Research article

The capacity of urban forest patches to infiltrate stormwater is influenced by soil physical properties and soil moisture

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ABSTRACT

Forest patches in developed landscapes perform ecohydrological functions that can reduce urban stormwater flows. However, urban forest patch contributions to runoff mitigation are not well understood due to a lack of performance data. In this study, we focus on the potential of urban forest patch soils to infiltrate rainfall by characterizing rates of unsaturated hydraulic conductivity (K) in 21 forest patches in Baltimore, Maryland. Soil bulk density, organic matter, soil moisture, percent of coarse fragments (≥ 2 mm), and texture were evaluated at the same locations to assess drivers of K. The K was significantly higher in soils with high sand content and related positively with the percent of coarse fragment material in the soil. Forest patch size did not impact K. We estimate that 68 percent of historic rainfall could be infiltrated by urban forest patch soils at the measured K rates. Continuous monitoring at one forest patch also showed that K is dynamic in time and influenced by antecedent soil moisture conditions. We conservatively estimate that unsaturated urban forest patch soils alone are capable of infiltrating most rain events of low to moderate intensities that fell within these forest patches in the Baltimore region. Considering this ecohydrologic function, the protection and expansion of forest patches can make substantial contributions to stormwater mitigation.

1. Introduction

Urbanization alters the hydrologic cycle by creating impervious surfaces (e.g. roofs, parking lots, and roads) and compacting soils, reducing watershed infiltration capacity. Rainfall is channeled through storm drains and pipes and, as a result, urban watersheds experience high volume and "flashy" stormwater runoff following precipitation events (Askarizadeh et al., 2015; Shuster et al., 2015). These conditions cause receiving water bodies to exhibit high discharge peaks and degraded water quality (Booth and Jackson, 1997; Hood et al., 2007; Walsh et al., 2005). In addition, urban areas are susceptible to flooding due to overflow at stream channels (fluvial flooding) or drainage failure and water accumulation over roads and surfaces (pluvial flooding) (Apel et al., 2016; Rosenzweig et al., 2018). Both types of flooding can lead to traffic disruption, property damage, and pose hazards and health risks to local residents (Ahern et al., 2005; Qin et al., 2013).

Stormwater green infrastructure (SWGI) practices and other nature-based solutions (e.g., urban forests) mimic natural hydrology by promoting infiltration, storage, and/or evapotranspiration of runoff (Askarizadeh et al., 2015; Golden and Hoghooghi, 2018; Kuehler et al., 2017). In addition to combating urban stormwater problems, these solutions are increasingly being thought of key strategies to building resilience and adapting to climate change in urban watersheds (Brink et al., 2016; Escobedo et al., 2018). Traditionally, SWGI practices have been designed in a centralized manner to increase the residency of stormwater before it is discharged to local water bodies. Since 2000, decentralized SWGI practices such as rain gardens, cisterns, and green roofs have become increasingly popular strategies to store, infiltrate, and treat a specific amount of rainfall at or near the source (Jefferson et al., 2017). The proliferation of such practices has coincided with a surge in research studies that demonstrate a range of SWGI efficiency and effectiveness at restoring urban watershed functions (Davis et al., 2009; Golden and Hoghooghi, 2018; Hunt et al., 2012; Jefferson et al., 2017; Lefevre et al., 2015).

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Urban trees and forests are increasingly being looked to as a component of stormwater management portfolios in cities because urban forests make up around 27% of urban land cover in the United States (Nowak et al., 2001). However, in contrast with SWGI practices, urban trees and forests are not engineered to handle specific rainfall quantities. Moreover, the degree to which urban forests and their underlying soils decrease runoff is not well researched and quantified to date (Berland et al., 2017; Kuehler et al., 2017). As such, urban trees and forests are not always promoted as a best management practice by stormwater practitioners (Kuehler et al., 2017). Urban trees and forests can reduce stormwater runoff through soil infiltration, as well as canopy interception, and transpiration. The rate at which water moves in soil is affected by soil physical properties such as bulk density (BD), soil organic matter (SOM), texture, and soil moisture (Gupta and Larson, 1979; Saxton and Rawls, 2006; Yang and Zhang, 2011). BD often serves as an indicator of soil compaction, a state that physically reduces the amount of pore space in the soil and impedes the soil's ability to infiltrate water (Kozlowski, 1999; Ossola et al., 2015; Yang and Zhang, 2011). SOM from leaf litter and other debris in forests enhances soil structure and increases porosity, thus promoting infiltration (Boyle et al., 1989; Chen et al., 2014). SOM also can increase soil water storage capacity, thereby affecting the dynamics of infiltration. The relationship between soil texture and hydraulic conductivity has been well-established for non-urban forested soils (Rawls et al., 1998; Jabro, 1992).

