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Monitoring infiltration rates with time domain reflectometers

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Abstract

The current study determines infiltration rates in six tree boxes located in Louisville, KY, and analyzes the effects of season, age of the tree box, and depth on infiltration. Street and parking lot runoff enter each tree box through a curb cut. Time domain reflectometers (TDRs) were embedded in the tree box media at different depths to continuously monitor volumetric soil moisture content and other parameters. The moisture content recorded by the TDRs was used to calculate steady-state infiltration rates through the media at the TDR location using the Green–Ampt equation. For each rain event, steady-state infiltration rate and drainage rate were separately calculated. For four of the six tree boxes, the steady-state infiltration rate did not vary with depth. However, the drainage rate varied with depth for five of the six tree boxes. Overall, the drainage rate through the entire depth is 1.7 times larger than in the upper layer. During the second year of the study, the steady-state infiltration rate and drainage rate decreased by 20% and 38%, respectively, from the first year. The steady-state infiltration rate and drainage rate vary with seasons. Some correlation ($r = -0.5$) was observed between initial soil moisture content and steady-state infiltration rate.

Keywords

sediments; soil; stormwater

INTRODUCTION

TREE boxes are a green infrastructure stormwater control measure (SCM) designed to collect the first flush of stormwater and treat it before discharging it into the storm sewer system (Rector, Obropta, & Brown, 2013). This bioinfiltration system is an attractive option where there is minimal available space. The structure is often a premanufactured concrete box filled with soil media planted with a tree or shrub. It can also be manufactured with a concrete box that is partially or fully opened to the surrounding native soil and filled with soil media with a tree. Tree boxes provide both water quality and quantity benefits by

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DISCLAIMER

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infiltration and filtration of stormwater runoff, interception, evaporation and uptake of pollutants and nutrients by trees, and associated microbes. Stormwater runoff enters the tree boxes through a curb-inlet opening and flows through a filter media mixture contained in a concrete container. The filter media captures pollutants; those pollutants are then incorporated into the biomass of the plant/tree. Their water quality treatment performance is often equivalent to other bioretention systems, particularly when distributed throughout the area (UNHSC, 2009).

Tree boxes rely primarily on infiltration to reduce runoff volume. Infiltration rates depend on the soil texture, antecedent soil moisture content, rain characteristics, maintenance history, soil compaction during construction, season, age, and other factors (Ahmed, Natarajan, Gulliver, Weiss, & Nieber, 2014a; Ahmed, Nestingen, Nieber, Gulliver, & Hozalski, 2014b; Ahmed, Nieber, & Gulliver, 2015; Emerson & Traver, 2008). Cerda (1999) investigated the seasonal effect on infiltration rates in badland landscapes under Mediterranean climatic conditions of the eastern Iberian Peninsula. Badlands indicates a distinctive landform that develops in semi-arid regions, characterized by a highly dissected topography, very high drainage rates, rapid erosion rates, and a sparse or even nonexistent plant cover (Bryan & Yair, 1982). In Cerda's study, the infiltration rate was measured using simulated rainfall at 17 sites where 12 sites were in sloped areas and five sites were flat. Seasonal changes resulted in larger infiltration rates in summer (1.89 and 1.16 cm/hr) than in winter (1.18 and 0.68 cm/hr), spring (0.38 and 0.87 cm/hr), and autumn (0.41 and 0.83 cm/hr) for slope and pediment, respectively. In summer, the infiltration rate is high due to the influence of cracks and macropore flow during the measurements. Although the infiltration test was always located between cracks, the existence of large voids or subsurface cracks on the badland slopes, which may not be visible on the soil surface, favors the connection of the surface pending to the parent material cracks during the test due to the pending pressure. In an earlier study by the same researcher, infiltration rates on north- and south-facing slopes on a small east-west-oriented watershed were measured for 1 year and it was determined that during winter, spring, and autumn, the steady-state infiltration rates were 29%, 33%, and 19% smaller, respectively, than in summer (Cerda, 1997).

Infiltration rate may also vary with depth along the vertical soil profile. Several studies have shown that most stormwater pollutants and sediments are trapped in the upper soil layers of the infiltration practice (Ahmed et al., 2015; Dierkes & Geiger, 1999; Komlos & Traver, 2012; Kwiatkowski, Welker, Traver, Vanacore, & Ladd, 2007; Mikkelsen et al., 1997; Wigington, Randall, & Grizzard, 1986), which reduces the infiltration rate of the upper layer.

Warnaars, Larsen, Jacobsen, and Mikkelsen (1999) studied long-term behavior of an infiltration trench in a densely built urban area in Denmark. They continuously monitored the rain, runoff volume, and water level inside two trenches for 2 years 9 months. They calculated the field saturated hydraulic conductivity (K_{fs}) for six overflow rain events and found that the values decreased in the range from 70% to 30% during the study. This indicated that the trenches were clogging. Field saturated hydraulic conductivity and infiltration rate are proportional to each other, so the infiltration rate will also decrease as the soil clogs.

