similar results were seen in Davis (2008). Further, Horst et al. (2011) showed that a pervious concrete infiltration basin captured an average of 91% of total monthly rainfall over a 3-year monitoring period, including during months with higher than average rainfall. Even older and severely undersized infiltrating SCMs have been shown to outperform designed volume capture early in their lifespan (Bergman et al. 2011; Emerson et al. 2010). Part of the observed outperformance is because the design focus is only on small events and SCMs are not considered to contribute to management for larger events. For example, the Philadelphia area receives

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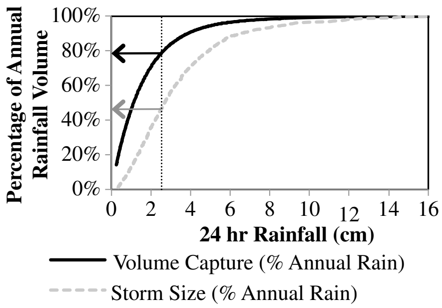

Fig. 1. Storm size by percentage of the annual rainfall volume (gray dotted line) and volume captured by percentage of the annual rainfall volume (thick black line); the thin black line indicates the 2.5 cm (1 in.) design storm; the gray arrow shows that slightly less than 50% of the annual rainfalls are less than 2.5 cm; the black arrow shows that nearly 80% of the total annual rainfall volume would be captured if the first 2.5 cm of rain was retained by a SCM (data from National Climatic Data Center 2015)

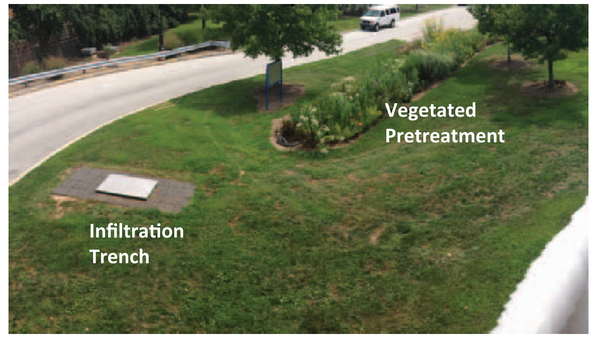

Fig. 2. Picture of the Villanova infiltration trench with vegetated pretreatment; runoff moves from the vegetated pretreatment to the infiltration trench via an underground pipe (images by C. Lewellyn)

on average 97 cm of rainfall annually (PWD 2013). Events that are 2.5 cm or less account for approximately 50% of the annual events (Fig. 1, dashed gray line). From a volume perspective, if the first 2.5 cm of a large storm is absorbed by a SCM, only the volume above 2.5 cm will discharge to the receiving body. In this case, nearly 80% of annual rainfall volume is captured for a SCM designed to hold 2.5 cm (Fig. 1, black line). Another reason for outperformance is because typical assessment of SCMs' volumetric performance sometimes neglects or minimizes the effect of runoff volume reduction as a result of continual infiltration [e.g., West Virginia Department of Environmental Protection (WVDEP) 2012]. Therefore, the designed performance of certain SCMs generally underestimates volume reduction during storm events. Understanding the extent of SCM performance for the full range of rainfall volumes and intensities is necessary for urban areas to maximize stormwater volume reduction benefits to develop resilient and cost-effective stormwater management.

The goal of the present work was to assess volume reduction performance of an infiltration trench system and evaluate the pattern of rainfall events that caused overflow. Infiltration trenches (ITs) provide significant volume reduction, peak attenuation and groundwater recharge through storage (Shaver 1986). This paper illustrates the performance of an IT over a 2-year study period based on infiltration and overflow rates as a basis of discussion for demonstrating that performance for an infiltration SCM during larger events significantly contributes to high volume reduction. Additionally, this paper shows how factors such as rainfall intensity, antecedent soil moisture, and seasonal variation in temperature affected a ITs performance.

Methods

Infiltration Trench Description

Infiltration trenches are one type of SCM that provide runoff volume reduction (Shaver 1986) and improved runoff quality as a result of sorption and filtration methods (Akan 2002; Birch et al. 2005; Emerson et al. 2010; Siriwardene et al. 2007; Scholz and Yazdi 2009). Infiltration trenches are often utilized in urban stormwater management, as they are compact and can readily fit into an urban landscape. In fall 2011, an infiltration trench with vegetated pretreatment was constructed at Villanova University in southeastern Pennsylvania; it started to accept runoff in spring 2012. A vegetated swale and two rain gardens in series served as pretreatment to the IT and reduced stormwater runoff volume reaching the IT with the intent to increase the IT's longevity and reduce maintenance needs (Fig. 2). The site has a 930 m^2 (0.2 acre), 100% impervious drainage area (upper level of a nearby parking garage), and the entire system (IT and vegetated portion) was designed according to Pennsylvania design recommendations [Pennsylvania Department of Environmental Protection (PADEP) 2006] for a 2.5 cm storm with a 7.5:1 drainage area to SCM area ratio. The Pennsylvania design recommendations are similar to several other state reference manuals, which recommend a maximum drainage area for an IT between 2 and 5 acres [Maryland Department of the Environment (MDE) 2009; Minnesota Stormwater Steering Committee (MSSC) 2008; Center for Watershed Protection (CWP) 2015]. The system was monitored for volume capture performance from July 2012 through June 2014.

