Performance of two prevalent infiltration models for disturbed urban soils

Xixi Wang, David J. Sample, Shohreh Pedram and Xiao Zhao

ABSTRACT

Estimating infiltration losses is very important for calculating runoff and recharge. However, the accuracy of contemporary infiltration models for disturbed urban soils may not be adequate, potentially compromising calculations based upon them. The objective of this study was to assess the performance of the two most prevalent infiltration models, Horton and Green–Ampt, for applications in urban soils. The data were measured by the US Environmental Protection Agency in a large city for soils with various characteristics of texture, structure, age, compactness, and dryness/wetness. The results indicate both models performed better in predicting infiltration rates for clayey rather than sandy soils, for new rather than old soils, and for wet rather than dry soils. For the clayey soils, both models performed better for the noncompact than compact soils. The opposite was true for sandy soils. Overall, neither infiltration model performed well for most soils, with the sole exception of the new clayey, wet, noncompact soils. The generally poor performance of the models in disturbed soils will likely increase uncertainty in model predictions. This study demonstrates the need to develop improved, more robust infiltration algorithms applicable to urban soils and various kinds of urban development that are based on carefully measured field experimental data.

Key words | compaction, infiltration models, stormwater, texture, urban soils

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INTRODUCTION

Urban soil infiltration (hereinafter simply termed as infiltration except as otherwise specified) is a very important component of the hydrologic cycle (Viessman & Lewis 2003), directly impacting calculations of runoff. Since estimating runoff depends upon accurate estimates of infiltration, the method for estimating infiltration needs to be appropriately determined for most urban stormwater management decisions (Elliott & Trowsdale 2007; Rossmiller 2014; Askarizadeh *et al.* 2015; Wang *et al.* 2016). Urbanization reduces infiltration while increasing runoff, resulting in more frequent and larger magnitude floods (Konrad 2014). Direct measurements of infiltration have been conducted in laboratories using soil-column tests or in fields using dual-ring infiltrometer experiments (Eash *et al.* 2015; Di Prima *et al.* 2016). However, since direct measurements only represent localized and instantaneous values of infiltration under specific test/experimental conditions, they are difficult to generalize because of the spatial heterogeneity of soil characteristics such as texture, age, structure, degree of compaction (i.e., compactness), and moisture.

Soil texture can be treated as an intrinsic characteristic because it does not change much with time, whereas the other four (i.e., soil age, structure, compactness, and moisture) are extrinsic characteristics because they are functions of time (Yang & Zhang 2011). The last three characteristics (i.e., structure, compactness, and moisture) can be changed easily by external loadings from vehicles, pedestrians, and wetting/drying processes (Schmidt & Michael 2004; Marković *et al.* 2014; Sajjadi *et al.* 2016). Thus, such direct measurements of infiltration can rarely be used to model the hydrologic processes in an urban drainage area (i.e., at a catchment scale), which is normally used as the smallest

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spatial unit for analysis of stormwater impacts (Viessman & Lewis 2003; Rossmiller 2014). Instead, limited measurements have been used to develop and validate various mathematical infiltration models (e.g., Lassabatere *et al.* 2010), which in turn have been used to model infiltration in a catchment at a continuous time step (e.g., Hamel *et al.* 2013; Rosa *et al.* 2015).

In the literature (e.g., Mishra *et al.* 1999), existing infiltration models are classified into three groups: physically based, semi-empirical, and empirical. The physically based models are direct derivatives from the mass-conservation and Darcy's laws (Todd & Mays 2005) with a variety of simplifications and assumptions (Hilpert & Glantz 2013). The most popular such models were developed by Green & Ampt (1911), Philip (1957, 1969), and Mein & Larson (1973). In contrast, empirical models, which have various forms and complexities (e.g., linear versus nonlinear), are solely based on test/experimental data. Examples of these models include those developed by Kostiakov (1932), Huggins & Monke (1966), Smith (1972), Collis-George (1977), Smith & Parlange (1978), US Department of Agriculture (USDA-NRCS 1986), and Parhi *et al.* (2007). Moreover, between the physically based and empirical models are the semi-empirical models, which satisfy continuity and simple hypotheses of water movement in soil. The representatives of such models were developed by Horton (1940), Holtan (1961), Overton (1964), Swartzendruber (1987), Singh & Yu (1990), and Grigorjev & Iritz (1991).