There are different methods to measure the infiltration rate in the field, for example, with double ring infiltrometer, modified Philip Dunne infiltrometer, and minidisc infiltrometer. But these infiltrometers cannot continuously monitor the infiltration rate of the soil. Some studies have used TDRs to measure soil infiltration rate. One study used TDRs inside and away from soil cracks to estimate when water from simulated rainfall entered the cracks (Topp & Davis, 1981). Timlin and Pachepsky (2002) installed TDRs vertically into the soil to track the wetting front propagation during infiltration. From the propagation, the infiltration rate was calculated during rainfall or irrigation. TDRs can be used in SCMs to detect the progression of the wetting front and measure soil water content to verify model predictions for rain gardens (Aravena & Dussaillant, 2009). The current study determined infiltration rates in tree boxes. The infiltration rates were calculated using continuously monitored data from time domain reflectometers (TDRs). The selected TDRs monitored the volumetric water content, electrical conductivity, dielectric permittivity, and temperature of the soil media.

The site for this study was in Louisville, KY where green infrastructure (GI) has been incorporated into the combined sewer overflow consent decree. The Louisville and Jefferson County Metropolitan Sewer District (MSD) teamed up with U.S. EPA's Office of Research and Development, URS Corporation, and the Center for Infrastructure Research at the University of Louisville (U of L) to monitor performance of selected SCMs and to evaluate the effectiveness of groups of controls in volume reduction to CSS flow. MSD completed GI projects during 2011 and 2013, which included permeable pavement, infiltration trenches, and tree boxes. Continuous monitoring embedded sensors were installed in several GI practices including six tree boxes to determine the effective surface infiltration and exfiltration into the underlying soils. Continuous monitoring helps define the hydrologic processes within a SCM. Here, the continuous monitoring results from six tree boxes will be presented. The monitored data were used to calculate steady-state infiltration rate and drainage rate of the tree boxes. In this study, steady-state infiltration rate refers to the infiltration rate of saturated soil after the rain starts and the soil moisture is in initial condition to start with. Drainage rate refers to the infiltration rate of the saturated soil after the rain stops and the soil moisture is saturated to start with. The objectives of this study were to improve the understanding of spatial-temporal variations in soil steady-state infiltration rate and drainage rate in tree boxes by completing following tasks: (a) calculate the steady-state infiltration and drainage rate of 121 rain events from 2 years of soil moisture monitoring data, (b) test for the attribution of location of the tree box and season on the steady-state infiltration and drainage rate, (c) compare the steady-state infiltration and drainage rate between first- and second-year data, and (d) analyze how the steady-state infiltration and drainage rate change with soil depth. In this study, steady-state infiltration and drainage rate of six tree boxes were calculated for two sections of the media: upper and lower section, and for combined section. The upper section starts from the soil surface and extends up to 0.3 m below surface, so the thickness is 0.3 m. The bottom section starts just below upper section and extends 1.2 m below the soil surface, so the thickness of this layer is 0.9 m (0.9 m thick). The combined section starts below the soil surface and extends up to 1.2 m deep.

An innovative approach was initiated in this study. Monitored data from sensors were collected and incorporate into Green–Ampt model for estimating the steady-state infiltration rate and drainage rate of tree boxes. Findings from this study exhibit the performance of tree boxes in reducing runoff volume. The result will help to schedule maintenance and estimate the volume of runoff that can be reduced through tree boxes. By knowing the rate of change in steady-state infiltration rate and drainage rate with time can guide us to improve the design of tree boxes.

SITE DESCRIPTION

In March 2013, MSD installed twenty-nine tree boxes at 7.6–10.7 m spacing along the sidewalk of Story Avenue east of Adams St. and North Spring St. in the Butchertown section of Louisville, KY. Each tree box was open bottom, 1.5 m wide, 1.5 m long, and 1.8 m deep. Runoff enters each tree box from the street through a 0.6-m long curb cut. If the runoff exceeds, the tree box capacity or the flow exceeds the curb cut capacity; runoff bypasses and flows to the next downgradient tree box. Runoff that bypasses the final tree box enters the existing combined sewer system. A single tree (*Syringa reticulata*; common name Ivory silk lilac) was planted in each tree box (Figure 1).

MATERIALS AND METHODS

Method

This study monitored two sets of three tree boxes: set A and set B. Set A and set B were 93 m apart. Monitoring began in 2013 and is ongoing. A single data logger (Campbell Scientific, CR1000) was installed for each set of tree boxes. Set A was located near the east end of the grouping of tree boxes (closest to the catch basin) (Figure 2a). Set B was located downstream of set A near Adam St. and was expected to receive larger runoff volumes (i.e., immediately downstream of a parking lot driveway) (Figure 2b). The tree boxes are connected by 0.9-m-deep infiltration trenches. The tree boxes in each set were numbered sequentially beginning at the upgradient tree box. The drainage area and the hydraulic loading ratio (HLR, ratio of drainage area to tree box surface area) of each tree box, estimated using Google Earth, are shown in Table 1. The HLR of all tree boxes of set A and of box 3 of set B are similar while box 1 of set B has a 10 times larger HLR and box 2 of set B has a 33% smaller HLR. Tree boxes with larger hydraulic loading ratio might receive larger runoff volume compared with other tree boxes. Larger runoff volume is associated with transporting more sediment from the street, and sediment can reduce the drainage rate with time.