Soil samples were collected during excavation and analyzed using a wash sieve analysis and hydrometer test [ASTM D422-63 (ASTM 2007)]. The underlying IT soil is 3% gravel, 61% sand, 28% silt, and 8% clay. The in situ soil according to the Unified Soil Classification System is ML (i.e., silt with low plasticity), and the estimated saturated hydraulic conductivity is 2.3 cm/h (range of 1.0–6.9 cm/h (Rawls et al. 1998). The 5.4×1.3 m deep IT was formed with R-Tanks (95% porosity, ACF Environmental, Wilmington, Delaware) and surrounded by geotextile and crushed stone; the IT was designed to store 0.8 cm of a 2.5 cm storm. There is no underdrain or controlled overflow system. The IT is covered with a metal door for experimental and maintenance access (0.6 m^2), which is surrounded by Xeripave (LLC, Vancouver, Washington) pervious pavers (4.8 $m^2 \times 0.05$ m) that allow flow out through the top when the IT is filled. The pavers are surrounded by grass and overflow runs overland into a street inlet.

A vegetated swale and two rain gardens were constructed upstream of the IT to provide pretreatment of stormwater runoff from the drainage area. The 40 m long vegetated swale is designed to capture the first 0.7 cm of runoff. Following the vegetated swale, there are two oval-shaped rain gardens (4 m long, 1 m bottom width, and 2 m top width) in series designed to capture 1 cm of runoff. The vegetated swale and rain gardens were designed with engineered media (85% sand, 10% fines, and 5% organics) and have high infiltrating capacity. The volume capture calculated for each SCM is defined as the surface storage volume [design ponding depth by SCM bed area; Hunt and White 2001; North Carolina Department of Environment and Natural Resources (NCDENR) 2009] relative to the surface storage volume the soil storage is minimal in this system.

Water Depth Sampling and Analysis

A Campbell Scientific (Logan, Utah) pressure transducer (CS450-L) rated up to 5.1 m with ±0.1% accuracy and field calibrated quarterly was used to record water depth and temperature in the IT. Rainfall was measured on site with an American Sigma (Hach, Loveland, Colorado) tipping bucket rain gauge Model 2149 that measures 0.025 cm of rainfall per bucket tip at 0.5% accuracy for intensities up to 1.3 cm/h. Rainfall events were considered once measured rainfall was greater than 0.13 cm (0.05 in), as 0.13 cm was considered the initial abstraction for the drainage area and rainfall less than this amount rarely generates meaningful runoff (Fassman-Beck et al. 2013). A period of at least 6 h between measurable rainfall was chosen to differentiate events; therefore, it was possible to have multiple storm events in a single day (Driscoll et al. 1989). Event duration was defined from rainfall start to finish (Geosyntec Consultants and Wright Water Engineers 2009). Rainfall intensity was calculated from the measured rainfall depth for the entire event duration. Antecedent dry time was calculated from the end of an event to the start of the next event. A temperature sensor (CS450-L) was placed at the upstream end of the vegetated pretreatment and air temperature was recorded by a Campbell Scientific Model 107 temperature sensor. All measurement devices were connected to a Campbell Scientific datalogger (CR1000) and data was recorded at 1-min intervals.

Barraud et al. (2014), Emerson et al. (2010), and Gonzalez-Merchan et al. (2012) found that infiltration is substantial through the sidewalls in addition to the bottom of an IT. The recession rate (i.e., how quickly the water depth in the IT dropped) was used to calculate the infiltration rate over the entire IT surface area that included the bottom (5.4 m^2) and sides (peak depth for each incremental depth range). Infiltration rates in the IT were determined for different depths: 0–0.3 m, 0.3–0.6 m, 0.6–0.9, 0.9–1.3 m (e.g., Fig. 3). For multiple peak storms, a depth increment may have several infiltration rates that are averaged. Emerson and Traver (2008) showed a correlation between infiltration rate and temperature based on water viscosity's dependence on temperature. A Student t-test ($p = 0.05$) was applied to compare observed infiltration rates to the average temperature for each event (Ayyub and McCuen 2003).

