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K in an Urban World: New Contexts for Hydraulic Conductivity

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Research Impact Statement: Hydraulic conductivity (*K*) is not typically measured on nor specifically predictable for urban landscapes. We take a data-based approach to inform authentic estimation of *K* in urbanized soils.

ABSTRACT: Hydraulic conductivity (*K*) is a key hydrologic parameter widely recognized to be difficult to estimate and constrain, with little consistent assessment in disturbed, urbanized soils. To estimate *K*, it is either measured, or simulated by pedotransfer functions, which relate *K* to easily measured soil properties. We measured *K* in urbanized soils by double-ring infiltrometer (K_{dring}), near-saturated tension infiltrometry (K_{minidisk}), and constant head borehole permeametry (K_{borehole}), along with other soil properties across the major soil orders in 12 United States cities. We compared measured *K* with that predicted from the pedotransfer function, ROSETTA. We found that regardless of soil texture, K_{dring} was consistently larger than K_{minidisk}; with the latter having slightly less sample variance. K_{borehole} was dependent upon specific subsurface conditions, and contrary to common expectations, did not always decrease with depth. Based on either soil textural class, or percent textural separates (sand, silt clay), ROSETTA did not accurately predict measured *K* for surface nor subsurface soils. We go on to discuss how *K* varies in urban landscapes, the role of measurement methods and artifacts in the perception of this metric, and implications for hydrologic modeling. Overall, we aim to inspire consistency and coherence when addressing *K*-related challenges in sustainable urban water management.

(KEYWORDS: urban hydrology; hydraulic conductivity; urban soils; infiltration; hydrologic modeling.)

INTRODUCTION

Hydraulic conductivity is a hydrologic variable of wide interest. While there are numerous definitions of this parameter, we define hydraulic conductivity (hereafter referred to as *K*) in its most general sense, as a physical descriptor of how easily water moves into and through a porous media such as soil. *K* describes water movement in all three dimensions, in which water can move laterally when it encounters a restrictive soil horizon, or in other directions depending on local soil texture and other factors. Overall, *K* is usually viewed in terms of moving water vertically through the soil profile. In formal terms, *K* (*L*/*T*) is defined as the proportionality constant that relates

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the hydraulic flux (Q, L/T) to a driving force such that:

$$Q = K\nabla\Phi \quad (1)$$

where Φ represents net hydraulic head.

The actual measurement of hydraulic conductivity has an impressive, if daunting, menu of methods. At the simplest (and most unconstrained) end of the spectrum, the rate of water movement into soil is estimated by digging a cylindrical hole in soil, filling the hole with water, and observing the decline in water level over time. This process is often observed until such a time that the rate of inflow reaches a quasi steady-state. However, this simple procedure does not involve a formal measure of K, because the hydraulic driving force is not specified. Other, more specific, methods attempt to constrain and otherwise account for real-world, highly dynamic pressure head conditions. These methods can impose hydraulic head gradients involving positive or negative (i.e., tension) drivers for water flow in soils. K is sensitive to soil texture, layering of horizons and restrictive layers, and unique to urban systems, the type, volume, and concentration of anthropogenic materials (Shuster, et al. 2014). Altogether, the physical imprints of urbanization layer on top of intrinsically high variability in K across relatively small spatial extents (e.g., meters; Warrick and Nielsen 1980; Rienzner and Gandolfi 2014) wherein coefficients of variation often exceed 100% (Asleson et al. 2009).

Within urban areas, K represents a major unknown. Urbanized soils are different from other soils in that they are a product of a disturbance regime that can include development, demolition, and redevelopment (Figure 1a). Disturbances involve importing borrow fill from another location, moving and otherwise mixing soils, compaction and leveling of the landscape, addition of anthropogenic materials, varying degrees of re-vegetation, and overall resetting the baseline condition from which a new soil forms. Specifically, urban soils (Figure 1b, 1c) exhibit distinct texture and structure within soil profiles; compact, dense soil structure (Olson et al. 2013); surface crusts on bare soil that restrict aeration and drainage (Assouline and Mualem 2002); presence of anthropogenic materials (Barbu and Ballestero 2014; Shuster et al. 2014); losses of fine-textured, subsurface "B" horizons due to anthropogenic activity (Herrmann et al. 2018); and altered vegetation or other biota (see Godefroid and Koedam 2007; Rienzner and Gandolfi 2014).

Given these complexities, along with the high spatial variability of K, field measurements of K are often time consuming. Instead, a more common approach in agricultural systems has been to synthesize large samples of physical data from soil horizons and to generalize this information as pedotransfer functions. The pedotransfer function estimates properties such as hydraulic conductivity from more easily measured soil attributes like soil texture via linear regression equations (Rawls et al. 1982; Schaap et al. 2001). Pedotransfer functions involve a general tradeoff among level of effort (e.g., type and extent of field measurements) and accuracy in prediction, which is treated in Schaap et al. (2001). The combined impacts of both extrinsic (e.g., urbanization) and intrinsic (e.g., spatial variability) influences on K may be particularly important in the case of simulation with pedotransfer functions that are largely based on data from agricultural soil horizons. The reduced accuracy of pedotransfer functions with depth, even in agricultural soils, is often attributed to the model sensitivity to clay and organic matter content (Wagner et al. 2004). Soils in urban environments exhibit different textural and organic matter compositions compared to agricultural, near-surface soils. This suggests that pedotransfer functions may need to be re-calculated to generalize across what are unique urban soil properties. In short, variation in materials and arrangement of the soil profile encountered in urban soils creates a soil whose K defies generalizable estimation.

As K regulates the movement of water into landscapes and its redistribution within the subsurface, its estimation is key to informed urban water resources management. In this way, urban landscape-level hydrology is an ascendant context for mitigating stormwater runoff and managing wastewater with hybrid gray-green infrastructure (GI). The hydraulic interface between soils and constructed pipe networks are regulated in part by K (Figure 1c) and local conditions. The perforation of soil profiles by often leaky conveyances and their exchange with surrounding soils forms what Garcia-Fresca and Sharp (2005) termed an urban karst. Rainfall that infiltrates into the soil profile can concentrate soil moisture around leaky pipe-joint infrastructure or allow groundwater to enter the pipe (Bhaskar and Welty 2012; Bonneau et al. 2017). These sources of inflow and infiltration into the pipe network serve to reduce overall sewer system capacity, which can lead to combined sewer system overflows.