An open bottom precast square concrete frame was placed in the excavated pit to provide structural stability (Figure 3a,b). In Figure 3, the concrete frame is represented by the bold solid black line. A 5.3-m to 6.1-m deep, 45-cm-diameter shaft was drilled through the bottom soil of each tree box to reach the underlying soil layer with larger hydraulic conductivity previously identified in a geotechnical survey. A 40-cm-diameter slotted PVC pipe was inserted vertically in the shaft and filled with American Association of State Highway and Transportation Officials (AASHTO) No 3 (2-inch to 1-inch nominal sized opening) aggregate. The annular space between the pipe and the boring wall was filled with

coarse sand. A 30.5-cm-thick layer of AASHTO No. 57 (1-inch nominal sized opening) aggregate was placed at the bottom of the tree box. The gravel was covered by about 1.7 m of media prepared from 60% sand, 30% compost, and 10% topsoil. The measured particle size distribution of the media for the boxes showed 74%–84% sand, 10%–19% silt, and 6%–8% clay. The compost was made of municipal compost that passes through ½ inch screen. The pH of the material was between 6 and 8, and carbon/nitrogen ratio was <25:1. The organic content was between 35% and 65%. The unsaturated hydraulic conductivity on the media surface (measured with a minidisc infiltrometer) in two of the tree boxes were 0.05 and 0.08 cm/hr with a soil suction of 0.5 cm. Infiltrating water flowed through the media and gravel, then through the shaft into the underlying soil layer. Based on the texture triangle method (Klute, 1986), the underlying soil above the bottom of the shaft was mostly clay loam or silty loam or silty clay loam. The concrete sidewalls of the tree box and the clayey soil surrounding the shaft prevented lateral water exfiltration from the tree box and shaft, respectively.

Instrumentation

The media in each tree box received four TDRs (Campbell Scientific, CS650) (Figure 3a,b). The TDRs were calibrated across the expected range of values using air dry media (0.009 m³/m³), saturated soil, and three roughly equally spaced intermediate values (0.059, 0.109, and 0.159). After calibration, a least-squares linear regression (correlation coefficient 0.97) was used to convert the raw soil moisture data to the calibrated soil moisture data. With the exception of one TDR installed 15 cm below the media surface and 30 cm from the curb cut inlet (in blue in Figure 3a,b), all TDRs were installed at the east side of the tree box halfway between the curb cut inlet and the back of the tree box (in red in Figure 3a,b). The TDRs on the east edge of the tree box were installed 30 cm, 60 cm, and 1.5 m below the surface of the tree box media. TDR1 was installed at the curb cut discharge to indicate when runoff first enters the tree box. TDR2, TDR3, and TDR4 were installed to calculate the infiltration rate, specifically at the TDR locations. Rainfall data were collected from MSD monitored rainfall with next-generation radar (NEXRAD) on 1-km² pixels and 5-min intervals. There are three 1-km² pixels [identification number: 8027, 8160, 8161] spanning the study area. During the construction period, an on-site rain gauge was also installed in March 2013. For 53 events when the on-site rain gauge was operational, the measured rain data were compared with NEXRAD data and they were consistent with each other with a coefficient of determination (r^2) of 0.95 for a linear fit.

Infiltration calculation and statistical analysis

For each tree box, the infiltration rate was calculated by using the data from three TDRs: TDR2, TDR3, and TDR4 as shown in Figure 3a,b. Data from TDR1 were not included in the calculation because the horizontal distance between TDR1 and the rest of the TDRs was 47.5 cm while TDR2, TDR3, and TDR4 were stacked vertically at different depths. Infiltration rates through the 30-cm soil section between TDR2 and TDR3, through the 90-cm soil section between TDR3 and TDR4 and the combined infiltration rate through the 1.2-m soil section between TDR2 and TDR4 were calculated. The media between TDR2 and TDR3 is designated as “Upper section,” the media between TDR3 and TDR4 as “Lower section” and the media between TDR2 and TDR4 as “Combined section.” The combined

section covers 73% of the total media depth making it representative of the average infiltration rate through the entire media depth at the TDR locations. The upper section covers 18% of the total media depth.

For each rain event, steady-state infiltration rate and drainage rate were calculated. The infiltration rate was calculated for antecedent soil moisture content and the drainage rate was calculated for saturated soil moisture content. Steady-state infiltration rates and drainage rates were calculated for the upper section, lower section, and combined section. To qualify a new rain event, the minimum time difference between the end of previous rain and starting of new rain was set to be 6 hr. Figures 4 and 5 illustrate necessary parameters for the infiltration calculation. Four hypotheses to be tested for these data are as follows:

1. Steady-state infiltration rate of the media will be larger than the drainage rate,
2. Steady-state infiltration and drainage rate of media in the individual tree boxes will vary with season,
3. Steady-state infiltration and drainage rate in second year will be smaller than first year.
4. Steady-state infiltration and drainage rate will not vary with media depth since the soil texture is homogenous.