Runoff volume (V_{runoff}) was calculated using the small storm hydrology method (Pitt 1999) for a large, completely impervious drainage area for each rainfall event. The runoff volume into the IT (V_{IT}) after the vegetated pretreatment was calculated as height of peak ponding multiplied by the IT bottom area and the porosity of the R-tanks [Eq. (1)]

$$V_{\mathrm{IT}} = 0.95(y_{\mathrm{peak}} - y_o)A \tag{1}$$

where y_{peak} is the peak depth reached in the infiltration trench, y_o is the height of the water in the IT when runoff first enters, and A is the IT bottom area (5.4 m^2).

Periods of IT overflow through the pavers were observed, although not measured directly. Overflow was considered to occur when the measured IT water depth remained constant at 1.3 m (i.e., the top of the R-Tanks) and higher. Overflow was calculated in two ways to develop a range for possible overflow values. To conservatively estimate the overflow volume ($V_{\mathrm{over,1}}$), the rate of peak rise was multiplied by the duration of elevated ponding (t_{over}) and the paver area ($A_{\mathrm{pavers}} = 4.8$ m^2) [Eq. (2)]

$$V_{\mathrm{over,1}} = \left(\frac{y_{\mathrm{peak}} - y_o}{t_{\mathrm{peak}} - t_o}\right) t_{\mathrm{over}} A_{\mathrm{pavers}} \tag{2}$$

For a less conservative overflow estimate, volume of infiltration (V_{inf}) was calculated for each overflow event to account for infiltration occurring during the storm event, as well as runoff that reenters the IT after overflowing through the pervious paver. The V_{inf} was calculated multiplying the infiltration rate from the upper depth increment of the IT ($I_{0.9\text{–}1.3}$), t_{over} and the total surface area available for infiltration (IT sidewalls and bottom, $A_{\mathrm{IT,total}}$ 17.9 m^2) [Eq. (3)]

$$V_{\mathrm{inf}} = I_{0.9\text{–}1.3} t_{\mathrm{over}} A_{\mathrm{IT,total}} \tag{3}$$

The V_{inf} was subtracted from the V_{over} estimate [Eq. (2)] to yield a less conservative estimate of $V_{\mathrm{over,2}}$. The total volume reaching the IT ($V_{\mathrm{IT,total}}$) is the sum of V_{IT} and $V_{\mathrm{over,1}}$ based on the more conservative estimate overflow, and the sum of V_{IT}, $V_{\mathrm{over,2}}$, and V_{inf} based on the less conservative estimate. In both overflow scenarios, $V_{\mathrm{IT,total}}$ is the same. The volume captured by the system (V_{sys}) is

$$V_{\mathrm{sys}} = V_{\mathrm{runoff}} - V_{\mathrm{over}} \tag{4}$$

which was computed for both $V_{\mathrm{over,1}}$ and $V_{\mathrm{over,2}}$.

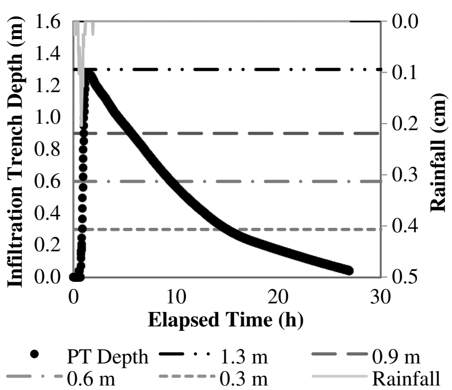

Fig. 3. An example of the response in the IT due to a 3.6 cm rainfall event (light gray, solid line), which came close to the top of the IT but did not overtop; the observed depth (black dots) was used to calculate the infiltration rates at four different depth ranges (0–0.3 m, 0.3–0.6 m, 0.6–0.9 m, and 0.9–1.3 m); the dashed lines indicate the upper boundary of each range

Results and Discussion

Seasonal Performance

Emerson and Traver (2008) showed that infiltration rates can vary substantially with temperature as the viscosity of water is temperature dependent. It is interesting to examine runoff temperature as it moves through the IT system (Fig. 4). The air and runoff temperatures are quite variable through seasonal changes, with a range over 30°C. It appears runoff entering the vegetated pretreatment is generally warmer than the air temperature because the surface of the parking lot warms stormwater runoff (note, the trend line is above the 1:1 line in Fig. 4). Likewise, the temperature of the runoff entering the IT appears to be slightly greater than the air temperature. However, both runoff temperatures were statistically similar to each other (as noted by the trend lines being nearly the same) and to the air temperature, indicating that the pretreatment does not provide significant temperature buffering and infiltration rates in the IT will vary greatly as seasons change.