K in urban soils is different than in other soils, but there has been no comprehensive, consistent assessment of urban soil hydraulic conductivity. In order to better understand how urban K may be different due to its unique disturbance regime, we pose the general hypothesis that simulated K estimates — from a generalized pedotransfer function based on agricultural soils and disaggregated soil horizons — are similar to those measured in urban soils. We address this

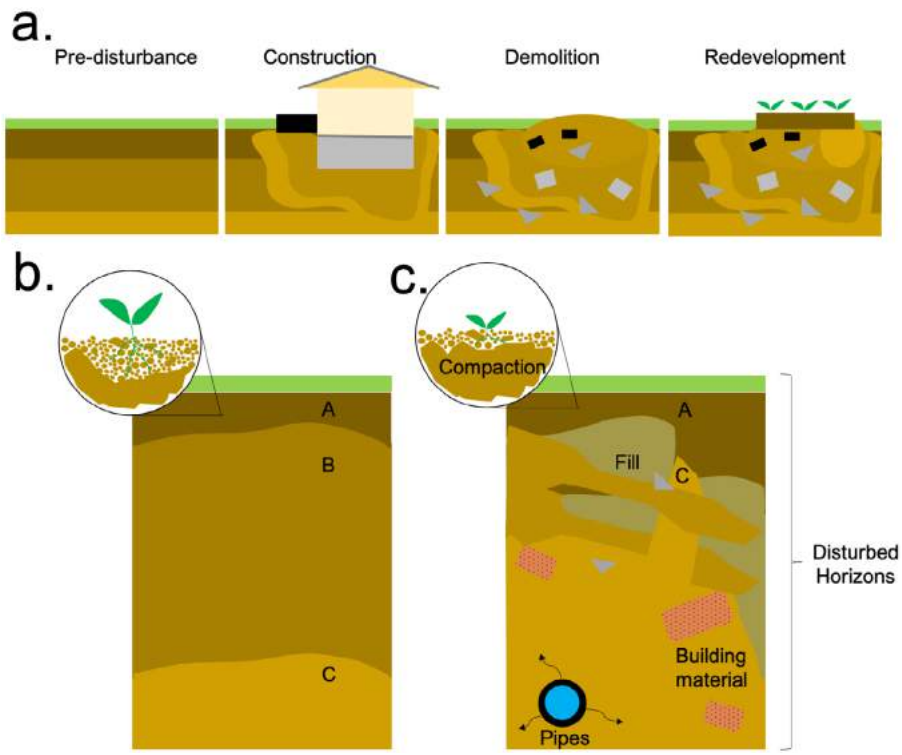

FIGURE 1. Schematic illustrates: (a) how urbanization can sequentially impact soils and their arrangement compared to (b) soils with traditional A-B-C horizons; (c) urban soils have distinct features including disturbed or altogether missing B horizons, the presence of anthropogenic artifacts, uneven vegetative cover and compaction, and buried infrastructure.

hypothesis with three questions: (1) How do different approaches to the field measurement of K in urban landscapes vary and otherwise compare?; (2) How does K vary in the urbanized subsurface?; and (3) How do estimates from popular pedotransfer functions (a standard of prediction) compare to measured K in the urbanized surface and subsurface? We use an extensive set of one-time field measurements made in 12 cities across the United States (U.S.) to characterize hydraulic conductivity under different conditions and thereby address our hypothesis and questions.

METHODS

In the period 2010-2016, we undertook field assessment work in different cities throughout the U.S., accounting for 10 of the 12 major soil orders. In chronological order of their assessment, these cities are: Cleveland, Ohio (Alfisol); Cincinnati, Ohio (Alfisol); Omaha, Nebraska (Alfisol); Detroit, Michigan (Alfisol, Mollisol); Phoenix, Arizona (Aridisol); New Orleans, Louisiana (Vertisol, Histosol); Tacoma, Washington (Andisol); San Juan, Puerto Rico (Oxisol, Ultisol); Camden, New Jersey (Spodosol); Portland, Maine (Spodosol); Atlanta, Georgia (Ultisol); and Majuro atoll Republic of the Marshall Islands (Entisol). This work involved deep-soil borings, full taxonomic characterization (including soil textural class, color, evidence of anthropogenic activity and artifacts, legacy water table depth, sand size breakouts) of these borings, and near-surface hydraulic datasets (Herrmann et al. 2018; Schifman and Shuster 2019). Measurements were made on urbanized land parcels, and land uses included: vacant residential and commercial parcels, parks, and right-of-way in residential or commercial areas.

There are several measurement options available to researchers and practitioners for observing K; we therefore used multiple methods for comparison. We employed double-ring infiltrometry to represent a simple, well-recognized method to estimate K as infiltration rate (Reynolds et al. 2002), hereon K_{dring}. The procedure involved: pounding rings into a representative patch on the urbanized plot to 50 mm ring penetration depth; placing rings of furnace filter material on the soil surface to protect from splash erosion; maintaining a steady 100 mm water level in both the inner and outer rings; noting inflow rate in the inner-ring over time; and replenishing both ring areas as necessary to maintain a constant head. Across all cities, this measurement was performed at two locations in each parcel, one at the center, the other at the rear of the parcel and outside of the built envelope of the previously developed area. This latter subarea would be nominally less disturbed than the interior demolished area. For parks, right-of-way, and other unbounded parcels, we used the centroid of the area permitted for access as a reference point to set out equidistant measurement points along a line transect. We recorded water level in the infiltrometer at 0, 1, 2, 3, 4, 5, 10, 15, 20 min, and either in this period, or at additional readings at five-minute intervals, three equal drops in water level at equal five-minute intervals indicated the quasi-steady infiltration rate (mm/h). Due to the positive pressure head, vertical one-dimensional gravitational flow was assumed as is customary for this experimental condition.