Infiltration rate calculation for dry condition

Figure 4 demonstrates the soil moisture profile of the tree box media before the rain started and after the top 1.5 m of soil media becomes saturated or after the wetting front advances to TDR4. According to Green–Ampt model, it is assumed that the wetting front in the soil profile is a sharp wetting front, which means that behind the wetting front soil is saturated and ahead of the wetting front soil moisture is at the antecedent condition. In Figure 4:

X -axis = Soil moisture content

Y -axis = Downward distance from soil surface

L_1 = Distance between TDR2 and TDR3 or wetting front depth for upper section = 30 cm

L_2 = Distance between TDR3 and TDR4 or wetting front depth for lower section = 90 cm

L_3 = Distance between TDR2 and TDR4 or wetting front depth for combined section = 1.2 m

$\theta_{iTDR_j\text{init}}$ = Antecedent soil moisture content at the location where TDR $_j$ is installed, $j = 2, 3, 4$

$\theta_{fTDR_j\text{init}}$ = Saturated soil moisture content at the location where TDR $_j$ is installed, $j = 2, 3, 4$

$\text{Cum}_{\text{inf_upper}}$ = Cumulative infiltrated volume per unit area in upper section

Cum_{inf_lower} = Cumulative infiltrated volume per unit area in lower section

$Cum_{inf_combined}$ = Cumulative infiltrated volume per unit area in combined section

t_1 = Time needed for the wetting front to advance from TDR2 to TDR3

t_2 = Time needed for the wetting front to advance from TDR3 to TDR4

θ = Change in soil moisture

L_1 , L_2 , and L_3 were measured during sensor installation. Average steady-state infiltration rate of the soil in initial condition for upper section based on Green–Ampt assumption (Mays, 2005):

$$= \frac{Cum_{inf_upper}}{t_1} \quad (1)$$

$$= \frac{\Delta\theta * L_1}{t_1} \quad (2)$$

$$= \frac{\left\{ \left[\frac{(\theta_f TDR2_{init} + \theta_f TDR3_{init})}{2} - \frac{(\theta_i TDR2_{init} + \theta_i TDR3_{init})}{2} \right] L_1 \right\}}{t_1} \quad (3)$$

Similar to Equations 1 and 3, the average infiltration rate of the soil in initial condition for lower section:

$$= \frac{Cum_{inf_upper}}{t_2} \quad (4)$$

$$= \frac{\Delta\theta * L_2}{t_2} \quad (5)$$

$$= \frac{\left\{ \left[\frac{(\theta_f TDR3_{init} + \theta_f TDR4_{init})}{2} - \frac{(\theta_i TDR3_{init} + \theta_i TDR4_{init})}{2} \right] L_2 \right\}}{t_2} \quad (6)$$

Average steady-state infiltration rate between TDR2 and TDR4 or combined section was divided into two segments. Length of soil profile for first segment is L_1 and second segment is L_2 . Similar to Equations 1–3, the steady-state infiltration rate of the soil in initial condition for combined section:

$$= \frac{Cum_{inf_combined}}{t_1 + t_2} \quad (7)$$

$$= \frac{\left\{ \left[\frac{(\theta_{fTDR2_{init}} + \theta_{fTDR3_{init}})}{2} - \frac{(\theta_{iTDR2_{init}} + \theta_{iTDR3_{init}})}{2} \right] L_1 \right\} + \left\{ \left[\frac{(\theta_{fTDR3_{init}} + \theta_{fTDR4_{init}})}{2} - \frac{(\theta_{iTDR3_{init}} + \theta_{iTDR4_{init}})}{2} \right] L_2 \right\}}{t_1 + t_2} \quad (8)$$

Drainage rate calculation for saturated condition

Figure 5 demonstrates the soil moisture profile of the tree box media after the top 60 cm and top 1.6 m of soil media has drained from saturation. Also, the soil was saturated all the way to the bottom of the media. In Figure 5:

X -axis = Soil moisture content

Y -axis = Downward distance from soil surface

$\theta_{iTDRm_{sat}}$ = Saturated soil moisture content at the location where TDR_{*m*} is installed, $m = 2, 3, 4$

$\theta_{fTDR2L1_{sat}}$ = Soil moisture content at the location where TDR2 is installed, after top (60 cm) media drained

$\theta_{fTDR2L1,2_{sat}}$ = Soil moisture content at the location where TDR2 is installed, after top (1.6 m) media drained

$\theta_{fTDR3L1,2_{sat}}$ = Soil moisture content at the location where TDR3 is installed, after top 1.6-m media drained

Cum_{dm_upper} = Cumulative drained volume per unit area in upper section

Cum_{dm_lower} = Cumulative drained volume per unit area in lower section

$Cum_{dm_combined}$ = Cumulative drained volume per unit area in combined section

t_3 = Time needed for the wetting front to advance from TDR2 to TDR3

t_4 = Time needed for the wetting front to advance from TDR3 to TDR4

Average drainage rate of the soil in saturated condition for upper section:

$$= \frac{Cum_{drn_upper}}{t_3} \quad (9)$$

$$= \frac{\frac{1}{2}L_1(\theta_{iTDR2_{sat}} - \theta_{fTDR2_{L1_{sat}}})}{t_3} \quad (10)$$