The infiltration rate, which dictates the capture volume, varies with temperature and IT ponding depth throughout the storm

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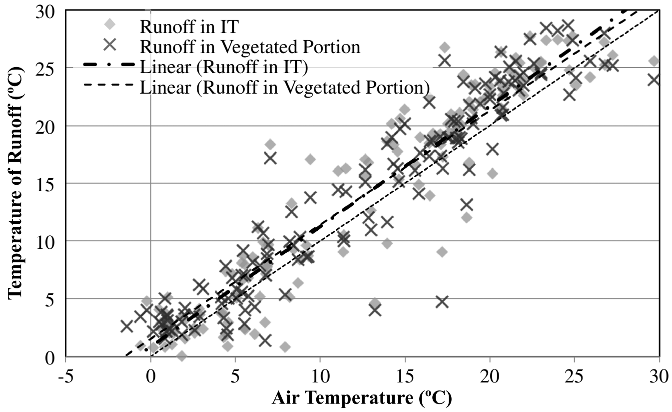

Fig. 4. Comparisons of temperature of runoff to the vegetated pretreatment (dark gray *x*) and to the IT (light gray diamond) to air temperature.; the linear regression for each data set is represented by the thick dot-dash line (to IT) and the thin dotted line (to vegetated pretreatment); the thin dotted line represents a 1:1 relationship

(Fig. 5). Braga et al. (2007), Emerson and Traver (2008), Emerson et al. (2010), and Horst et al. (2011) found similar seasonal variations in SCM infiltration rates. There was seasonal variability in infiltration rates at each depth related to temperature—higher temperatures enable higher rates (Fig. 6). The infiltration rate fluctuates over a wider range with warmer temperatures (>15°C) than colder temperatures; there were both high and relatively low infiltration rates with warm temperatures. A Student t-test ($p = 0.05$) shows that the infiltration rates in the higher depths (0.9–1.3 m, 0.6–0.9 m) were not significantly dependent on temperature (Table 1). Infiltration rates at lower depths (0–0.3 m, 0.3–0.6 m) were significantly dependent on temperature. The infiltration at the bottom of the IT may be more dependent on temperature, rather than the limited area available for infiltration and lower head [Fig. 6(d)], exampled by

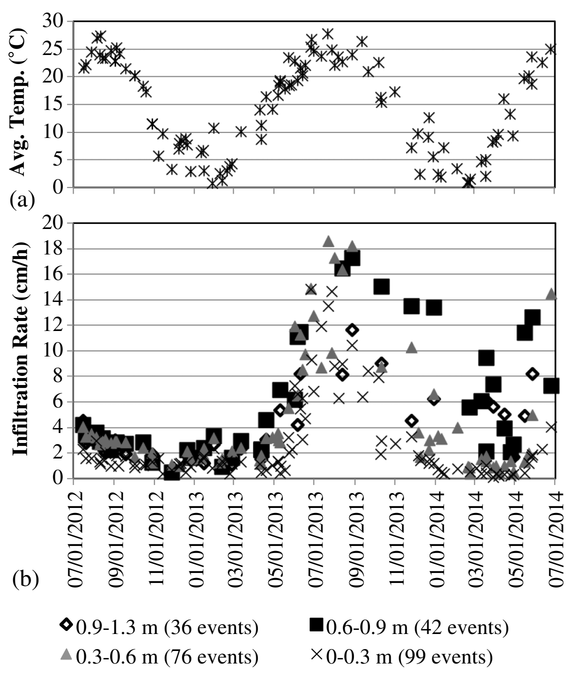

Fig. 5. Temperature (a) and maximum infiltration rates (b) in the IT at each depth range throughout the study period

several cases where infiltration rates are greater for shallower ponding depths than the deeper depths. The maximum infiltration rate for the 0–0.3 m range is 14.8 cm/h [Fig. 6(d)] and only 10.3 cm/h for the 0.9–1.3 m range [Fig. 6(a)].

Generally, a reduction in infiltrating surface area and a decrease in head results in lower infiltration rates. When the IT is completely full (1.3 m) runoff ponds in the upstream rain garden. As water continues to infiltrate, runoff continues to flow from the rain garden into the IT resulting in what appears to be lower infiltration rates at deeper depths. It is evident that infiltration rates are dependent on the ponded level in the IT (Table 2). Infiltration rates were highest for the middle two depth ranges (0.3–0.6 m and 0.6–0.9 m) and these rates were statistically similar. The middle depth infiltration rates were not statistically different than the highest range (0.9–1.3 m), but were statistically different than the lowest depth range (0–0.3 m). A decrease in the water level not only decreases the surface area, but decreases the head of water and resulting pressure in the IT. Based on findings from Emerson et al. (2010), side wall infiltration is substantial and therefore when the IT is full infiltration appears to be using all surfaces to infiltrate water out of the IT, but the sides are no longer a substantially large surface when the water depth drops below 0.3 m.