Unlike soils in undisturbed areas, however, urban soils are highly modified by humans and experience urbanization effects that influence their properties and therefore how they function ecohydrologically (Effland and Pouyat, 1997; Herrmann et al., 2018, 2017; McDonnell et al., 1997; Pavao-Zuckerman, 2008). For instance, urban forests in the Northeastern U.S. have been shown to support high numbers of non-native earthworm species (McDonnell et al., 1997) that contribute to a decrease in the SOM in the O horizon (Burtelow et al., 1998). Additionally, compacted soils in urban landscapes in Baltimore, MD exhibit low infiltration rates (Schwartz and Smith, 2016). Given the diverse soil physical conditions caused by direct and indirect effects from urbanization, study of the urban forest soil's properties is key to understanding the soil's ability to infiltrate stormwater runoff.

Urban forest soils likely contribute to hydrological processes in cities, but we know relatively little about their function (Kuehler et al., 2017). This is important because urban forest soils are being looked to as a key element of stormwater management in built environments, yet there is a need for better quantification and empirical studies (Law and Hanson, 2016; Berland et al., 2017; Kuehler et al., 2017). In North America, 'urban forests' have a broad definition, including all trees and woody shrubs in locations in and around cities, and therefore including street trees, trees grown in yards and parks, woodlots, and remnant forest patches (Konijnendijk et al., 2006). In this study, we focus specifically on 'urban forest patches,' woodlots and remnant forests in cities, and discuss implications for the broader concept of 'urban forests' (and do not use these terms interchangeably). Here, we evaluate the potential of urban forest patches in Baltimore, Maryland to infiltrate stormwater by analyzing the soil unsaturated hydraulic conductivity (K), a key process in regulating flow into unsaturated soils (Perkins, 2011). Further, we assess soil properties including BD, SOM, texture, percent of coarse fragment material, and soil volumetric water content as potential drivers of K. We further assess whether K differs between forest patches of different sizes that influence how they are categorized and classified for management.

2. Materials and methods

2.1. Study sites

Baltimore, Maryland, receives about 108 cm of precipitation each year, an amount that is evenly distributed throughout all months. The
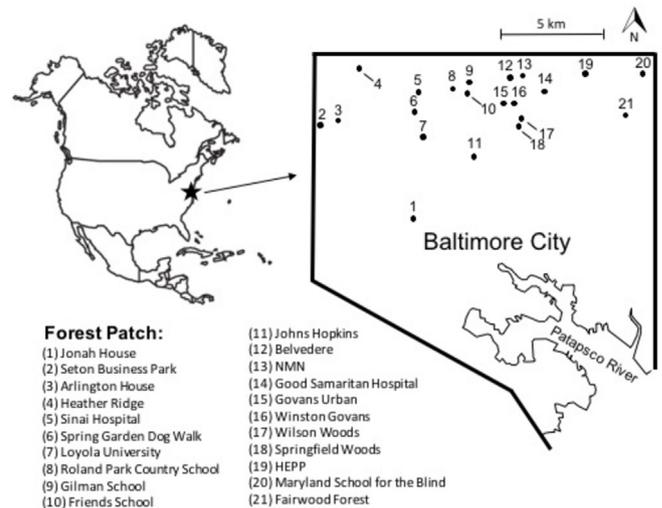

Fig. 1. Locations of study sites, 21 forest patches within Baltimore City, Maryland, USA. Patch names are derived from the entity that owns them (e.g., Johns Hopkins University), or are a given name (e.g., Fairwood Forest).

city has cold winters and hot, humid summers, averaging a low of 5.6 °C in January and a high of 31.7 °C in July. This study was conducted within the Piedmont Plateau province. This province has deep and well-drained upland soils with moderate slopes that overlay semi-basic, mixed basic, and acidic rocks, and the dominant soil type is Ultic Hapludalfs (USDA Forest Service https://www.nrs.fs.fed.us/ef/locations/md/baltimore/).

Forest patches are areas of tree canopy at least ~0.1 ha in size with complex habitat structures that include understory shrubs, small trees, woody debris, and leaf litter (Avins, 2013). In Baltimore forest patches account for 34% of the city's tree canopy cover (Avins, 2013). Twenty-one forest patches across Baltimore City were chosen as the study sites (Fig. 1). These patches were chosen because they are part of an ongoing research and conservation effort (a partnership between Baltimore Green Space, a land trust organization, and researchers with the Baltimore Ecosystem LTER Study and USDA Forest Service). They are predominately located in northern Baltimore and include 11 larger forest patches (15.62 ha ± 2.91) that are protected under city easements and 10 smaller forest patches (1.9 ha ± 0.52) that are nested within neighborhoods and overseen by local stewards and Baltimore Green Space. Although the term "forest patch" suggests one area of connected forest cover, in actuality some of the larger sites include two or more patches of forest, or are part of an even larger forested area that extends beyond the defined perimeter of the forest patch. The dominant tree species across all forest patches are native to eastern North America and include, *Liriodendron tulipifera, Quercus alba, Acer rubrum, Quercus rubra, Fagus grandifolia,* and *Fraxinus pennsylvanica* (Baker, Lautar, Yesilonis, Avins, *unpub. data*). On average, 7.7% of trees and 56.4% of groundcover species in the patches are non-native. The most common non-native groundcover species are vines: *Hedera helix, Lonicera japonica, Ampelopsis brevipedunculata,* and *Celastrus orbiculatus* (Baker, Lautar, Yesilonis, Avins, *unpub. data*).