Average drainage rate of the soil in saturated condition for lower section:

$$= \frac{Cum_{drn_lower}}{t_4} \quad (11)$$

$$= \frac{\frac{1}{2}L_2(\theta_{iTDR3_{sat}} - \theta_{fTDR3_{L1,2_{sat}}})}{t_4} \quad (12)$$

Similar to initial condition, drained volume per unit area for saturated condition between TDR2 and TDR4 or combined section was divided into two segments of upper section and lower section. Average drainage rate of the soil in saturated condition for combined section:

$$= \frac{Cum_{drn_combined}}{t_3 + t_4} \quad (13)$$

$$= \frac{\left[\left(\theta_{iTDR2_{sat}} - \theta_{fTDR2_{L1,2_{sat}}} \right) + \left(\theta_{iTDR3_{sat}} - \theta_{fTDR3_{L1,2_{sat}}} \right) \right] \times \frac{L_1}{2} + \left[\left(\theta_{iTDR3_{sat}} - \theta_{fTDR3_{L1,2_{sat}}} \right) \times \frac{L_2}{2} \right]}{t_3 + t_4} \quad (14)$$

Strategy for statistical analysis

The steady-state infiltration rate and drainage rate of six tree boxes were calculated for 121 rain events from June 17, 2013 to May 31, 2015. Rain events from June 17, 2013 to June 16, 2014 are year 1 and events from June 17, 2014 to May 31, 2015 are year 2. For tree box A1, A2, and A3, soil moisture data from April 28, 2014 to July 30, 2014 and from August 2, 2014 to September 26, 2014 were not recorded because of a malfunction of the data logger connected to the TDRs. Drainage rates for the bottom and combined sections were not calculated for 65% (on an average of six tree boxes) of the total rain events because either TDR4 did not drain in 2 hr or TDR4 and TDR3 drained at the same time. For the first case, if TDR4 remained saturated for more than 2 hr while TDR2 and TDR3 drains that could be because of water backup from the shaft. TDR4 usually drained within 4–80 min. So, in that case the draining rate of TDR4 will not represent the draining rate of the media, rather it will represent the draining rate of the shaft. Also, there could be fingering in the wetting front and the shape of the wetting front will be unpredictable. It may not match the assumed profile in Figure 5b or c. In the second case, the soil moisture at both TDR3 and TR4 can

drop at the same time, because water is draining due to gravity; draining is not uniform through the soil media with depth.

Distribution testing with the Kolmogorov–Smirnov method on the combined data of six tree boxes showed that the infiltration rate data were not normally distributed. For most groups, the data sets are log-normally distributed as shown in the bold font in Table 2. The statistical analysis of the infiltration data was log-transformed. Groups for each normality test are media sections (upper, lower, and combined), seasons [based on USNO (2015) established equinox and solstice (fall, winter, spring, and summer)], growing seasons based on frost-free days (growing and nongrowing periods) and age (year 1 and year 2).

A factorial analysis of variance (ANOVA) was performed on the pooled log-transformed data. All statistical analyses used Statistica 9.1 (StatSoft, Tulsa, Oklahoma), with significance levels set at $\alpha = 0.05$. The categorical factors are season, growing seasons, age (year 1 or year 2), and media section. Effects of both astronomical (equinox and solstice defined) based season and growing season on infiltration rate were analyzed, because equinox-based seasons are commonly used by other researchers (Cerdeira, 1997, 1999) while growing season represents geographic variation. Post hoc comparison by pair using Fisher's least significant difference method was used when infiltration rate was found to be significantly different for any categorical factor to identify which tree boxes are different. Growing season is April 15 to October 25 for the Louisville, KY area.

ANOVA was also performed on log-transformed drainage rate. The categorical factors are season, growing seasons, age (year 1 and year 2), and media section with a significance level of 0.05. Table 3 shows the number of log-transformed infiltration rate and drainage rate data of six tree boxes.

The current study assumed that during draining the shape of the wetting front is triangular or trapezoidal. But the shape could be nonuniform, and during initial condition, fingering could form at the bottom of the wetting front instead of a sharp interface (Hillel & Baker, 1988). The calculations assumed one-dimensional flow for infiltration and drainage rate calculations.

RESULTS AND DISCUSSION

ANOVA test result for geometric mean value of individual tree box

The steady-state infiltration rate varied among all six tree boxes [$F(5, 814) = 26.65, p < 0.0001$]. The drainage rate also varied among tree boxes [$F(5, 680) = 13.136, p < 0.0001$]. The drainage rate did not vary among tree boxes within set B. It could be due to more uniform mix of media for tree boxes from set B than tree boxes from set A. Different batches of media could have slightly different soil textures that lead to measurably different rates.

One possible reason of variability in steady-state infiltration rate could be the effect of soil moisture. The initial infiltration rate ($r = -0.5$) shows a stronger correlation with media moisture content than with the drainage rate ($r = -0.3$). No trend was observed between

average soil moisture and geometric mean infiltration rate among all six tree boxes but largest infiltration (127 cm/hr) was observed for the tree box (A3) with driest soil ($0.27 \text{ m}^3/\text{m}^3$) and smallest infiltration (53 cm/hr) was observed for the tree box (A1) with wettest soil ($0.42 \text{ m}^3/\text{m}^3$).