Infiltration rates for the upper depth increment have increased when looking at monthly averages from year to year where the water in the IT reached above 0.9 m (Fig. 7). Furthermore, infiltration rates in the 0.6–0.9 m depth increment have increased based on monthly average from year to year for every month except April. The average infiltration rate for April 2013 was 3.03 cm/h compared with 2.89 cm/h in April 2014 and were determined to be statistically different. Infiltration rates for the lowest depth range in the IT are variable from month to month and show a decrease in performance from January through June from 2013 to 2014. Infiltration rates at the lowest depth increment during January, March, April, and June were statistically different from 2013 to 2014. The decrease in infiltration rates during this time period may have been a result of storm size, antecedent dry time, or lower 2014 than 2013 temperatures (note, 2014 winter and spring temperatures were significantly lower than 2013 temperatures, $p = 0.10$) at the site and not clogging. Further, settling of soil surrounding the IT may have resulted in more compacted soil with less infiltration potential. Small storm events would result in less runoff entering the IT and lower infiltration rates below 0.3 m due to low head. Short time periods between rainfall events may have resulted in reduced infiltration capacity due to elevated soil moisture conditions. Infiltration models, such as the Natural Resource Conservation Service curve number method and the Green-Ampt method, are dependent on antecedent soil moisture conditions (Fennessey and Hawkins 2001; Rawls et al. 1983).

While infiltration rates at the IT vary based on season and antecedent dry time and range from 0.12 to 18.6 cm/h, overall the average infiltration rates at the IT (Table 2) are high enough at all depths to be considered effective by EPA standards (at least 1.27 cm/h; Clar et al. 2004), and the vegetative system provides some pretreatment so there is no immediate concern of decreasing performance. Additionally, the average infiltration rate in the IT exceeds the minimum requirements listed in various state manuals [e.g., the Pennsylvania best practices manual (PADEP 2006) states that a rate of 0.64 cm/h is required for infiltrating SCMs in a sandy loam; the Maryland manual suggests a rate of at least 1.33 cm/h (MDE 2009); the Minnesota manual suggests a minimum 0.51 cm/h (MSSC 2008)]. Average infiltration rates for all depth increments are greater than the average saturated hydraulic conductivity for the soil surrounding the IT (2.3 cm/h, Rawls et al. 1998).

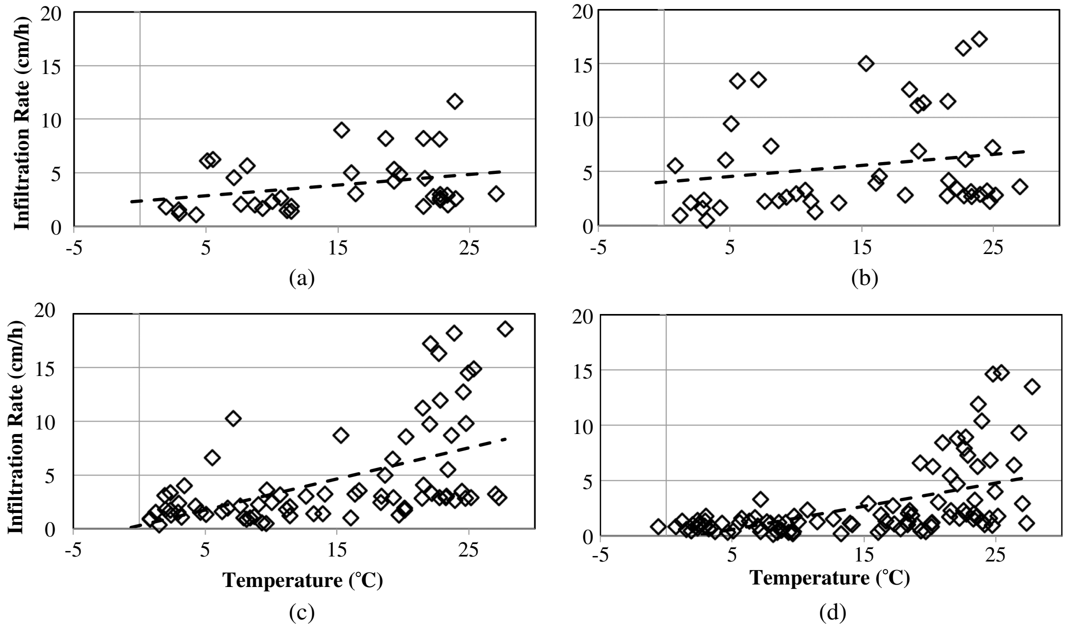

Fig. 6. Temperature effect on infiltration rate at the IT for each depth range: (a) 0.9–1.3 m; (b) 0.6–0.9 m; (c) 0.3–0.6 m; (d) 0–0.3 m; the dashed line represents the linear regression for each data set