Driven by the practical needs of agriculture and river basin management, the aforementioned models have been extensively evaluated using data from infiltration tests/experiments of rural soils. Mishra *et al.* (2003) evaluated 14 models using test/experimental data at 23 agricultural sites in the United States of America (USA) and India. The evaluation revealed that all of the models generally performed poorly for the sandy soils, whereas the physically based models performed better in the laboratory rather than the field. The semi-empirical or empirical models overall performed better than the physically based models. Both the Green–Ampt (G-A) (Green & Ampt 1911) and Horton (1940) models did poorly for most of the soils, although the Horton model had a slightly better performance than the G-A model. Mishra *et al.* (2003) attributed the poor performance of the physically based models to possible violations of the underlying assumptions (e.g., homogeneity and nonexistence of macropores). Similarly, Mirzaee *et al.* (2013) evaluated eight infiltration models using experimental data at 95 agricultural sites in Iran. The results revealed that the G-A and Horton models performed worse than the empirical Kostiakov (1932) model and its two modified/revised versions (Smith 1972; Parhi *et al.* 2007). The results also revealed that all models tended to have a better performance for the clayey rather than loamy soils. However, Mishra *et al.* (2003) did not discuss the reasons for such results. Overall, the models presented in Mirzaee *et al.* (2013) did better than the models presented in Mishra *et al.* (2003) because most soils in the former study are clayey, while most soils in the latter study are sandy. This implies that infiltration models tend to demonstrate a better fit to observed data for clayey as opposed to sandy soils.

Few studies have evaluated the performance of infiltration models when applied to urban soils (Pitt *et al.* 1999; Yang & Zhang 2011; Sajjadi *et al.* 2016). In comparison with rural or agricultural soils, urban soils are frequently subject to various artificial forces associated with static loadings and dynamic impacts (Jim 1993), causing widespread and severe compaction of soils (Guan *et al.* 1998). As a result, the characteristics (e.g., structure, compactness, and soil-water properties) of urban soils can be distinctly different from those of rural soils even if the two soils have an identical texture (Pitt *et al.* 2002; Yang & Zhang 2011; Markovič *et al.* 2014). At present, there is limited knowledge on the performance of infiltration models in urban soils. However, almost all existing urban hydrologic modeling software packages (Elliott & Trowsdale 2007; Fletcher *et al.* 2013), including the widely used Storm Water Management Model (SWMM, version 5.1.010) (Gironás *et al.* 2009; Rossman 2010), incorporate the G-A and Horton models. SWMM has also been widely used to design and assess low impact development (LID) devices (e.g., bioswales, bioretention, permeable pavement, green roofs) (Wang *et al.* 2016). LID relies on infiltration, so as these practices become more common, it becomes more critical to improve the underlying infiltration models. Thus, a central question has emerged: how well do these two models perform for urban soils? The objective of this study was to address this question using analysis of the field experimental data presented in Pitt *et al.* (1999).