ANOVA test result for uniformity of infiltration rate and drainage rate with media depth

For the initial condition, the steady-state infiltration rate varied with the media layer [$F(10, 802) = 2.245, p = 0.0139$]. For four of the six tree boxes, there was no significant difference in the calculated steady-state infiltration rate among upper, lower, or combined sections. However, for tree box A1, the rate in the lower section was 76% larger than the upper section and for A2 the rate in the upper section was 36% larger than the lower section. For most of the tree boxes, the steady-state infiltration rate was uniform over the depth of the media.

The drainage rate varied with the media section [$F(10, 668) = 6.447, p < 0.0001$] for all tree boxes except B2. Overall, the drainage rate of the combined section was 70% larger than the upper section but the drainage rate in the lower and combined sections was not statistically different. The steady-state infiltration rate of combined data also showed no significant difference between lower and combined section. In tree box A1, the drainage rate in the combined section is 2.8 and 2.4 times larger than in upper and lower sections, respectively. For tree box A3, in the combined section, the steady-state infiltration rate is 3.7 and 1.4 times larger than upper and lower sections. It is unexpected to have a steady-state infiltration rate in combined section larger than the upper or lower section. But in our study, the steady-state infiltration rate for combined section was calculated using soil moisture values after soil at TDR4 location started to drain, while for upper section soil moisture values after soil at TDR3 location started to drain was used. To calculate the steady-state infiltration rate of upper section, the shape of the soil moisture profile was assumed to be triangular (Figure 5b) and for the combined section it was assumed to be trapezoidal (Figure 5c,d). Because of larger area of soil moisture profile for the combined section, the steady-state infiltration rate was higher than upper or lower section.

In tree boxes B1 and B3, the drainage rate in the lower section was larger than the upper section and tree box A2 is opposite. When the media is draining due to gravity, the drying front is not sharp that means behind the front the soil is not totally dry as assumed in the model. Some water can be stored behind the front because of soil suction. For this reason, drainage is not uniform through the soil profile. In addition, water can bypass through some pores making the drainage faster in some locations of the soil profile. Therefore, the drainage rate between the upper and lower sections can be different.

ANOVA test result to compare first- and second-year infiltration and drainage rate

Steady-state infiltration rates of four of the six tree boxes showed no significant difference between year 1 and year 2 [$F(5, 808) = 8.898, p < 0.0001$]; however, steady-state infiltration rates for other two tree boxes which is the most upgradient tree boxes of both sets A1 and B1 are significantly larger in year 1 than year 2. Tree box B1 has 10 times larger HLR compared with other tree boxes and presumably receives more runoff. Larger runoff

volumes might convey more solid particles that can be deposited on the media and reduce the infiltration rate. Drainage rates of tree boxes in group B in year 1 were significantly larger than year 2 [$F(5, 674) = 5.3551, p < 0.0001$]. For the combined data, it was found that, in the second year, steady-state infiltration rate and drainage rate decreased by 20%, and 38%, respectively, from first year.

ANOVA test result for seasonal effect on infiltration rate and drainage rate

Steady-state infiltration rates varied with celestial season [$F(15, 796) = 6.43, p < 0.0001$], except for tree box A3. Individual tree boxes did not follow any specific pattern of seasonal change in infiltration rate. However, post hoc tests on combined data show that steady-state infiltration rate in winter and spring are significantly different from each other but there is no significant difference in steady-state infiltration rates between summer and fall. Steady-state infiltration rates in the winter are 34%, 56%, and 59% less than that in spring, fall, and summer, respectively, and in the spring, steady-state infiltration rates are 32% and 38% less than fall and summer, respectively.

There is a seasonal difference in the calculated drainage rates among all tree boxes [$F(15, 662) = 6.6081, p < 0.0001$] but no specific pattern on individual tree boxes was observed. Post hoc tests show that drainage rates in spring and winter are not significantly different, but they are different in other seasons. Drainage rates in summer and fall are significantly different between each other and with other seasons. Drainage rates are the largest in summer, and they are 97%, 288%, and 276% larger than the drainage rate in fall, winter, and spring, respectively. In the fall, the drainage rate is 96% and 91% larger than the drainage rate in winter and spring, respectively.

ANOVA test result for growing/nongrowing seasonal effect on infiltration rate

Steady-state infiltration rates for four tree boxes (A1, A2, B1, and B3) were significantly larger in the growing season than in the nongrowing season [$F(5, 808) = 12.094, p < 0.0001$]. The combined data steady-state infiltration rate in growing season is 80% larger than nongrowing season. That is similar to the finding on astronomical seasonal effect on infiltration rate. For instance, steady-state infiltration rates in winter and spring are significantly less than in summer and fall. The reason might be that growing/nongrowing season coincides with astronomical seasons. The drainage rate of all of the tree boxes was significantly larger in growing season than nongrowing season [$(F(5, 674) = 3.3804, p = 0.005)$]. The steady-state infiltration rate in the growing season was three times larger than nongrowing season.