Table 1. Slope (m), R-Squared, Correlation Coefficients, and t-Test Results for Comparing Infiltration Rates to Temperature at Each Ponding Depth Range

Infiltration versus temperature							
Range (m)	m	R^2	Correlation	n	t-critical ($p = 0.05$)	$t_{(n-2)}$	Significant ?
0.9–1.3	0.11	0.09	0.30	36	2.06	1.86	No
0.6–0.9	0.08	0.02	0.15	42	2.03	0.97	No
0.3–0.6	**0.29**	**0.29**	**0.54**	**76**	**1.99**	**5.45**	**Yes**
0–0.3	**0.21**	**0.29**	**0.54**	**99**	**1.99**	**6.27**	**Yes**

Note: Bold indicates statistical significance.

Large Event Performance

Over the 24-month study period there were 159 events, with 101 events that produced enough runoff to reach the IT, and 20 events that overflowed [Fig. 8(a)]. While there were events smaller than the design rain of 1.8 cm that reached the IT due to high rainfall intensity [Fig. 8(b)], seasonal variation in infiltration rates, and antecedent dry time, the vegetated pretreatment prevented 53% of storms from reaching the IT, which will extend the longevity of the IT by inhibiting influent sediments from entering. When looking at Fig. 1 (black line), 53% corresponds to approximately 1.2 cm of annual rainfall volumes in the Philadelphia area. It should be noted that the contribution to the IT for 55% of small events (<1.8 cm) was minor (V_{IT}/V_{sys} below 0.1). The smallest rainfall event to reach the IT but not overflow was 0.2 cm; this event occurred on December 18, 2012 when the temperature at the IT was 6°C, with a peak ponding depth of 0.3 m, a relatively high average rainfall intensity of 0.7 cm/h, and a relatively low maximum infiltration rate of 0.9 cm/h, compared with a reference saturated hydraulic conductivity ranging between 1.0 and 6.9 cm/h (Rawls et al. 1998). Rainfall events as small as 1 cm generated overflow (April 12, 2013), but this was a higher intensity event (0.7 cm/h) that had only 7.6 h to recover since the previous rain event of 1.4 cm. Conversely, there are large rainfall events (e.g., November 26, 2013 had 9.0 cm, but a low average intensity event (0.30 cm/h) and an 8-day antecedent dry period) where approximately 95% of the total volume was captured by the system. When viewed as a system, there was not one specific rainfall depth that automatically triggered overflow, and of the events with overflow 89% were greater than the design capture volume (2.5 cm, Table 3).

As a system, the strengths of the components are complementary. During an overflow event, infiltration is still occurring so storage is simultaneously being recovered as the IT is overflowing. Typically only a short duration of the event had overflow occur (Fig. 9). Superstorm Sandy (October 28–29, 2012) yielded 11 cm of rainfall ($V_{runoff} = 101\ m^3$) over 67 h; a large volume event but low average intensity (0.065 cm/h). The volume ponding and infiltrating in the IT (V_{IT}) was 8 m^3. There was overflow for approximately 6 h with an estimated overflow volume (V_{over}) of between

Table 2. Infiltration Rate Statistics (in cm/h) and Statistical Comparison of Depth Ranges of Infiltration Rates

						P-value			
Range (m)	Mean	Standard deviation	Median	Q1	Q3	0.9–1.3	0.6–0.9	0.3–0.6	0–0.3
0.9–1.3	4.01	2.79	2.82	1.95	5.42	—	0.14	0.54	**0.02**
0.6–0.9	5.27	4.52	3.18	2.32	6.74	—	—	0.34	**0.00**
0.3–0.6	4.44	4.59	2.87	1.54	4.26	—	—	—	**0.00**
0–0.3	2.66	3.27	1.34	0.88	2.54	—	—	—	—

Note: Bold values indicate statistical significance.