In practice, because of its simplicity and ease for parameterization, the SCS (Soil Conservation Service, now Natural Resources Conservation Service) curve number (CN) method (USDA-NRCS 1986) is also incorporated into various modeling software packages, including SWMM, as an alternative infiltration model. The SCS-CN method was originally developed for agricultural watersheds and empirically migrated to urban catchments with little scientific base. Nevertheless, a number of studies (e.g., Holman-Dodds *et al.* 2003; Ahiablame *et al.* 2013; Ahmadisharaf *et al.* 2016) have successfully used the SCS-CN method as infiltration model to evaluate the effectiveness of LID practices and flood management alternatives in urbanized watersheds. The SCS-CN method can be a good choice in the absence of detailed soil data for urban catchments (Chahinian *et al.* 2005; Gao *et al.* 2013; Salvadore *et al.* 2015); it, however, has proved to be more applicable for rural watersheds (Wilcox *et al.* 1990; Zarriello 1998; Wang *et al.* 2008, 2012). For instance, the study of Chahinian *et al.* (2005) was done for a rural area but a similar study was not found for urban environments. Thus, the SCS-CN method was not included in this study.

DESCRIPTION OF THE HORTON AND G-A MODELS

The Horton model

The semi-empirical Horton infiltration model can be expressed as (Horton 1940):

$$f_t = f_c + (f_0 - f_c)e^{-kt} \tag{1}$$

where f_t [L T^{-1}] is the infiltration rate capacity at time t; f_c [L T^{-1}] is the final infiltration rate capacity; f_0 [L T^{-1}] is the initial infiltration rate capacity; and k [T^{-1}] is the infiltration rate capacity decay constant. A key assumption of the Horton method is that k is independent of soil moisture content.

The G-A model

The G-A model (Green & Ampt 1911; Hilpert & Glantz 2013) assumes that: (1) the soil profile is homogenous and isotropic; (2) the antecedent (i.e., initial) moisture is uniformly distributed throughout the profile; (3) the soils above 'wetting front' are naturally saturated before the front moves further down; (4) the soils below the front maintain their initial moisture; and (5) water is always available for infiltration.

The physically based G-A model can be expressed as (Green & Ampt 1911):

$$f_t = \frac{K_s}{2}\left[1 + \frac{\psi_f(\theta_{ns} - \theta_a)}{F_t}\right] \tag{2}$$

where f_t [L T^{-1}] is the infiltration rate capacity at time t; F_t [L] is the cumulative infiltration amount until time t; K_s [L T^{-1}] is the saturated hydraulic conductivity; θ_{ns} [-] is the naturally saturated soil moisture (i.e., volumetric water content); θ_a [-] is the antecedent soil moisture at the beginning of infiltration; and ψ_f [L] is the capillary pressure head at wetting front. ψ_f can be computed as (Charbeneau 2006):

$$\psi_f = \left(\frac{3\lambda + 2}{3\lambda + 1}\right)\frac{\psi_b}{2} \tag{3}$$

where λ [-] is the pore-size distribution index; and ψ_b [L] is the bubbling (or air-entry) capillary pressure head.

MATERIALS AND METHODS

The experimental data

Pitt *et al.* (1999) selected ten sites of disturbed urban soils across the city of Birmingham, Alabama, USA, to measure infiltration capacity. The soils beneath these sites were determined by those authors to be either clayey (>50% clay and silt particles, which have a diameter of <0.062 mm) or sandy (>50% sand particles, which have a diameter of 0.062 to 2.0 mm), either new (age <15 years) or old (age ≥15 years), and either noncompact (compactness ≤2,067 kPa) or compact (compactness >2,067 kPa). Hereinafter, new soils refer to soils at newly developed sites. The noncompact soils were determined to have a bulk density of 1.23 to 1.83 g cm^{-3}, whereas the compact soils were determined to have a bulk density of 0.84 to 1.20 g cm^{-3}. For a given site, the bulk density of the noncompact soil was 27 to 35% larger than that of the compact soil. For a given soil, it was determined to be either dry (i.e., moisture, θ, less than half of the field capacity, θ_{fc}) or wet ($\theta \geq \theta_{fc}/2$). The measurements were conducted for the 16 soil combinations listed in Table 1.