Figure 6 compares the geometric mean combined infiltration rate among the upper, lower, and combined section of the media for steady-state infiltration rate and drainage rate. Steady-state infiltration rates are larger than the drainage rate because of low soil moisture and high soil suction during initial condition. The plot shows that the drainage rate of combined section is 70% larger than the upper and 30% larger than the lower section. This figure and the statistical analysis show that infiltration and drainage rate can vary with depth which does not satisfy the hypotheses that the media uniformity would produce the same rates. There are studies showing spatial variation in infiltration rates on soil surface in

stormwater control measures (Ahmed et al., 2015; Olson, Gulliver, Nieber, & Kayhanian, 2012), but the current study suggests that vertical variation in infiltration and drainage rate should be expected, as well. Archer et al. (2016) studied infiltration rate and soil hydrologic characteristics at different depths in forests under 300-year-old individual Scots pine tree. The soil type was peaty podzols with peat and peaty gleys, which mean these soils are acidic, nutrient-deficient soils and are developed under conditions of intermittent or permanent waterlogging. The researchers found that the field hydraulic conductivity of top 0.04–0.15 m (0.88–25.60 cm/hr) was larger than 0.15–0.25 m (0.30–2.30 cm/hr) depth. The current study observed less variability in infiltration rate with depth compared with Archer's et al. (2016) study.

In the second year, the geometric mean infiltration rate and drainage rate of the combined data were less than the first-year values which match the hypotheses, although this difference was not statistically significant. The initial infiltration rate in second year (50.94 cm/hr) decreased by 20% compared with the first year (60.28 cm/hr). The drainage rate in second year (4.92 cm/hr) decreased by 38% compared with the first year (7.98 cm/hr). However, for tree box B1 both infiltration rate and drainage rates were significantly larger in first year than in the second year, which could be because of the larger ratio of drainage area to surface area of tree box B1. For this tree box, this ratio is 294:1 and it receives runoff from the street and adjacent parking lot, thus, having large HLR can affect the hydrologic performance of tree boxes. Longer-term monitoring is needed to make a conclusion about the age effects.

The steady-state infiltration rate and drainage rate are largest during the summer (i.e., growing season) (Figures 7 and 8). The smallest infiltration rates were observed during the winter and nongrowing season. In the summer, the infiltration rate was larger because soil is driest during that season. Although initial soil moisture did not vary significantly with seasons [$F(3, 345) = 2.0923, p = 0.1000$], in four tree boxes (A1, B1, B2, and B3) the average soil moisture in summer was the smallest and in two tree boxes (A2 and A3) the average soil moisture in fall was the smallest compared to other seasons. The initial soil moisture was negatively correlated with the steady-state infiltration rate ($r = -0.54$) of the media. Summer, or growing season, is associated with increased temperature that reduces the viscosity of water and results in a higher infiltration rate. Duke (1992) and Emerson and Traver (2008) documented that an increase in temperature reduced the viscosity of water sufficiently to increase the hydraulic conductivity. Clancy and Alba (2011) observed a 25% increase in steady-state infiltration rate (from 17.28 to 21.60 cm/hr) for sand and loamy sand type of soil with a temperature increase from 14 to 16°C in the field but did not observe any significant difference between first and second year of measured infiltration rate data. Jaynes (1990) reported that the infiltration rate in a clay loam field site decreased from 2.69 to 1.45 cm/hr with a temperature increase from 14.9 to 31.5°C within 24 hr. In winter, infiltration rate is low because of frozen soil or presence of ice reducing the pore space. In the current study, below freezing temperature was recorded by TDRs for several days. However, Cerda (1997, 1999) found that in his study, the lowest infiltration rate was during spring (0.38–0.87 cm/hr) and autumn (0.41–0.83 cm/hr).

The steady-state infiltration rate and drainage rate values from this current study are comparable to the literature cited above. The steady-state infiltration rates reported in Clancy and Alba's (2011) study fall between the infiltration rate and drainage rate of the current study. Since the soil type for both studies is loam sand, the results can be compared.

CONCLUSIONS

In this study, the infiltration rates of six tree boxes were measured from two-year soil moisture data and the effects of season, growing season, soil moisture, and depth on infiltration rate were analyzed. The difference in steady-state infiltration rates and drainage rate between the first and second year of monitoring period was compared. The steady-state infiltration rate was uniform throughout the media but when the soil was draining, the drainage rate was not uniform. The drainage rates of the bottom section and combined section were significantly larger than the upper section for two tree boxes. The infiltration rate was largest in the summer and smallest in the winter. That study noted that the smallest infiltration rate in a badland surface was in spring and autumn. Initial infiltration rate in the two upgradient tree boxes, and drainage rate in three of the six tree boxes decreased in the second year. Initial infiltration rate of the upgradient tree boxes of one set decreased in the second year which might be because of larger HLR and sediment deposition.

Antecedent soil moisture showed moderate correlation with steady-state infiltration rate but poor co-relation with drainage rate. The steady-state infiltration rate varied with the tree boxes. This means that even though the soil texture was similar, the steady-state infiltration rate could be different for different tree boxes. No difference was observed among mean soil moisture of different tree boxes but the tree box with the wettest soil had the smallest infiltration rate and the tree box with the driest soil had the largest infiltration rate.