As an alternative to the double ring, we also estimated surface K via tension infiltrometer (hereafter K_{minidisk}; Mini-Disk Infiltrometer, METER, Pullman, Washington). The tension infiltrometer was set to pressure head of −20 mm, placed on the soil surface (coarse organic matter brushed away, if necessary), and a time series of inflow rates were recorded. This measurement was made at four locations in a given vacant parcel, along a transect from front to rear of the parcel, with assessment within and outside of the demolition envelope. Other landuse-land covers were assessed as described above for double-ring methods. After recording infiltrometer water level readings at 0, 1, 2, 3, 4, 5, 10, 15, 20 min, either within this period, or as additional readings at five-minute intervals, a consecutive three equal drops in water level at equal time intervals indicated the quasi-steady infiltration rate (mm/h) at the specified tension. The inflow was assumed to be three-dimensional into the soil matrix, and predominantly driven by matric potential gradients. To calculate K_{minidisk} values under these near-saturated conditions, we used recommended manufacturer procedures, which are based on the method of Zhang (1997). Estimation of K_{minidisk} required specification of soil texture. On each parcel, we determined surface soil texture in two ways: in the field with a qualitative soil textural class by feel protocol (Thien 1979), and in the lab by quantitatively by calculating the proportion sand, silt, and clay fractions via the pipette method (Gee and Bauder 1986). The van Genuchten parameters (n, α) correspondending to soil textural class were selected to complete the calculation of K_{minidisk} following Zhang (1997).

Also unknown is how K varies with depth in urban soils. Therefore, we estimated subsurface K at 2 locations per vacant parcel, at the center of the parcel, and then again at the rear of the parcel. Other landuse-land covers were assessed as described above for double-ring methods. To estimate saturated hydraulic conductivity in subsoils (K_{borehole}), a constant head permeameter was set to maintain a 150–250 mm depth of water in a borehole evolved to the depth just above the shallowest restrictive layer (i.e., nominal range of 1,000–3,000 mm; see Shuster et al. 2014). We recorded water level in the permeameter at 0, 1, 2, 3, 4, 5, 10, 15, 20 min, and either in this period, or through additional readings at five-minute intervals, consecutive three equal drops in water level at equal five-minute intervals indicated the quasi-steady infiltration rate (mm/h). Three equal drops in water level at equal time intervals indicated the quasi-steady infiltration rate (mm/h) under assumed saturated conditions. Using numerical methods suggested by Amoozegar (1989), we transformed observed outflow to K_{borehole}.

To complement measured K, we predicted K via a pedotransfer function that is encapsulated in the software package ROSETTA (Schaap et al. 2001). The ROSETTA algorithm estimates K via parameters based on van Genuchten (1980) hydraulic models, using soil texture attributes as the most basic input parameters. In this study we input textural data from each urban sampling location into ROSETTA to predict K, based on two types of data input: qualitative soil textural class (TEX); and as percent sand, silt, and clay (SSC) fractions. We use these predicted K from ROSETTA as a standard for comparison. The common and frequent use of this software program for the prediction of K is an alternative to direct measurements, especially as its integration into popular hydrologic models, such as HYDRUS (Šimůnek et al. 2008). This approach produced two model estimates of K (based on texture, $K_{\text{ROSETTA-TEX}}$; based on sand, silt, and clay fractions, $K_{\text{ROSETTA-SSC}}$) as well as associated confidence intervals for each prediction. ROSETTA was applied at the surface (for comparison to K_{dring} and K_{minidisk}) as well as in the subsurface (for comparison to K_{borehole}).

To address our stated hypothesis and research objectives, we performed several comparisons among these five approaches to estimate K (K_{dring}, K_{minidisk}, K_{borehole}, $K_{\text{ROSETTA-TEX}}$, and $K_{\text{ROSETTA-SSC}}$). These comparisons were performed using observations made within the same parcel across 12 cities, though not all field measurements were conducted on all parcels. In total, we showed comparisons across 236 parcels consisting of measurements with the different field methods, along with prediction via the ROSETTA pedotransfer function.

RESULTS AND DISCUSSION

How Do Different Observations of Urban K *Compare?*

K_{dring} and $K_{minidisk}$ represent two surface-based estimates of K. Across all cities and 343 measurement pairs, K values extended across five orders of magnitude for each measurement approach, demonstrating a considerable range of urban K measured both inside and outside of the continental U.S. Double-ring infiltrometer observations (K_{dring}, y-axis) covered the interval from 1 to approximately 10,000 mm/h (Figure 2), whereas tension infiltrometer-based observations ($K_{minidisk}$, x-axis) ranged from 0.5 to approximately 1,000 mm/h.

By way of comparison, K_{dring} is typically larger than $K_{minidisk}$ across the full range of soil textural classes (Figure 2), and the two types of K measurements are uncorrelated ($R^2 = 0.08$, $n = 343$). Yet, K_{dring} was slightly smaller than $K_{minidisk}$ for a few measurements made in coarser soils (e.g., sandier soil texture). The different measurement mechanisms and soil conditions apparently were not material in the range of these higher K values. From a qualitative standpoint, $K_{minidisk}$ had more sensitivity in the lower range of K. This difference in range of variation is attributed to $K_{minidisk}$ data being constrained to a near-saturated measurement. Under these measurement conditions, the slight tension at the soil surface cuts off inflow to macropores, be they structural cracks at the surface of urban soils or biopores. From a practical perspective, the ease of $K_{minidisk}$ measurement compared to K_{dring} may encourage a higher density of measurements that would generate a metric of uncertainty (e.g., standard error of the mean), which itself would decrease with greater numbers of measurements. This approach would be important for quantifying and constraining uncertainty in K under urbanized landscape conditions.