2.2. Hydraulic conductivity (K) measurements as estimates of infiltration capacity

In the summer of 2017, we measured K at three locations per forest patch, with the exception of one smaller forest patch (Belvedere) where we took measurements at two locations. Locations for measurements in each forest patch were chosen based on locations of preliminary soil texture and BD data acquired by researchers who applied a systemic random design to sample across all forest patches (Baker, Lautar, Yesilonis, Avins, *pers. comm.*). Digital elevation models were also used

to guide the selection of locations to avoid areas of high slope. Sixty-two locations, in total, were sampled across all forest patches. At each location, three measurements of K were taken within a two m^2 area except for a few occasions in which an uneven slope led to taking measurements farther apart to site the infiltrometers on relatively flat areas.

We used tension infiltrometers (Mini-Disk Infiltrometer®, Decagon Devices, Pullman WA, USA) to take three measurements of K at each location. To ensure that measurements were performed on unsaturated soils, we avoided going out on days immediately following precipitation events. We applied a suction head of two cm to the infiltrometer to assess surface infiltration through meso- and micropores less than or equal to 1.45 mm in diameter. By preventing water from entering larger macropores, the effects of preferential flow paths are reduced and the infiltrometer captures infiltration capacity due to the matric potential and hydraulic forces present in the soil (Mini Disk Infiltrometer User Manual, Decagon Devices, Inc., Version: September 2, 2016). Roots and soil fauna in forests create macropores and preferential flow paths, so the device served as an accurate but conservative estimate of the ability of soil to infiltrate rainfall as measurements are conducted under tension that eliminate the influence of macropore flow.

Loose litter and organic debris were brushed out of the way, but without removing the O horizon if one was present, to ensure that the bottom of the infiltrometer made full contact with the surface soil. We then monitored and recorded the volume of water in the infiltrometer until at least 15 mL entered the soil. Manufacturer protocols were used to model the three measurements of K per location using the following equation:

$$k = \frac{C_1}{A}$$

where C_1 is the slope of the cumulative infiltration curve versus the square root of time, and A is a van Genuchten parameter based on the suction rate of the infiltrometer and texture class of the soil (Mini Disk Infiltrometer User Manual, Decagon Devices, Inc., Version: September 2, 2016).

2.3. Soil samples and physical properties

In the winter and spring of 2018, we used BD samplers to take three 5 cm diameter x 5 cm deep surface cores at 62 locations corresponding to the same places where we assessed soil infiltration capacity. To assess BD immediately below each infiltrometer measurement, all cores were taken without removing the O soil horizon. Soil BD was calculated by dividing the weight of the oven dried soil (105 °C, 72 h) by its volume. To calculate BD of the soil, mineral and decomposed organic material, large rocks and roots were accounted for by measuring total weight and volume through water displacement.

At the same locations, SOM, percent coarse fragment, and soil texture were determined. Three additional soil cores (0–5 cm) were homogenized and sieved to 2 mm to remove coarse fragments. Percent SOM was determined based upon loss on ignition of sieved soil (550 °C, 2 h). The percent of coarse fragments in each location was calculated as the weight of the cleaned and dried coarse fragment material divided by the oven-dried weight of the entire soil sample. Soil texture of the sieved soil was determined by feel analysis (Thien, 1979). In the field, prior to initiating each infiltration capacity test, we used a HydroSense Soil Water Measurement System (Campbell Scientific, Inc., Logan UT, USA) to measure soil moisture (volumetric soil water content) in the upper 20 cm of soil.

2.4. Soil capacity to infiltrate stormwater

We calculated the percent of precipitation infiltrated by these Baltimore forest patch soils based on the mean K measurements from each sampled location. We downloaded 38 years (1975–2013) of hourly

precipitation amounts in the Baltimore region from the NOAA National Centers for Environmental Information website (https://www.ncdc.noaa.gov/cdo-web/datatools/findstation). In these calculations, we excluded small wet-up events with one mm or less rainfall accumulation (following Ossola et al. 2015). Average K values at each sampled location were compared to how much precipitation fell during each hour of all of the storms combined. We assessed soil infiltration capacity by calculating the proportion of rainfall that could have been infiltrated during the 38-year period based on the measured K rates. In addition, we compare the mean K values per soil type to rainfall rates that are generated by storms of different durations and recurrence intervals (1-, 2-, 10-, 50-, and 100-year storms) (NOAA National Weather Service Hydrometeorological Design Studies Center Precipitation Frequency Data Server: https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=md). This gave us an approximation of the capacity of soil in urban forest patches to infiltrate stormwater generated by higher intensity storm events that occur less frequently.

2.5. Temporal changes in hydraulic conductivity

In July and August of 2018, we measured K rates about once every week in one location (39° 21′ 59.09" N, 76° 32′ 5.75" W) of the Maryland School for the Blind forest patch. This location was chosen for these measurements because it was also the location of another ongoing study that required weekly visits to monitor environmental sensors. This forest patch is characterized with having surface soils that are predominately sandy loam in texture, with an average BD of 0.95 g per cm^3 and an average SOM content of 11.89 percent. As part of a separate ecohydrologic monitoring study, we had installed 15 soil volumetric water content reflectometers (CS616, Campbell Scientific, Inc.) in this forest patch and deployed a weather station (HOBO U30 USB Weather Station, Onset Computer Corporation) outside of the forest patch to continuously monitor precipitation (0.2 mm Rainfall Smart Sensor, Onset Computer Corporation), temperature (Temperature and Relative Humidity Smart Sensor, Onset Computer Corporation), and additional weather parameters. This set-up allowed us to assess how changes to K rates over time are influenced by weather parameters and soil moisture conditions.