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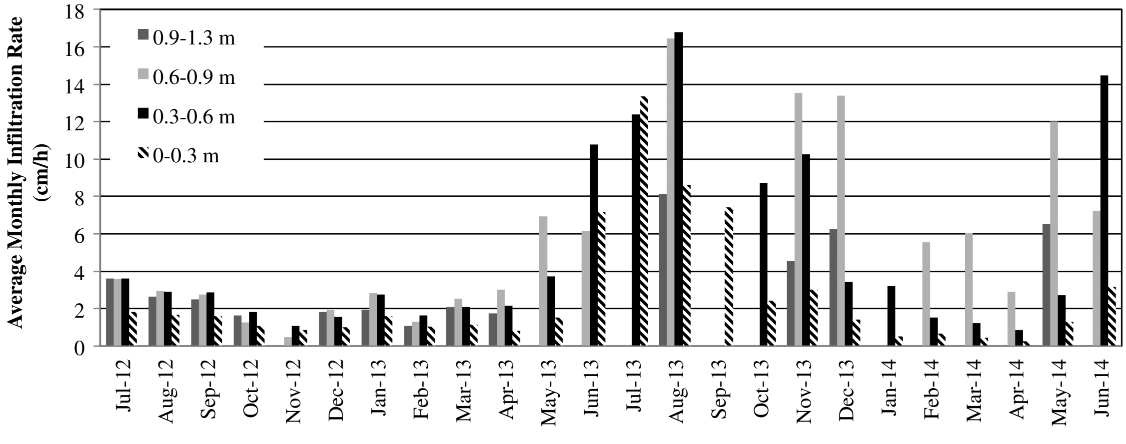

Fig. 7. Monthly averages of infiltration rates at each depth range throughout the study period

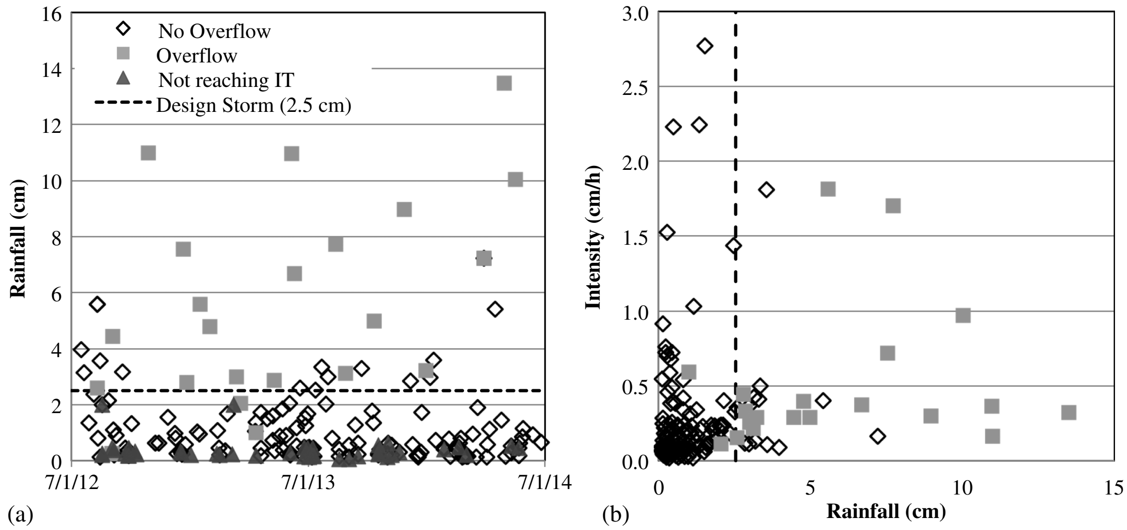

Fig. 8. (a) All rain events during the study period, delineated by events reaching the IT and overflowing; (b) events reaching the IT that did and did not overflow with rainfall depth and intensity; the design event for the entire system is 2.5 cm (black dashed line) and the design event to reach the IT is 1.8 cm

1 and 3 m^3. The $V_{IT,total}$ was 11 m^3 and the volume captured by the system (V_{sys}) was between 98 and 100 m^3, yielding a total capture between 97 and 99%. Superstorm Sandy was not an outlier; there were several relatively large events that triggered some overflow, but the system was able to capture the majority of the runoff volume (Fig. 10), far exceeding the expected capture. The expected capture is 100% of all events less than 2.5 cm and the first 2.5 cm of any event greater than 2.5 cm. For example, the system is expected to

Table 3. Rainfall Distribution for Overflow Events

Rainfall amount (cm)	Percentage of occurrences of overflow events (%)
<2.5	10.5
2.5–3.8	31.6
3.8–5	10.5
5–7.5	15.8
7.5–10	10.5
>10	21.1

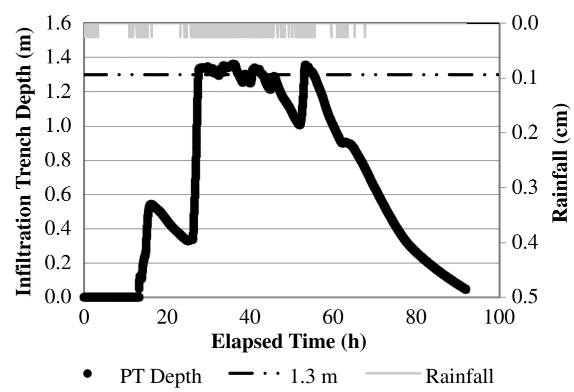

Fig. 9. Superstorm Sandy IT depth and rainfall; there was a large rainfall volume (11 cm), but low intensity as there was no 1-min rainfall observation greater than 0.03 cm; the event was 67 h long, but overflow was observed for only two periods of 5 and 1 h, where the depth is greater than 1.3 m