A series of 153 experiments was conducted. For each experiment, three infiltrometers were placed close together (1 meter apart) to better reflect the possible localized site variability. Readings were taken every 5 minutes for 2 hours, at which the soil was expected to reach its saturation and final infiltration rate. The instantaneous infiltration rates were calculated by noting the drop of water level in the inner compartment of infiltrometer over the 5 minutes time interval. Whenever an experiment was performed, the compactness of the area was measured. In addition, a soil sample was taken to analyze the gravimetric water content using the standard oven-drying method (Eash et al. 2015). Further, Pitt et al. (1999) measured and used the particle density to convert the gravimetric water content to the responding volumetric water content (i.e., soil moisture) using a formula that can be found in popular textbooks (e.g., Barnes 2000; Todd & Mays 2005). Figure 1 summarizes and illustrates the measured infiltration rates to help audiences better understand this study.

Assessment methods

For either the Horton or G-A model, parameters were determined using the Levenberg–Marquardt global-optimization algorithm (Levenberg 1944; Marquardt 1963), programmed by the authors using the VBA programming language in Microsoft® Excel. The optimization was implemented by adjusting the parameters within assumed physical ranges (Table 2) (Rawls et al. 1983; Charbeneau 2006) to maximize the Nash–Sutcliffe coefficient (*NS*) (Nash & Sutcliffe 1970). *NS* can be computed as:

$$NS = 1 - \frac{\sum_t (f_{t,s} - f_{t,o})^2}{\sum_t \left(f_{t,o} - \overline{f_{t,o}}\right)^2} \quad (4)$$

where $f_{t,s}$ [L T^{-1}] is the modeled infiltrate rate at time t; $f_{t,o}$ [L T^{-1}] is the measured infiltration rate at time t; and $\overline{f_{t,o}}$ [L T^{-1}] is the average of $f_{t,o}$ across the entire time period.

The value of *NS* can range from $-\infty$ to 1.0, with higher values indicating a better overall fit and 1.0 indicating a perfect fit. A negative *NS* indicates that the modeled infiltration rates are less reliable than if one had used the average of the measured infiltration rates, while a positive value indicates that they are more reliable than using this average (Wang et al. 2008). In this study, the modeled infiltration rates were considered 'good' for values of $NS > 0.75$, while for values of *NS* between 0.75 and 0.36, the modeled infiltration rates were considered 'acceptable' (Motovilov et al. 1999; Gassman et al. 2007; Moriasi et al. 2007). In addition, coefficient of determination (R^2) (Neter et al. 1996) was also computed and used to verify the model performance. R^2 can range from zero to 1.0, with a larger value indicating a better model performance. Further, percent bias (*PBIAS*) (Gupta et al. 1999), which measures the average tendency of the modeled data to be larger or smaller than their observed counterparts, was computed to assess the model prediction error. The optimal value of *PBIAS* is 0.0, with low-magnitude values indicating accurate model simulation. Positive values

Table 1 | Symbols (numbers) of the experiments by soil characteristics[a]

Soil characteristic	New clayey[c]	Old clayey[c]	New sandy[c]	Old sandy[c]	Total
Dry compact[b]	NCDC (6)	OCDC (9)	NSDC (6)	OSDC (15)	36
Wet compact[b]	NCWC (6)	OCWC (12)	NSWC (6)	OSWC (12)	36
Dry noncompact[b]	NCDN (6)	OCDN (12)	NSDN (12)	OSDN (12)	42
Wet noncompact[b]	NCWN (6)	OCWN (21)	NSWN (6)	OSWN (6)	39
Total	24	54	30	45	153

[a]The soil characteristics are documented in detail in Table C-1 of Pitt et al. (1999).
[b]If moisture is less than half of the field capacity (θ_{fc}), the soil is dry; otherwise, it is wet. If compactness >2,067 kPa, the soil is compact; otherwise, it is noncompact.
[c]If age <15 years, the soil is new; otherwise, it is old. If percent sand (diameter ≥0.062 mm) >50, the soil is sandy; otherwise, it is clayey (Todd & Mays 2005).