Because of seasonal effects, the infiltration rate can vary with geographic location and climate even though the hydrologic parameters and soil properties are same. Therefore, design or simulations of SCMs should be viewed in a climatic context. The mixed results in the effect of age demonstrate the importance of long-term monitoring. In this study, only two years' worth of data were analyzed which proved insufficient to draw a conclusion on the age effect. Long-term monitoring will inform development of a maintenance cycle. It can show the trend of performance of the SCM with time, change in infiltration rate with time, and standard maintenance scheduling. Due to variation in infiltration rate in tree boxes, post-construction infiltration testing is encouraged to insure whether the targeted infiltration rate is achieved.

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Practitioner points

- Initial infiltration rate and drainage rate decrease by 20% and 30%, respectively, within a year.
- The smallest infiltration rates were observed during winter and largest infiltration rates were observed in summer.
- Initial and saturated infiltration rates varied among all six tree boxes.

Figure 1.
Tree boxes with connecting trenches installed along Story Ave. in Louisville, KY.

Figure 2. Runoff contributing area of tree boxes of (a) set A and (b) set B (Source: Google Earth). The light blue line indicates the boundary of the contributing area for each set.

Figure 3. (a) Plan view and (b) cross section A-A of the tree boxes showing the locations of TDRs. The solid black line represents the concrete structure of the tree box.

Figure 4.

Schematic diagram of soil moisture profile for steady-state infiltration rate calculation (a) before and (b) after the wetting front has advanced to TDR4. Here, horizontal axis = soil moisture content, vertical axis = downward distance from soil surface, L_1 = distance between TDR2 and TDR3 = 0.3 m, L_2 = distance between TDR3 and TDR4 = 0.9 m, L_3 = distance between TDR2 and TDR4 = 1.2 m, $\theta_{iTDRj_{init}}$ = antecedent soil moisture content at the location where TDR_j is installed, $j = 2, 3, 4$, $\theta_{fTDRj_{init}}$ = saturated soil moisture content at the location where TDR_j is installed, $j = 2, 3, 4$.

Figure 5.

Schematic diagram of soil moisture profile for drainage rate calculation (a) before the soil at TDR2 location started to drain, (b) after the soil at TDR3 location started to drain and (c) or (d) after the soil at TDR4 location started to drain. Here, horizontal axis = soil moisture content, vertical axis = downward distance from soil surface, $\theta_{iTDRm_{sat}}$ = saturated soil moisture content at the location where TDRm is installed, $m = 2, 3, 4$, $\theta_{fTDR2L1_{sat}}$ = soil moisture content at the location where TDR2 is installed, after top 0.6-m media drained, $\theta_{fTDR2L1,2_{sat}}$ = soil moisture content at the location where TDR2 is installed, after top 1.6-m media drained, $\theta_{fTDR3L1,2_{sat}}$ = soil moisture content at the location where TDR3 is installed, after top 1.5-m media drained.

Figure 6. Comparing the geometric mean infiltration rate and drainage rate (all tree boxes combined) among sections. Drainage rate is significantly different with media section but not for initial condition.

Figure 7. Comparing the infiltration rates and drainage rates for different astronomical seasons. Both infiltration rate and drainage rate both are significantly different among seasons.

Figure 8. Comparing the infiltration rate and drainage rate between growing/nongrowing seasons. Both infiltration rate and drainage rate are significantly different between seasons.

Table 1.

The drainage area and hydraulic loading ratio of each tree box

TREE BOX NUMBER	SET	ESTIMATED DRAINAGE AREA (FT ²)	HYDRAULIC LOADING RATIO
#1 (most upgradient)	A	810	32:1
#2		740	29:1
#3 (most downgradient)		740	29:1
#1 (most upgradient)	B	7,360	294:1
#2		500	20:1
#3 (most downgradient)		840	34:1

Table 2.

Statistics on normality test for initial condition. Bolded values indicate normal distribution of the data

CATEGORICAL VARIABLE	P VALUE FOR UNTRANSFORMED DATA	P VALUE FOR LOG-NORMALLY TRANSFORMED DATA
Seasons based on equinox and solstice		
Fall	<0.05	>0.2
Winter	<0.05	>0.2
Spring	<0.01	>0.2
Summer	<0.01	>0.2
Season based on frost-free days		
Growing	<0.01	>0.2
Nongrowing	<0.01	>0.15
Age		
Year 1	<0.01	>0.2
Year 2	<0.01	>0.2
Section		
Upper	<0.01	<0.05
Lower	<0.01	<0.1
Combined	<0.01	<0.01

Table 3.

Sample size of each category for ANOVA test. Infiltration and drainage rate data were combined for six tree boxes

CATEGORICAL VARIABLE	NO. OF DATA FOR INFILTRATION RATE	NO. OF DATA FOR DRAINAGE RATE
Seasons based on equinox and solstice		
Fall	191	170
Winter	100	85
Spring	235	226
Summer	294	205
Season based on frost-free days		
Growing	461	360
Nongrowing	359	326
Age		
Year 1	463	342
Year 2	357	344
Section		
Upper	320	346
Lower	247	170
Combined	253	170