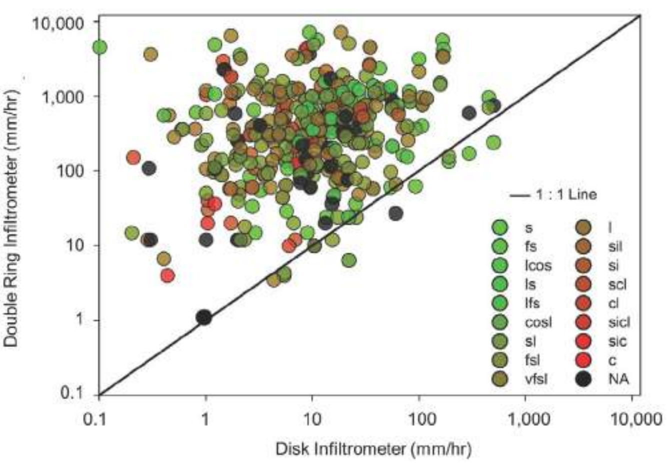

FIGURE 2. Comparison of surface K measurements ($n = 343$) obtained through tension infiltrometer ($K_{minidisk}$) and double-ring infiltrometers (K_{dring}). Points are color coded by soil texture: s, sand; fs, fine sand; lcos, loamy coarse sand; ls, loamy sand; lfs, loamy fine sand; cosl, coarse loamy sand; sl, sandy loam; fsl, fine sandy loam; vfsl, very fine sandy loam; l, loam; sil, silty loam; si, silt; scl, sandy clay loam; cl, clay loam; sicl, silty clay loam; sic, silty clay; c, clay; NA, texture class not noted.

The difference in magnitude between these two measurement approaches is important to recognize, and may be due to several different factors. First, it may be attributed to differences in sampling surface area. The area of the tension infiltrometer base is a fraction of that for double-ring methods; thus, there is a difference in the actual surface area measured. A larger sampling area and surface disturbance from placing infiltrometer rings may have incorporated, or created, macropores or cracks. The double-ring technique uses a positive hydraulic head to push water into all surface-connected pores to estimate K_{dring}. An increased capture of macropores in the larger double ring sampling area, flowing under gravity from ponding, would serve to increase K_{dring}. The double-ring method suffers from other sources of uncertainty, such as lateral flow from the inner ring (Lai and Ren 2007). This is a deviation from the assumed vertical flow, and would serve to increase K_{dring}.

Likewise, differences in magnitude may arise from assumptions required by these methods. The procedure used to compute $K_{minidisk}$ from tension infiltration data requires selecting appropriate van Genuchten n and α parameters (Zhang 1997). These parameters govern the specific shape of the curve that determines the K estimate. The n and α parameters can vary widely for any given soil texture class, and this generalization of parameters imparts a source of uncertainty in $K_{minidisk}$. We note here that urbanized soils in different cities possessed unique texture, clay minerology, or both soil attributes, thereby falling outside of standard soil textural classes. For example, soils assessed in New Orleans, Louisiana featured expanding clays in Vertic soil horizons and organic soils in Histic horizons. Soils in Detroit, Michigan often had a sand fraction predominantly composed of fine- and very fine-sized sand classes. These finer sand size classes were either smaller than or approached the size silt-sized particles. In terms of hydraulics, these more finely textured sands depressed measured $K_{minidisk}$ values (Schifman and Shuster 2019). Therefore, using generally accepted parameters for traditional soil textural classes implicitly assumes that users are knowledgeable of how uncertainty in these parameters is subsequently propagated through to the calculation of $K_{minidisk}$.

How Do Estimates from Pedotransfer Functions Differ from Observations of Urban K?

ROSETTA underpredicted 80% of $K_{minidisk}$ values and nearly all K_{dring} values (Figure 3). Furthermore, ROSETTA estimated discrete K values when a categorical soil textural class was used as the input ($K_{ROSETTA-TEX}$; Figure 3), with each texture associated with one average value (Schaap et al. 2001). In contrast, K predicted from the continuous variables of percent sand, silt, clay ($K_{ROSETTA-SSC}$) yielded similarly continuous estimates of K. These predicted K were more evenly distributed about the 1:1 line. In contrast to the nearly five order-of-magnitude differences measured in $K_{minidisk}$, the uncertainty bounds of the ROSETTA-estimated K only varied from ~0.8 to ~10 mm/h (Figure 4), and overlapped with field observations for low K values only (<10 mm/h). ROSETTA and field observations overlapped for lower K (<10 mm/h), whereas the field observations were consistently larger than ROSETTA estimates for higher K (>10 mm/h).

We conclude that ROSETTA cannot be expected to predict the range of K values measured in urban settings, especially for high conductivity soils. As for any predictive relationship, pedotransfer functions like ROSETTA are inextricably tied to and constrained by the sampling data upon which they were built. This sample set was composed of soil data (soil texture, K) from numerous soil horizons that were treated as independent samples. Furthermore, the sample set was predominantly drawn from agricultural soil horizons, with little representation of extremes in soil texture, like clay or sand soil textural classes (Rawls et al. 1982; Nemes et al. 2003, 2009; Cronican and Gribb 2004; Gribb et al. 2004; Rubio 2008; Or 2019; Schifman and Shuster 2019). The absence of extremes and predominance of certain soil textural classes under widely varying soil structural conditions presents bias. This bias can be amplified in the regression procedures used to relate soil characteristics to predict a value for K. Schaap et al. (2001) provide a great deal of detail as to limitations and cautionary advice with regard to the application of algorithms like ROSETTA. For these reasons, all of the factors that contribute to variability in K are part of the measurement context. The lack of agreement between observed and simulated data is likely attributed to high variability in texture and hydraulic conductivity across horizons within soil profiles;