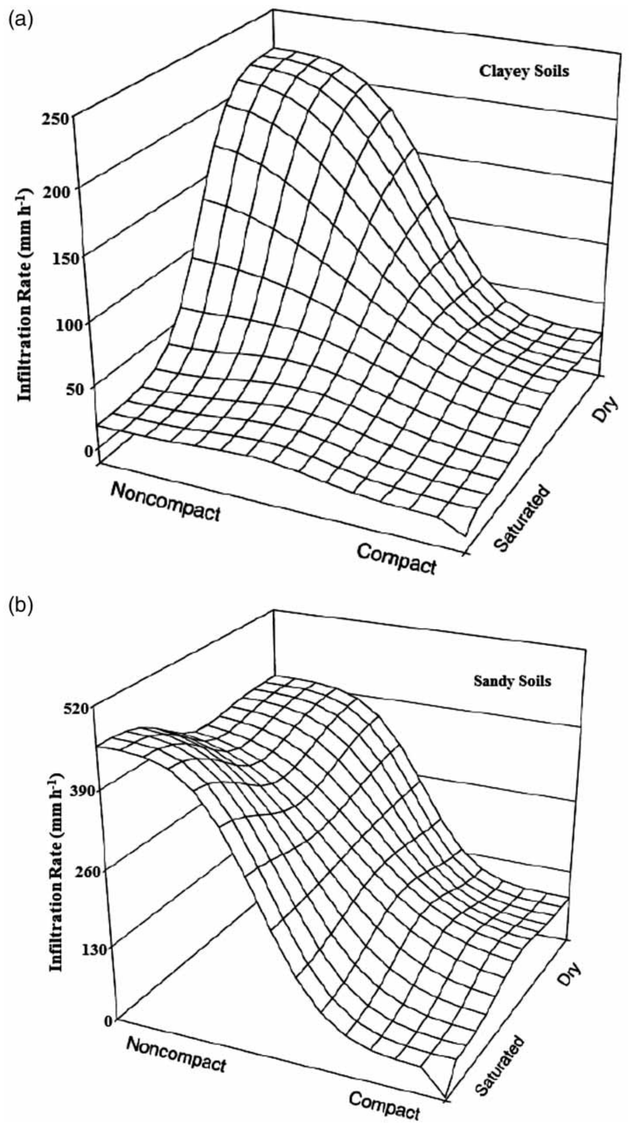

Figure 1 | Plots showing the measured infiltration rates for: (a) clayey soils and (b) sandy soils (after Pitt *et al.* 1999).

indicate model underestimation bias, whereas negative values indicate model overestimation bias.

First, the model parameters were determined using each of the 153 time series, leading to 153 sets of parameter values for each of the two models. The model performance was assessed by comparing the *NS* and R^2 values for one soil combination (e.g., NCDC in Table 1) with the responding values for other soil combinations (e.g., NCWC). In addition, the model performance for a given soil combination was assessed by examining the discrepancies between the sets of parameter values for this soil combination. For instance, for the Horton or G-A model, the soil combination NCDC had six sets of parameter values, while the soil combination OSDC had 15 sets of parameter values (Table 1). The model was judged to be better for a soil combination than another if the parameter discrepancies for the former combination were smaller than those for the latter combination. Here, the rationale behind such a judgment is that a model tended to be more robust for a soil combination that could give relatively consistent parameter values.

Second, for either the clayey or sandy and either new or old soils, the time series for the compact soils were pooled together into one dataset, whereas the time series for the noncompact soils were pooled together into another dataset. As a result, eight datasets (four for the clayey soils and another four for the sandy soils) were formulated. Afterwards, each was further divided into two subdatasets: one for model calibration and another for model validation. The model performance was assessed by comparing the *NS* and R^2 values for the eight soil combinations, including new clayey compact, old clayey compact, new clayey noncompact, old clayey noncompact, new sandy compact, old sandy compact, new sandy noncompact, and old sandy noncompact.