2.6. Statistical analyses

Due to the non-normality and heteroscedasticity of the data, we used Spearman's rank correlation to assess for monotonic relationships between explanatory and response environmental variables. We further explored linear associations using linear regression analyses of log-transformed data and accounted for a potential lack of independence among samples by checking for spatial autocorrelation using a semi-variogram and Moran's I coefficient. Kruskal-Wallis rank sum tests were used to assess soil texture class effects on K values and Wilcoxon two-sample tests using the BH (Benjamini-Hochberg) adjustment were used to identify which texture classes were significantly different from each other. We used the statistical package R (ver. 3.4.1, R Foundation for Statistical Computing, 2016) and RStudio (1.0.153 RStudio, Inc., 2009-2017) to perform our analyses.

3. Results

3.1. Soil physical properties

Mean soil physical property values for each forest patch are reported in Table 1. Soil BD averaged 0.88 ± 0.03 g per cm^3 (± 1 SE) and ranged from 0.41 to 1.47 g per cm^3 in the upper 5 cm of soil. SOM was significantly related to BD (rho = −0.82, n = 62, p < 0.0001), with low BD values corresponding to high SOM content. SOM ranged from 3.8 to 29.4 percent and averaged 11.4 ± 0.6 percent. In addition, the mean percent of coarse fragments for all 62 sampled locations was 7.4 ±

Table 1
Soil physical properties, unsaturated hydraulic conductivity (K), and calculated precipitation infiltration capacity for 21 forest patches in Baltimore, Maryland, USA. Reported values are means ± the standard error. From cores of the upper 5 cm of soil (including surface fine organic matter), BD = bulk density, SOM = soil organic matter, and CF = coarse fragments. VWC = volumetric water content in upper 20 cm of soil. Precipitation infiltration capacity (%) is calculated using NOAA precipitation records and measured K values. Forest patches identified by asterisks (*) are smaller forest patches nested within neighborhoods. All other forest patches are generally larger in size and protected under easement.

Forest Patch	Approx. size (ha)	BD (g/cm^3)	SOM (%)	CF (%)	VWC (%)	K (cm/hr)	Precipitation infiltrated (%)
Jonah House*	5	1.10 ± 0.08	8.5 ± 1.6	8.2 ± 3.6	18.4 ± 1.9	0.16 ± 0.04	40.5 ± 13.7
Seton Business Park	16	1.04 ± 0.09	9.6 ± 2.3	2.5 ± 2.2	26.9 ± 1.9	0.28 ± 0.06	58.6 ± 7.6
Arlington House	5	0.94 ± 0.02	10.9 ± 0.0	0.6 ± 0.1	30.4 ± 2.9	0.23 ± 0.05	48.7 ± 12.9
Heather Ridge	3	0.81 ± 0.15	12.0 ± 0.7	29.8 ± 27.8	29.3 ± 2.7	0.73 ± 0.27	75.4 ± 10.2
Sinai Hospital	15	1.06 ± 0.04	7.8 ± 0.8	17.1 ± 5.3	20.2 ± 4.4	0.54 ± 0.12	75.8 ± 8.0
Spring Garden Dog Walk*	2.5	0.82 ± 0.12	16.4 ± 6.6	0.1 ± 0.0	11.2 ± 0.6	0.24 ± 0.05	55.0 ± 7.3
Loyola University	22	0.81 ± 0.11	13.3 ± 1.7	24.1 ± 10.6	19.1 ± 2.4	1.51 ± 0.55	86.1 ± 8.5
Roland Park Country School	4	0.76 ± 0.08	12.5 ± 2.1	3.3 ± 2.0	8.5 ± 0.6	0.25 ± 0.03	58.6 ± 2.8
Gilman School	7	0.84 ± 0.14	13.2 ± 3.2	2.8 ± 1.8	15.4 ± 3.0	0.43 ± 0.11	72.3 ± 5.4
Friends School	6	0.88 ± 0.18	9.1 ± 1.3	35.4 ± 23.9	26.8 ± 2.3	1.53 ± 0.40	91.7 ± 3.7
Johns Hopkins University	28	1.20 ± 0.20	6.6 ± 2.8	20.9 ± 5.7	21.5 ± 0.9	0.69 ± 0.11	80.9 ± 6.9
Belvedere*	0.3	0.85 ± 0.03	12.0 ± 1.2	11.5 ± 4.1	28.3 ± 1.9	1.98 ± 0.35	88.4 ± 4.8
NMN*	0.5	0.96 ± 0.07	8.6 ± 1.4	9.1 ± 7.1	7.5 ± 1.3	0.73 ± 0.15	83.3 ± 5.0
Good Samaritan Hospital	6	1.06 ± 0.04	7.9 ± 1.4	1.4 ± 0.5	13.1 ± 1.7	0.14 ± 0.06	36.7 ± 10.4
Govans Urban*	0.4	0.84 ± 0.01	9.9 ± 1.3	1.7 ± 1.5	25.2 ± 1.6	0.67 ± 0.13	79.7 ± 8.4
Winston Govans*	1.5	0.75 ± 0.17	14.0 ± 3.3	9.9 ± 7.4	23.3 ± 2.5	1.63 ± 0.53	84.7 ± 9.7
Wilson Woods*	1	0.90 ± 0.09	9.6 ± 2.6	0.1 ± 0.0	21.5 ± 1.4	0.44 ± 0.10	71.4 ± 8.7
Springfield Woods*	2.5	0.80 ± 0.10	15.4 ± 1.7	3.7 ± 2.0	8.2 ± 0.7	0.55 ± 0.16	74.7 ± 10.0
HEPP*	3.5	0.62 ± 0.04	15.1 ± 1.6	17.8 ± 7.4	5.6 ± 0.8	0.64 ± 0.19	72.9 ± 10.5
Maryland School for the Blind	15	0.95 ± 0.05	11.9 ± 2.5	1.1 ± 0.6	11.8 ± 1.2	0.27 ± 0.07	55.7 ± 13.1
Fairwood Forest*	4	0.62 ± 0.07	15.7 ± 2.2	3.6 ± 0.9	14.9 ± 1.5	0.26 ± 0.06	51.9 ± 14.5