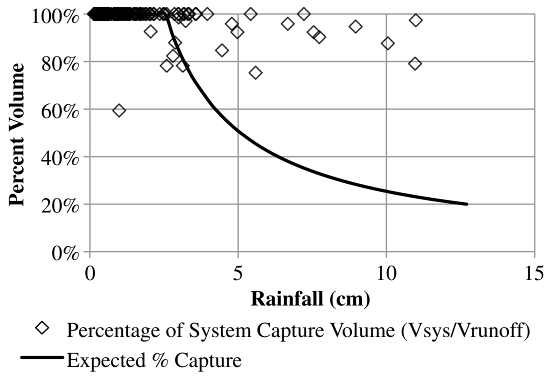

Fig. 10. Total system performance based on system capture volume over total runoff; expected system percent capture (solid black line) is shown as a basis for comparison; overflow volumes were calculated assuming that no infiltration occurs during overflow [Eq. (2)]; to the right of the solid black line are events that captured more than the design

capture 50% of a 5 cm event. For all observed events greater than 2.5 cm, there was an observed average capture of 93%. The worst performing event 59% volume capture was the aforementioned April 12, 2013 event.

The analysis shows the IT system as a whole usually performs better than what would be expected from a volume approach during large storm events. The complementary strengths of the SCMs in the system has thus far provided resiliency during large storm events by continuing to capture larger volumes than expected. While this IT is just one example of how infiltrating SCMs continue to recover storage capacity during a large rainfall event via infiltration, the processes can be conveyed to any infiltrating SCM.

Summary

The goal of this research was to assess volume capture performance of an infiltrating green infrastructure system and investigate the pattern of rainfall events that caused overflow. Seasonal and large storm performance was evaluated over a 2-year study period. Infiltration rates in the infiltration trench tend to vary with ponded depth and temperature with higher rates at the middepths and higher temperatures (>15°C). Although infiltration rates in the lowest depth increment have decreased through the first half of 2014, there was a general increase in infiltration rates over the course of the study period. The infiltration trench system was designed for 2.5 cm of total volume control based on the dimensions of the vegetated swale, rain gardens, and IT. The system has been able to capture and remove a significantly greater amount of runoff volume. While periods of overflow have been observed, the IT system's ability to capture, retain, and infiltrate runoff from a 100% impervious area has shown its resiliency during large storms. The IT overflowed during 20 of the 159 analyzed storms over the period of study, which is less than the 32 storms greater than 2.5 cm that occurred and were expected to cause overflow based on the design volume capacity of the system. Capture performance based on the total volume into the system and overflow volume not accounting for infiltration during rain events was a minimum of 59%, with an average of 93%, meaning that the annual volume of runoff from almost every storm was completely captured. Of the storms analyzed, a total of 2,365 m^3 entered the system (259 cm of rain over the entire drainage area) and approximately 420 m^3 entered the IT. Between 73 and 103 m^3 of rainfall was determined to overflow from the IT. This infiltration SCM system has proven to be very dynamic in terms of volume capture. Infiltration (recharge) capacity of the system has accounted for significant runoff volume reduction during storm events larger than 2.5 cm. Rainfall characteristics prove to be an important factor in the system performance. High intensity storms were more likely to cause overflow, regardless of total rainfall volume. While the results here are specific to an infiltration trench, given that this IT has similar seasonal performance to other infiltration trench systems (Emerson et al. 2010; Horst et al. 2011), the performance during large events is transferable. Additionally, these findings are applicable to other types of infiltrating SCMs such as bioretention systems and pervious pavements (Braga et al. 2007; Emerson and Traver 2008; Horst et al. 2011; Lord et al. 2013).

Design standards and regulations for SCMs often only consider the volume capacity of a system based on surface storage, which is an underestimate of the observations from this study. Even considering the soil storage capacity in design still underestimates performance as infiltration is a continual process constantly recovering capacity during a storm event as opposed to a finite storage volume. Many SCMs are designed with gravel, sand, or engineered media that have relatively high saturated conductivity which allows for significant infiltration even under saturated conditions. Adjusting design standards and regulations to include infiltration during storm events would properly account for additional volume capture and pollutant reduction for infiltrating SCMs. Approaches would need to consider an individual system's ability to infiltrate and retain runoff during storm events that could lead to more effective SCM design and stormwater management.

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