Third, for either the new or old soils, the time series for the clayey soils were pooled together into one dataset, whereas the time series for the sandy soils were pooled together into another dataset. As a result, four datasets (two for the clayey soils and another two for the sandy soils) were formulated. Afterwards, each was further divided into two subdatatsets: one for model calibration and another for model validation. Again, the model performance was assessed by comparing the *NS* and R^2 values for the four soil combinations, including new clayey, old clayey, new sandy, and old sandy. Finally, the performance of the Horton model versus that of the G-A model was evaluated in terms of values of *NS*, R^2 and the consistency of model parameter values for all combinations mentioned above.

RESULTS

Infiltration capacity of clayey soils by both Horton and G-A models

As shown in Table 3, for a new compact clayey soil, its infiltration capacity was better estimated when it was dry

Table 2 | Physical ranges of the model parameters

Model	Parameter	Definition	Physical range		Source
			Clayey soil	Sandy soil	
Horton	f_0 (mm h^{-1})	Maximum infiltration rate	4.23–76.20	42.34–2,032	Rawls *et al.* (1983)
	f_c (mm h^{-1})	Minimum infiltration rate	0.13–0.76	6.60–120.40	Rawls *et al.* (1983); $=K_s/2$
	k (h^{-1})	Infiltration rate decay constant	2–7	2–7	Rawls *et al.* (1983)
G-A[a]	λ (-)	Soil pore-size distribution index	0–0.61	0.29–1.97	Charbeneau (2006)
	θ_r (-)	Irreducible soil moisture	0.034–0.1	0.035–0.082	Charbeneau (2006)
	θ_{fc} (-)	Field capacity	0.244–0.378	0.062–0.284	Rawls *et al.* (1983)
	n (-)	Porosity	0.398–0.479	0.437–0.501	Rawls *et al.* (1983)
	ψ_b (mm)	Air-entry capillary pressure head	110–3,130	55–600	Charbeneau (2006)
	K_s (mm h^{-1})	Saturated hydraulic conductivity	0.254–1.524	3.302–120.396	Rawls *et al.* (1983)

[a]G-A model.

($NS = 0.14$–0.62; $R^2 = 0.27$–0.87) than when it was wet ($NS = -0.062$–0.62; $R^2 = 0.063$–0.64), whereas, for an old compact clayey soil, the infiltration capacity tended to be less accurately estimated when it was dry ($NS = -2.41$–0.78; $R^2 = 0.11$–0.82) than when it was wet ($NS = -0.55$–0.56; $R^2 = 0.19$–0.56). Regardless of being dry or wet, the experimental data for the new soils were better reproduced than those for the old soils. For the new soils, more than 58% of the experiments were reproduced at an acceptable accuracy ($NS \geq 0.36$), and for any of the experiments the estimated infiltration capacity was more accurate than the average of the experimental data ($NS > 0$). In contrast, for the old soils, only 17 to 45% of the experiments were reproduced at an acceptable accuracy, and for up to 22% of the experiments the estimated infiltration capacity was less accurate than the average of the experimental data ($NS < 0$). Overall, the models can explain more than 27% of the variations presented in most of the experimental data for the compact clayey soils.

In contrast to the compact clayey soils, for both the new and old noncompact clayey soils, most of the wet-soil experiments ($NS = -1.80$–0.81; $R^2 = 0.10$–0.88) were more accurately reproduced than the dry-soil experiments ($NS = -13.50$–0.69; $R^2 = 0.002$–0.81). More than 56% of the wet-soil experiments were reproduced at an acceptable accuracy, whereas less than 20% of the dry-soil experiments were reproduced at an acceptable accuracy and more than 75% of the experiments were unable to be reproduced ($NS < 0$). On the other hand, consistent with the compact clayey soils, regardless of being dry or wet, the experimental data for the new noncompact soils were better reproduced than those for the old noncompact soils. For the new noncompact soils, more than 67% of the experiments were reproduced at an acceptable accuracy ($NS \geq 0.36$), while for less than 22% of the experiments, the estimated infiltration capacity was poorer than the average of the experimental data. In contrast, for the old noncompact soils, less than 34% of the experiments were reproduced at an acceptable accuracy, while for more than 45% of the experiments, the estimated infiltration capacity was less accurate than the average of the experimental data.