1.3 percent, with a minimum of 0 and a maximum of 46.0 percent. Volumetric water content (VWC) values prior to each infiltration capacity test ranged from 4.1 to 43.5 percent and averaged a value of 18.3 ± 1.2 percent. Most locations were classified as clay loam (n = 39), followed by loam (n = 12), clay (n = 8), and sand (n = 3) in soil texture.

3.2. Soil infiltration and capacity to infiltrate stormwater

We assessed soil infiltration potential in urban forest patches by measuring the unsaturated hydraulic conductivity in 21 Baltimore forest patches. Across all 62 sampled locations, hydraulic conductivity rate averaged 0.61 ± 0.3 cm per hr. Infiltration rates varied across forest patches (Table 1), and we detected no spatial autocorrelation of K values, suggesting that K rates are also dissimilar among locations within close proximity to each other (Moran's I. = 0.04, p = 0.2). Average K values for the 11 larger forest patches protected under easement did not significantly differ from the 10 smaller forest patches nested within neighborhoods (0.59 cm per hr and 0.62 cm per hr on average, respectively).

Based on 1978-2013 precipitation data from NOAA, 89% of the hourly recorded data generated precipitation that was either equal to or less than the average K value of 0.61 cm per hour or less. When accounting for how much rainfall fell during the higher intensity storm events that occurred for the other 11% of the hourly recorded data, these Baltimore forest patch soils have the capacity to infiltrate, on average, 68% of rainfall that fell during the time period of the NOAA data (Table 1).

3.3. Drivers of K

Spearman correlation analyses showed a positive, significant relationship between K and percent of coarse fragment (rho = 0.45, n = 62, p < 0.001). No significant correlations were found between K and SOM (rho = 0.07, n = 62, p = 0.6), and K and soil VWC (rho = 0.19, n = 62, p = 0.13). Linear regression analyses identified percent of coarse fragments as well as BD as significant (p < 0.05) predictors of K. However, the regression models had relatively weak R^2 values (Fig. 2a and b). Spatial autocorrelation within the data was

detected for soil BD and soil moisture (Moran's I. = 0.15, p < 0.01 and Moran's I = 0.26, p < 0.001, respectively), but not for percent of coarse fragments (Moran's I. = 0.05, p = 0.15) and SOM (Moran's I. = −0.02, p = 0.08).

Infiltration capacity was significantly higher in soils with high sand content compared to loam, clay loam, and clay soils (Fig. 3, Kruskal-Wallis rank sum and Wilcox two-sample tests, p < 0.05). K in loam, clay loam, and clay soils did not significantly differ from each other. Mean infiltration capacity (K/unit time) of each soil type was lower than rainfall rates produced by larger, less frequent storm events of ≤1 h durations and recurrence intervals of 1, 2, 10, 50, and 100 years, except for sandy soils in a 1 h, 1 year storm.

3.4. Temporal changes in K

Continuous monitoring of K in one forest patch revealed the dynamic nature of soil hydraulic conductivity (Table 2). Lower values of K rates were observed in mid-to late July of 2018, after a few weeks of minimal rainfall. In contrast, late July through mid-August saw high rates of K at the same location. This increase in K can be attributed to a continuous period of high rainfall starting in mid-July that led to a new rainfall record for the month of July in Baltimore. It can also be attributed to subsequent changes to the urban forest patch soil's water content, which more than doubled from July 5th to August 14th (Table 2).