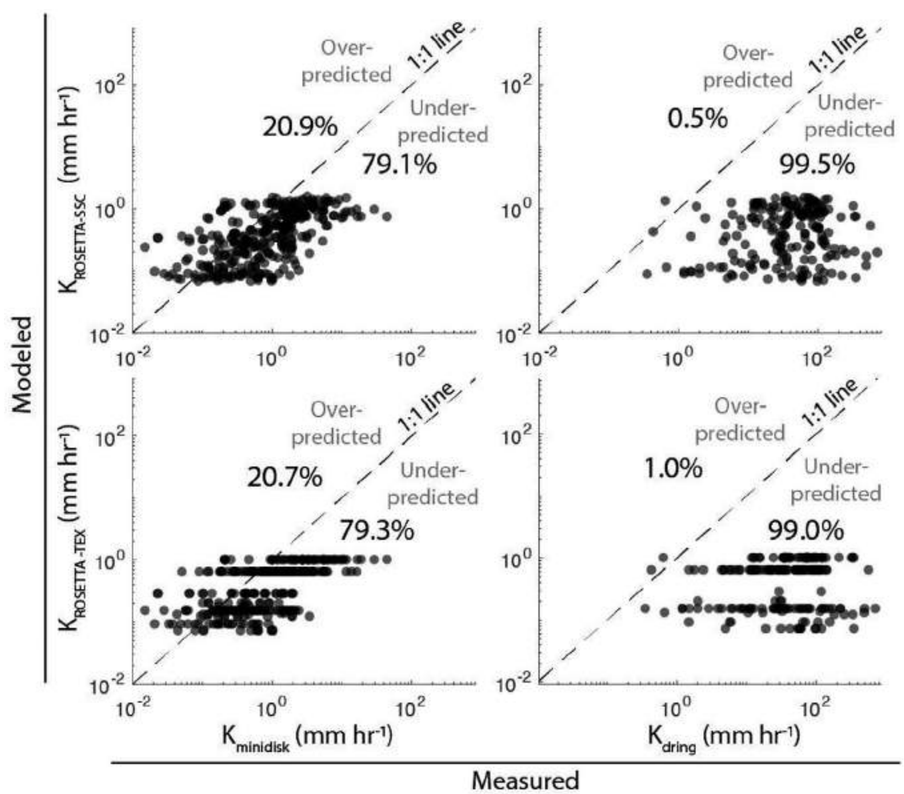

FIGURE 3. Comparison of measured K from tension infiltrometer (Mini Disk; $K_{minidisk}$), double-ring infiltrometer (K_{dring}) with K values modeled by ROSETTA, using inputs of either soil texture separates (percent sand, silt, clay; $K_{ROSETTA-SSC}$) or soil textural class (e.g., silt loam; $K_{ROSETTA-TEX}$) as predictors. Percentages in each panel indicate model over or under prediction.

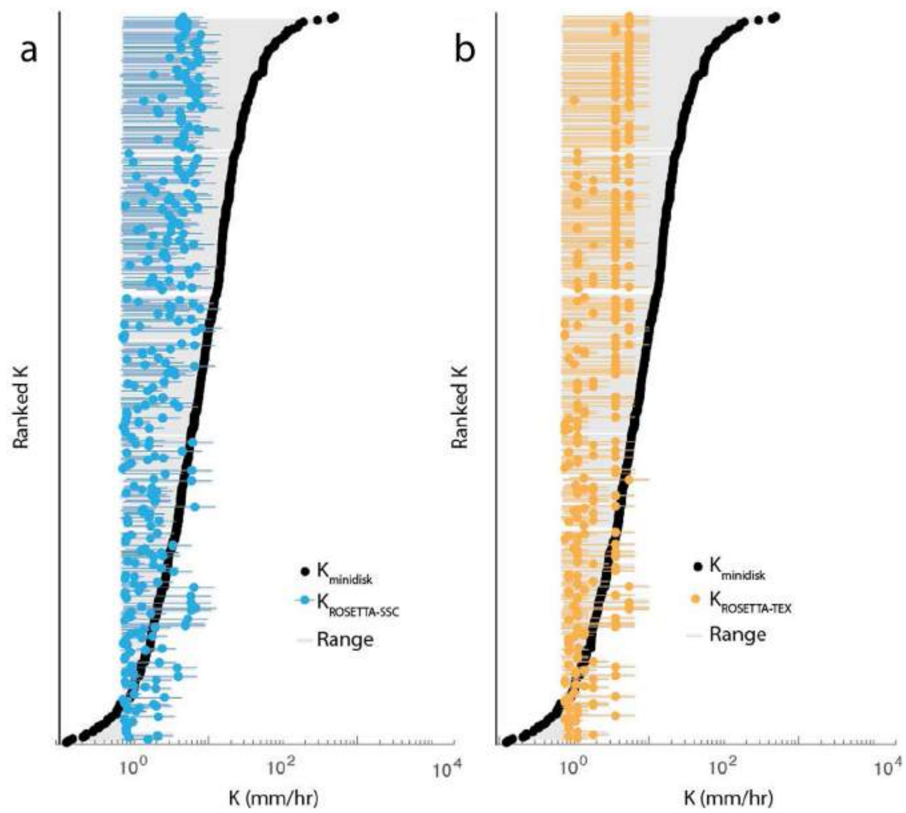

FIGURE 4. Comparisons between K_{minidisk} data and: (a) $K_{\mathrm{ROSETTA\text{-}SSC}}$ from ROSETTA simulated based on the input of soil texture separates (blue dots; percent sand, silt, clay); and (b) $K_{\mathrm{ROSETTA\text{-}TEX}}$ from ROSETTA simulated from soil textural class (orange dots; SSC, e.g., silt loam). The ROSETTA model generates an uncertainty metric, which is represented as blue and orange horizontal lines. The span between K_{ROSETTA} estimates and K_{minidisk} is shown as gray horizontal lines. Urban samples across sites were sorted along the *y*-axis by K_{minidisk} from small (bottom) to large (top).

compact, dense soil structure (Olson et al. 2013); presence of surface crusts on bare soil (Assouline and Mualem 2002); sensitivity of pedotransfer functions to clay and organic matter content (Wagner et al. 2004); the presence of anthropogenic materials (Barbu and Ballestero 2014; Shuster et al. 2014); and impacts of damage to or removal of vegetation (see Godefroid and Koedam 2007). There are also artifacts as differences between field and laboratory assessment of hydraulic characteristics as collected in Rawls et al. (1982). We acknowledge that field campaigns or laboratory measurements are difficult, costly, and often impractical for many hydrologic assessments, motivating work on the utility of pedotransfer functions for urban soils.

Given these limitations, ROSETTA and other pedotransfer functions are still used extensively, and perhaps overextended, in their application to predicting *K* in all types of soils. Overextension of these functions may be particularly important in urban landscapes where *K* estimates are used to develop, design, and plan green spaces and GI (Rubio 2008; Barbu and Ballestero 2014). These results suggest that *K* is typically underestimated with ROSETTA, leading to oversized infrastructure. Oversizing stormwater infrastructure lends a necessary safety factor, which should be considered as a tradeoff with higher construction and maintainence expenses.

K *in the Urban Subsurface*

Across all cities and parcels, we observed K_{borehole} measurements where outflow from the instrument was unrestricted, and such that a constant hydraulic head could not be maintained in the borehole. The cause of this behavior was usually observed in our soil cores as large subsurface void spaces created by unconsolidated anthropogenic demolition debris or gravelly layers (Shuster et al. 2014). Approximately 6% of all sites had K_{borehole} measures that were categorized as infinite-unrestricted (i.e., about 25 sites); with half of these observed in Cleveland, OH where demolition practices involved pushing demolition debris into the basement of the residence, and then backfilling with soil material. Working off of the common assumption that K decreases with depth (e.g., TOPMODEL), we compared $K_{borehole}$ (subsurface) with $K_{minidisk}$ (surface) data measured on urbanized landscapes. While we did find that $K_{borehole}$ values were often greater than paired $K_{minidisk}$ values, some soil profiles exhibited similar magnitudes between $K_{borehole}$ and $K_{minidisk}$, and surface $K_{minidisk}$ exceeded $K_{borehole}$ in other profiles (Figure 5). Borehole depth was a poor predictor of differences between $K_{borehole}$ vs. $K_{minidisk}$ (F-statistic (1, 437) = 0.17, p = 0.68). For $K_{borehole}$ measurements taken at shallower depths (~1,500 mm, gray circles), vs. those taken at deeper depths (~3,000 mm, blue circles), each category was either less than, or exceeded $K_{minidisk}$ (Figure 5), respectively.

ROSETTA more frequently predicted $K_{borehole}$ in a narrower range than measured data (Figure 6). Notably, the differences between observed and modeled K at depth (Figure 6) is in agreement with the behavior observed comparing observed and modeled K at the land surface (Figures 3 and 4). This once again underscores that modeled K values, in the absence of observations, may restrict variability in K as compared to in situ conditions. Our observation of a well-behaved distribution of measured data supports the importance, and perhaps the reward, of putting effort into a continental field assessment. Despite accurately determined sand, silt, and clay data for urban soils, $K_{ROSETTA\text{-}SSC}$ estimates did not predict the lower ranges of field-measured $K_{borehole}$ (Figure 6). Furthermore, K predicted with ROSETTA based on soil textural class ($K_{ROSETTA\text{-}TEX}$) show a multi-modal response, which is expected given its within-textural class averaging for K estimation. For predicted K based on percentage sand, silt, clay, the range in K is nearly identical to that predicted by soil textural class, with multi-modal peaks smoothed out. For soil textural classes that are not well-represented, such as soils with very fine sand fractions, K predicted with ROSETTA is not related to conditions represented in the training dataset, and may therefore be spurious.

Overall, the $K_{borehole}$ measurements in urban landscapes are different from predicted K, and so it should be treated accordingly in this respect. In a physical sense, the $K_{borehole}$ measurement integrates within or across soil horizons, and is inextricably related to their arrangement the soil profile. Depending upon how the $K_{borehole}$ data are used, the situational context may be very important. For example, infiltration-type GI can utilize subsoils with nonzero subsurface K to aid in drawdown, by redistributing

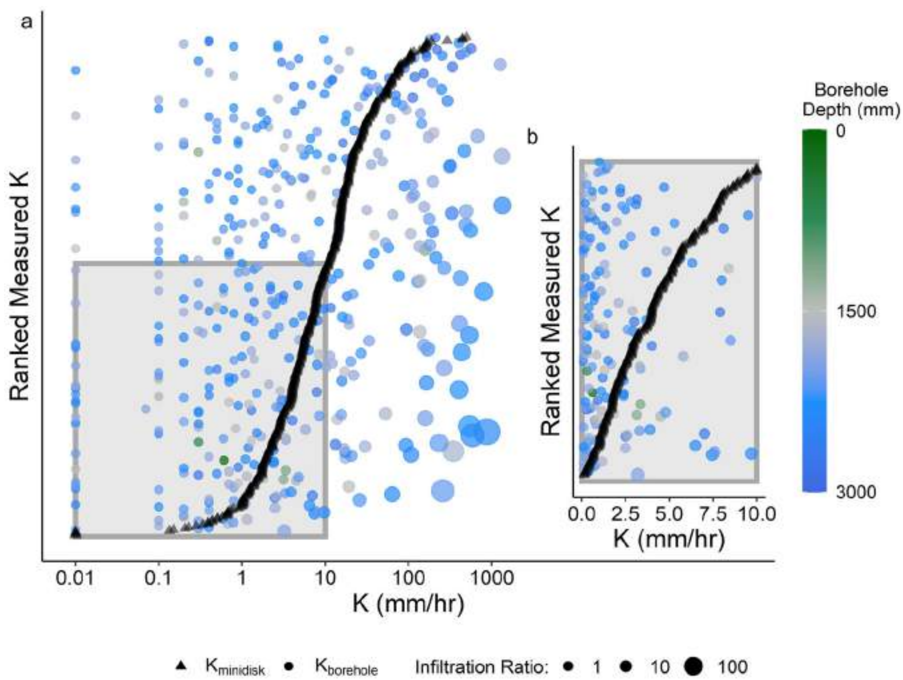

FIGURE 5. Paired relationships between unsaturated $K_{minidisk}$ (black triangles) and saturated $K_{borehole}$ (colored circles) shown in: (a) as a log-scaled distribution with (b) showing the linear subsection as an inset of the entire plot to highlight the distribution at the lower end of the K spectrum. The colored circles illustrate two attributes: (1) $K_{borehole}$ measurements are each colored relative to the ratio of $K_{borehole}$ to its co-located measured $K_{minidisk}$ infiltration rate, so larger circles indicate a higher $K_{borehole}$ to $K_{minidisk}$ ratio; and (2) the color of the circle represents the depth of the borehole in which the measurement was taken. Urban K measurements across sites were sorted along the y-axis by $K_{minidisk}$ from small (bottom) to large (top).