4. Discussion

4.1. Urban forest patch soil's capacity to infiltrate stormwater

Based on the observed average K rates, unsaturated surface soils in urban forest patches are capable of fully infiltrating low-intensity (< 0.25 cm per hr) to moderate-intensity (0.25–0.61 cm per hr) rainfall events that have been historically common (i.e. approximately 89 percent of hourly rainfall amounts greater than 1 mm) in the Baltimore region. In contrast, high-intensity storm events that occur less frequently, with 1, 2, 10, 50, and 100 year recurrence intervals in the Baltimore region, generate rainfall rates that exceed the average K. Therefore, urban forest patch soils infiltrate some but not all of the
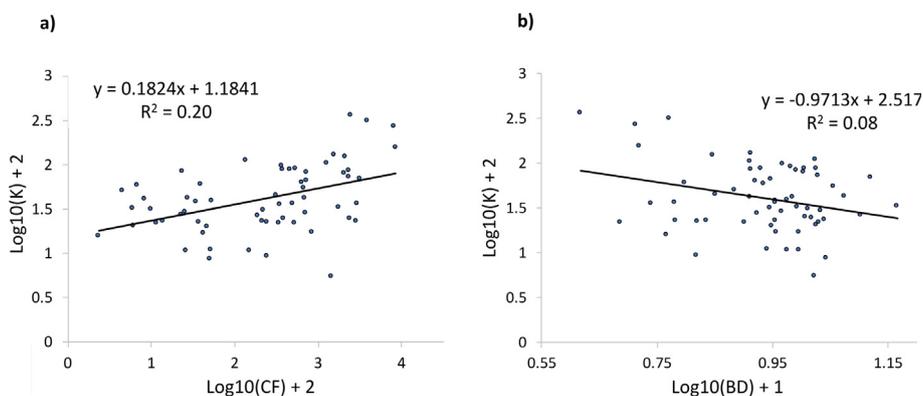
a)

b)

Fig. 2. The relationship between soil infiltration capacity, measured as the unsaturated hydraulic conductivity (K) in cm per hour, and (a) the percent of coarse fragments (CF) in soil and (b) soil bulk density (BD) in 21 forest patches in Baltimore, Maryland, USA.
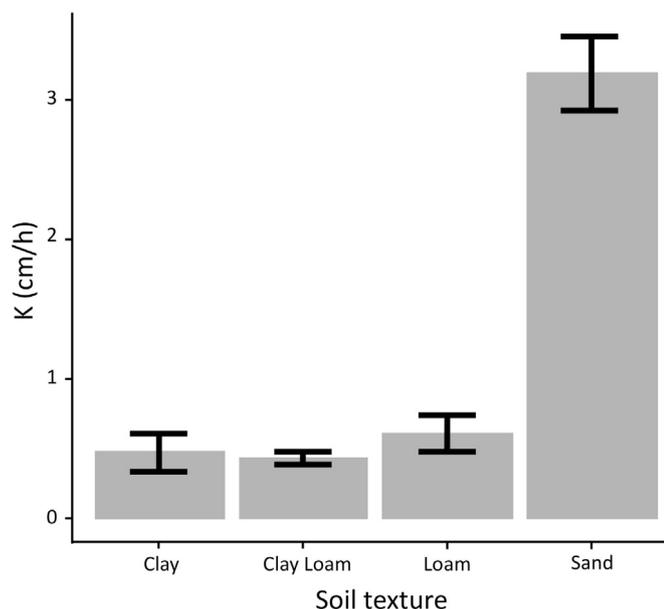

Fig. 3. Average unsaturated hydraulic conductivity (K) rates for different soil texture classes in 21 urban forest patches in Baltimore, MD, USA. Error bars represent the standard error.

Table 2
Temporal changes in unsaturated hydraulic conductivity (K) are associated with changes in soil volumetric water content and antecedent rainfall. Measurements of K and soil volumetric content were monitored at one forest patch, and a rain gauge outside of the patch monitored rainfall.

Date	K (cm/hr)	Soil Volumetric Water Content (%)	Date of last rainfall event > 1 mm	5-day total antecedent rainfall (mm)
07/05/2018	0.073	16.3[a]	6/24	0
07/13/2018	0.055	14.2[a]	6/24	0
07/19/2018	0.066	17.3	7/17	22.2
07/30/2018	1.226	33.4	7/29	20.4
08/07/2018	1.327	31.9	8/06	11.2
08/14/2018	2.162	33.7	8/13	44.4

Volumetric water content sensors at another location within the same forest patch.

[a] Due to sensor failure on July 5th and 13th, these data were taken from soil.

stormwater during those storm events. When accounting for the measured K rates and the total hourly precipitation amounts generated from 1975 to 2013, the urban forest patch soils could infiltrate 68% of rain that fell on these sites.

The observed K rates in Baltimore forest patches are similar to K rates in public and private urban forests and green spaces (Shuster et al., 2015, 2017; Herrmann et al., 2017; Ossola et al., 2015). Although we expect soils in urban forest patches to have relatively high infiltration rates compared to non-forested areas (Bartens et al., 2008; Kuehler et al., 2017), our measurements of K are conducted under a slight tension that eliminates macropore flow and are conservative estimates. Macropores are abundant in forest soils and conduct most of water flux under saturated soil conditions (Watson and Luxmoore, 1986). The difference between unsaturated and saturated hydraulic conductivity is evident in Ossola et al. (2015), who saw higher soil K rates in saturated conditions as opposed to in unsaturated conditions for remnant forests and urban parks with high-complexity habitats relative to urban parks with low-complexity habitats.