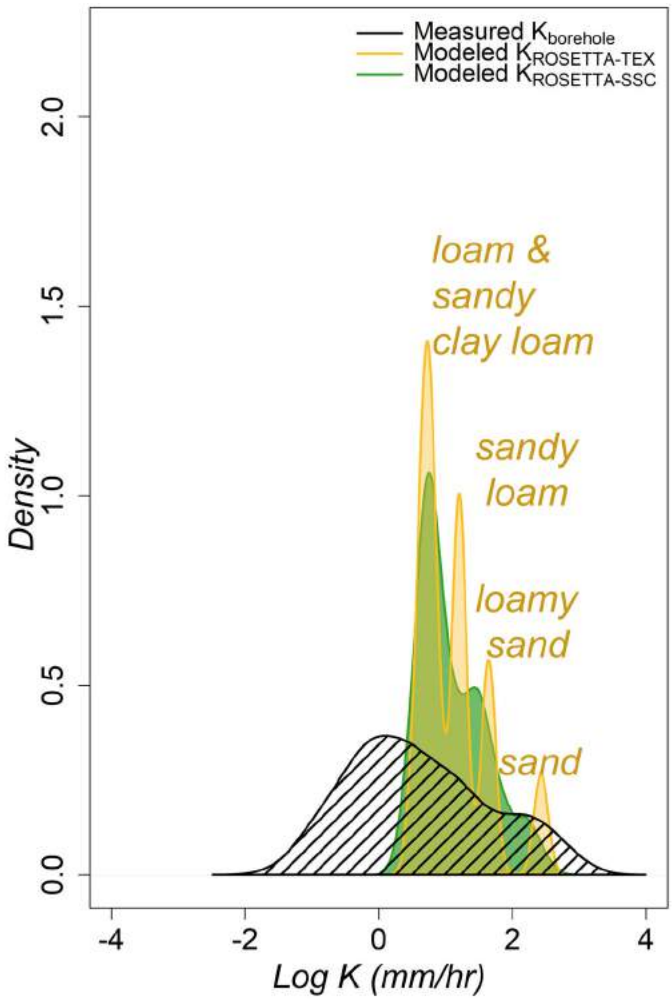

FIGURE 6. $K_{borehole}$ and predicted K are summarized as frequency distributions, as per Schifman and Shuster (2019). Subsurface Kborehole (shown on log-transformed axis) measured in 12 cities (black hatched) vs. estimates for saturated K from ROSETTA for soil textural class (TEX; yellow) and soil texture separates (SSC; green).

soil water deeper into the soil profile (Archer et al. 2020). These design considerations that leverage non-zero subsoil K could more efficiently maintain full GI effectiveness, and potentially reduce the size of or eliminate the need for an underdrain. In this case, it is important to consider that K predicted solely on the basis of texture (and ostensibly other ROSETTA input parameters like bulk density, or soil moisture retention) is unlikely to offer an accurate K parameter to guide hydrologic design work.

Implications of K *for Hydrologic Modeling in Urban Areas*

Urban soils present a unique set of influences on K. Therefore, in many contexts, we recommend estimating K by direct measurement, rather than using pedotransfer functions. From a practical perspective of GI design, documenting performance with observed storms can aid in verifying GI functionality. One of the biggest challenges faced when simulating hydrology within urban areas is how best to approximate K. This challenge involves making a choice between performing intensive measurements or, as with the use of ROSETTA, using another model to generate K values that can be used within a hydrologic modeling program. As we have shown, simulated K estimates differ substantially from those measured in urbanized soils (Figures 3, 4, and 6). Therefore, a thorough appreciation of the tradeoffs involved is needed to evaluate the necessity for accurate K values to inform design, policy, or investment decisions. For example, K predicted in ROSETTA would underestimate the potential for existing soils to infiltrate rainfall before generating runoff as infiltration-excess (Figure 2). In another scenario, one may possibly oversize stormwater infrastructure based on simulated K estimates that are actually smaller than measured.

Our findings regarding the behavior of K with subsurface depth have implications for rainfall-runoff modeling, especially as it relates to subsurface hydrologic processes. Models typically require assumptions about how K changes with depth. For example, TOPMODEL assumes that $K_{borehole}$ will decrease with soil depth, using user-selectable decay curves. However, our field data showed that this is a poor assumption in urbanized soils, as our borehole measurements did not reveal any consistent decline in $K_{borehole}$ with depth up to 3 m (Figure 5). Moreover, while recent work has attempted to better account for, and improve model assumptions regarding, spatial variability in K, e.g., by using depth-weighted profile values (Stewart et al. 2019) or log-normal spatial distributions (Morbidelli et al. 2017; Goyal et al. 2019), these approaches have not yet been incorporated into urban hydrologic models such as the Stormwater Management Model (Rossman 2010).