Results from studies of surface K measured under slight tension in bioretention cells indicate that designed green infrastructure elements are capable of infiltrating rainfall at a K rate at least twice as fast as what was observed on average in Baltimore forest patches. Shuster et al. (2017) studied a two-tiered infiltrative rain garden system during the warm-season periods from 2012 to 2015 and report near-saturated hydraulic conductivity rates of 2.2 ± 0.4 and 2.0 ± 0.5 cm per h for the mulch surface soils of the two rain gardens. Below the mulch layer, infiltration capacity in the loamy sand soil of one garden varied by year and peaked at 12.9 ± 1.7 cm per hr. In another rain garden in Cleveland, Ohio, hydraulic conductivity averaged a rate of 1.2 ± 0.82 cm per hr for the A horizon and approximately 8 cm per hr for the engineered biosoil (Stewart et al., 2017).

4.2. Soil physical properties as drivers of infiltration

The percent of coarse fragments in the top 5 cm of soil was the most important soil property for determining K rates. Soils with relatively high percentages of coarse fragments had higher K rates (Fig. 2). Soil BD was also determined as a key driver in linear regression analyses. However, a weak R^2 value for the relationship between BD and K (Fig. 2b) suggests that other soil properties are more important in determining K. Low BD soils did display high K rates but this was not consistent across all locations. Although other studies have shown that the saturated hydraulic conductivity decreases with soil compaction due to a reduction in macropore space (Gregory et al., 2006; Yang and Zhang, 2011), Ossola et al. (2015) found no significant relationship between BD and the saturated hydraulic conductivity in parks and forests in Australia. Therefore, although soil BD likely affects K, further research is needed to refine using BD as an ecosystem service indicator of infiltration capacity (Ahern et al., 2014; Herrmann et al., 2017). In our study, SOM, which was strongly related to BD, did not significantly correlate with K and may also be a poor indicator of infiltration capacity.

Percent of coarse fragments in a given soil and soil texture were key determinants of K. Urban forest patch soils with high sand content demonstrated higher infiltration potential compared to other soil texture classes (Fig. 3). Our study shows that urban soils confirm these theoretical soil relationships between texture and infiltration. Thus, coarser-textured urban forest patch soils that have high sand content and/or abundant coarse fragments ($\geq 2\,mm$) have a higher capacity to infiltrate rainfall and reduce surface runoff. These two soil physical characteristics could be used as indicators to identify locations of high infiltration potential.

4.3. Temporal changes in K and importance of soil moisture

Studies have depicted a non-linear, positive relationship between soil moisture and K until K reaches steady-state infiltration as expressed by the saturated hydraulic conductivity (Chaudhari et al., 2015; Homolák et al., 2009). We did not find a significant relationship between the average soil water content and average K per location. However, our results still point to the importance of soil moisture after monitoring the dynamics of K at one forest patch location over a period of time with substantial changes to the soil's water content (Table 2). As soil moisture content increased at this site, so did the hydraulic conductivity. A sharp increase in K with increasing soil moisture has also been reported in Gonzalez-Sosa et al. (2010) and Gadi et al. (2017). The former study attributed the increase to the macroporosity effect as soils approach saturation. Indeed, the hydraulic conductivity is a function of the soil matric potential, related to soil moisture content. As soil moisture decreases, the matric suction increases and hydraulic conductivity declines due to the drying of the largest macropores that empty out quickly and become filled with air, consequently obstructing water flow (Gallage et al., 2013; McCartney et al., 2007). The rate that water can move through the soil is then determined by flow through the smaller pores that are not filled with air or by slow movement of water along the walls of the larger pores. The path available for water to becomes more difficult with a decline in soil saturation (Gallage et al., 2013; McCartney et al., 2007). The opposite effect is the case as soil moisture increases and larger soil pores become filled with water, increasing the conductivity of water.

Our monitoring of K over time in one forest patch shows soil hydrological characteristics such as K vary over time and are a function of dynamic properties such as soil moisture. To assess infiltration capacity, we calculated the percent of stormwater infiltrated per location based on rainfall data from 1975 to 2013 and the measured K rates. By doing so, we assumed that the K measurements taken across the 21 forest patches were constant for all years. We already knew that the measurements of K in Baltimore forest patches serve as conservative estimates of infiltration capacity due to tension infiltrometer technique preventing flow in macropores greater than 1.45 mm in diameter. Still, the temporal dynamics observed indicate the macroporosity effect can also be registered by the tension infiltrometer for meso- and macropores less than 1.45 mm in diameter. Thus, we speculate that some of the measurements taken in relatively dry soil conditions (approximately ≤ 18% VWC) may have registered flow only through the smallest pores in the soil and therefore represent an even more conservative estimate of infiltration. Although our calculations made some assumptions about constant K values, urban forest patches are likely capable of infiltrating more stormwater than our estimate of 68% of rainfall in Baltimore.

4.4. Implications for urban stormwater management

Urban ecosystem service studies to support management rely on coarse-scale mapping or modeling techniques to evaluate ecohydrological processes (Gonzales-Sosa et al., 2017; Ossola et al., 2015; Revelli and Porporato, 2018; Rova et al., 2015; Tratalos et al., 2007). Yet, finer-scale local site conditions are important drivers of infiltration

services of forest patches. While measuring steady-state infiltration rates in the field can be difficult and time-consuming to do, empirical measurements of surface soil K are relatively quick and give an indication of infiltration capacity and how it varies between locations. Quantifying K in urban forest patches offers new data on infiltration capacity and contributes to the broader knowledge of the role of urban forests for management goals of reducing stormwater runoff.

A challenge of using urban forest patches for stormwater management is that they are not designed to store and infiltrate a certain amount of stormwater, so knowing the infiltration capacity at a site is necessary. Our research shows urban forest patch soil infiltration capacity is determined by soil physical properties such as texture and abundance of coarse fragments. Moreover, infiltration capacity and some soil physical properties (e.g., percent of coarse fragments) were not spatially autocorrelated. This reinforces the importance of site specific analyses of soil conditions for urban management and ecosystem service provision despite recent studies that report common patterns and convergences in urban soils across the USA (Herrmann et al., 2018) and the globe (Pouyat et al., 2015).

Stormwater management frequently uses impervious area as an indicator of urbanization stresses. Expansion and maintenance of urban forest cover will reduce impervious cover and allow the restoration of ecosystem and hydrologic processes (Law and Hanson, 2016). However, the nature of site connectivity and stormwater flow paths has implications for stormwater flow reduction, rather than simply reducing impervious cover (Jefferson et al., 2017; Meierdiercks et al., 2017; Roy and Shuster, 2009). Thus, integrating measures of soil infiltration into a predictive understanding of the flow paths that bring water into and out of a forest patch will be important for successfully managing stormwater flows with urban forest patches.

Mean K was relatively lower in urban forest patches compared to SWGI (i.e., rain gardens and bioretention cells) (Shuster et al., 2017; Stewart et al., 2017). Despite having similar goals with respect to stormwater mitigation, urban forest patches and SWGI practices offer differing management solutions for urban watersheds. SWGI can be designed for certain conditions, yet the performance of SWGI, and decisions about its cost-effectiveness and adoption, are linked to proper long-term maintenance and management (Montalto et al., 2011). Urban forest patches are multifunctional and provide additional ecosystem services that extend beyond water-based services of SWGI (Livesley et al., 2016). Managing urban forest patches from a position of multifunctionality proceeds from several potential 'rationales' (Ordóñez Barona, 2015). Public values of urban forest patches (Ordóñez Barona, 2015) include concepts such as, aesthetics, recreation, economic values, sense of place, and functional attributes (i.e., ecosystem services). Stormwater mitigation itself perhaps fits more squarely in a service-based rationale for urban forest patches. Urban forest management for multifunctionality should engage processes that incorporate diverse stakeholder and public values to minimize potential disconnects and conflicts (Lovell and Taylor, 2013).

Our study suggests urban forest patches impact the hydrology of cities via soil infiltration, and therefore they are an important element of the city's green infrastructure portfolio. Urban forest patches constitute 34% of the tree canopy in Baltimore (Avins, 2013), which in turn constitutes approximately 27% of the landscape in the city (Chuang et al., 2017). Smaller forest patches are as important as larger forest patches; in our study, the smallest patches nested in neighborhoods had similar K rates as larger forest patches protected under easement (Table 1). Urban forests contribute to stormwater runoff mitigation through other ecohydrological functions, such as interception (Inkiläinen et al., 2013; Nytch et al., 2018; Ossola et al., 2015), transpiration (Chen et al., 2011; Wang et al., 2012). The conservation and expansion of forest patches in cities can therefore make potentially large contributions to runoff mitigation by promoting ecohydrological functions that infiltrate, intercept, and transpire rainfall. Future research should investigate the effects of tree interception, transpiration,

antecedent moisture conditions, root channels, and soil macropores in urban forest patches to determine how these mechanisms integrate to affect runoff.

5. Conclusion

In this study we evaluated infiltration capacity across 21 urban forest patches in Baltimore. We found that infiltration capacity is temporally dynamic and dependent on soil moisture conditions, in addition to soil properties that are more stable over time. In particular, soil texture and the percent of coarse fragment material in soils can serve as ecosystem service indicators to identify locations in forest patches that exhibit higher infiltration capacity. Future research should investigate additional ecohydrologic mechanisms (i.e., interception, transpiration, and the effects of root channels and macropores), as well as landscape connectivity in urban forest patches to develop an integrative understanding of how urban forest patches affect runoff.

Our data show that urban forest patch soils have the potential to infiltrate most precipitation events. The infiltration capacities we observed in forest patches suggest that they are important stormwater control measures and contribute to reducing runoff and flooding in urban areas. Management of urban forest patches for stormwater mitigation is aided by site-specific knowledge of infiltration mechanisms and an approach that accounts for the multifunctional nature of the ecosystem services provided by urban forests.

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