When K is not accurately estimated — or if a single value of K is selected based on some set of criteria — model uncertainty is much greater when K is also highly uncertain. In recent work by Schifman et al. (2018), a comparison of measured $K_{minidisk}$ values and those derived from national soils databases in the U.S. Environmental Protection Agency (USEPA) National Stormwater Calculator highlighted that the tool's default hydraulic conductivity of 10.1 mm/h is poorly constrained. For example, in New Orleans, Louisiana, clay soils were assigned to legacy soil maps used in the USEPA National Stormwater Calculator and failed to account for recent post-Katrina conditions, where residential demolition sites had been backfilled with sand; as a result, K was underestimated compared to a measured 95.0 ± 27.0 mm/h. In Omaha, Nebraska, the opposite was true, as the USEPA National Stormwater calculator overestimated K where a measured 3.0 ± 1.0 mm/h was due to the soil maps not being able to account for dry, hydrophobic soil conditions.

Another approach to handling the issue of how uncertainty in K is propagated through a rainfall-runoff model involves presenting a range of K values as an input, which produces modeled predictions of runoff volume. In this way, the user could calibrate the model with the widest known range of measured or modeled K estimates, and from these, select several "best" models, rather than one optimal version of the model. A metric is used to quantify the quality of the calibration. As an example, a rule could be set that the model simulation must output predicted runoff values that match measured values according to an appropriate metric (e.g., Kling-Gupta Efficiency (KGE) value of >0.50). Once calibrated, the outputs for model simulation with KGE > 0.50 would set output uncertainty bounds around runoff volume. Presenting this model output uncertainty describes how K mediates runoff volume, and informs on a realistic range of predicted runoff volume. This type of enriched information can aid in authentically meeting urban water planning and management challenges.

In the face of K variability across cities, we need improved information regarding how model assumptions may be violated, and new approaches for assessing and representing the heterogeneity in K inherent to urban landscapes. This is challenging because variation in surface properties (here measured as K_{dring}, K_{minidisk}) and subsurface properties (here as K_{borehole}) are likely distinct for a given site. This uniqueness means that measured data are useful in that they realistically describe landscape responses to rainfall events. This may be important in predicting the circumstances under which overland flow is initiated from pervious surfaces. However, these conditions are distinct and likely unsuitable to be applied broadly. For example, most models assume that runoff production in urban areas is solely due to infiltration-excess overland flow. However, Stewart et al. (2019) developed rainfall-runoff models using the same data described here, finding that runoff in urban landscapes is generated via saturation-excess to a greater extent than previously thought, as urban variable source areas may be common (Miles and Band 2015). These findings suggest that depth to confining layer, soil structure in successively deeper horizons, and slope may be important field measurements to supplement and give context to an accurate estimate of K. While the community of practicing hydrologists and modelers are still disentangling how hydrologic fluxes move water through urban systems, these types of studies get us closer to this understanding.

SUMMARY AND CONCLUSIONS

Urban soils are unique, and only by understanding and properly representing the different types of K that exist within them can we create the appropriate context for urban water resources management. In this study we presented a large, multi-city field dataset to demonstrate how K is different in urban soils compared to nonurban soils, and how measurement approaches affect our impression of what might be a "true" value of K. We also used the same dataset as a benchmark for comparison with simulated K values. Through the synthesis of hundreds of observations, our analysis revealed that there are still unexpected and, to some extent, unexplained outcomes that underscore the uniqueness of K in urban areas. Future work is thus needed to reconcile the physical mechanisms that generate these unusual patterns, which can help to generalize the behavior of urban soils at broader spatial scales.

We ultimately recommend that K should be measured in ways that are most representative and physically authentic to the hydrologic setting and processes of interest. From a practical perspective, the cost of poor K estimation should be assessed against corresponding effects on design parameters, which otherwise could lead to over or underdesigned stormwater infrastructure. As an example, some stormwater infiltration system designs require loading estimates based on volume and timing of surface runoff, which can be strongly influenced by K of surficial soils. In our field assessments, K_{minidisk} provided an estimate of near-surface K that had lower sample variance (based on at least four measurements) than that of K_{dring}. Mean K_{minidisk} values were often, though not always, lower than the paired K_{dring} results. As a result, K_{minidisk} may provide a more consistent and conservative means to estimate the likelihood of runoff generation from urban landscapes. Another design consideration for infiltration-based stormwater infrastructure is the ability of the practice to drawdown and redistribute soil moisture, or otherwise drain between storms. To best characterize these processes, it may be necessary to characterize subsurface K (as K_{borehole}), and pair those measures with a qualitative examination of soil bore taxonomy to identify variety in soil texture and legacy soil moisture conditions (e.g., long-term saturation, as indicated by gray soil color from reduced minerals).

These types of combined assessments can be particularly useful for assessing overall site suitability and limitations when locating management practices.

Our analysis primarily focused on synthesis of field-based observations, yet our findings also have importance for evaluating how to best parameterize and perform hydrologic modeling within urban landscapes. We emphasize that current K datasets and predictive relationships (e.g., pedotransfer functions such as in ROSETTA) are not typically drawn from measurements made on urbanized soils. Therefore, the use of these functions introduces an unknown amount of uncertainty into model simulations and related urban design work. Our findings show that constraining or estimating K for inclusion within urban hydrologic models is likely more complex than previous work would suggest. Addressing uncertainty in K (and, likely, other soil properties) is imperative in urban hydrological models.

To conclude, through this work we sought to explore the significance of K in managing the urban water cycle, address the relatively new context of K in an increasingly urbanized world, and spur further discourse on this matter. We hope that, based on the findings and recommendations presented here, practitioners and others will provide the proper context for urban K in their own work.

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AUTHORS' CONTRIBUTIONS

W.D. Shuster: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; writing-original draft; writing-review & editing. **Laura Schifman:** Conceptualization; data curation; formal analysis; software; visualization; writing-review & editing. **Christa Kelleher:** Conceptualization; formal analysis; investigation; visualization; writing-review & editing. **Heather E. Golden:** Conceptualization; writing-review & editing. **Aditi S. Bhaskar:** Conceptualization; writing-review & editing. **Anthony J. Parolari:** Conceptualization; writing-review & editing. **Ryan D. Stewart:** Conceptualization; writing-review & editing. **Dustin L. Herrmann:** Conceptualization; writing-review & editing.

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