Regardless of being new or old, for both the calibration and validation data, the experiments for the compact soils were better reproduced than those for the noncompact soils, as indicated by the fact that the NS and R^2 for the compact soils ($NS = 0.013$–0.37; $R^2 = 0.12$–0.44) are mostly larger than those for the noncompact soils ($NS = -0.14$–0.029; $R^2 = 0.034$–0.57) (Table 3). Most of the experiments for the new compact soils were fairly well reproduced ($NS \geq 0.32$; $R^2 \geq 0.33$), whereas the experiments for the noncompact soils could not be reproduced because NS is negative except for the validation data. In consequence, if the data for the compact and noncompact soils were analyzed together, the estimations of infiltration capacity were not better than the averages of the pooled data. This indicates that the compact soils might have distinctly different infiltration characteristics from the noncompact soils. The relative performances of the infiltration models in reproducing the experiments of the clayey soils are summarized in Figure 2.

Table 3 | Performance and calibrated parameters of the models for clayey soils[a]

		Clayey soil						
Equation	**Parameter or measure**	**All**	**Compact**	**Noncompact**	**Dry compact**	**Wet compact**	**Dry noncompact**	**Wet noncompact**
Horton	f_0 (mm h^{-1})	76.2	76.2	76.2	68.741–76.2	27.09–76.2	62.852–76.2	71.593–76.2
		65.684	**58.344**	**69.545**	**18.98–6.2**	**29.953–57.495**	**11.182–76.2**	**15.159–76.2**
	f_c (mm h^{-1})	0.762	0.762	0.762	0.762	0.762	0.762	0.762
		0.762	**0.762**	**0.762**	**0.762**	**0.762**	**0.762**	**0.127–0.762**
	k (h^{-1})	2	2	2	2–3.125	2–4.057	2–7	2–2.121
		2	**2**	**2**	**2–2.059**	**2**	**2–7**	**2–7**
	NS (cal.)	0.046	0.340	−0.046	0.140–0.528	−0.026–0.623	−2.032–0.512	0.596–0.740
		− 0.021	**0.013**	**− 0.028**	**− 2.408–0.483**	**− 0.545–0.517**	**− 13.502–0.625**	**− 1.796–0.809**
	R^2 (cal.)	0.166	0.425	0.147	0.338–0.682	0.063–0.643	0.070–0.637	0.757–0.882
		0.044	**0.122**	**0.034**	**0.113–0.653**	**0.189–0.534**	**0.002–0.801**	**0.107–0.816**
	NS (val.)	−0.044	0.315	−0.139				
		− 0.093	**0.193**	**−0.105**				
	R^2 (val.)	0.045	0.334	0.036				
		0.064	**0.380**	**0.046**				
	PBIAS (cal)	9.4	7.2	9.0	4.6–7.9	5.3–8.3	5.5–9.4	3.5–9.8
		8.8	**7.7**	**8.9**	**4.4–7.7**	**4.8–6.8**	**3.8–8.1**	**4.2–9.1**
	PBIAS (val)	9.2	6.7	9.4				
		8.1	**5.8**	**8.4**				
G-A	λ (-)	0	0	0	0–0.297	0–0.61	0–0.043	0
		0.079	**0.609**	**0.122**	**0–0.61**	**0.182–0.61**	**0–0.61**	**0–0.61**
	θ_r (-)	0.034	0.034	0.034	0.034–0.1	0.034–0.1	0.034–0.1	0.034
		0.1	**0.093**	**0.071**	**0.034–0.1**	**0.034–0.1**	**0.034–0.1**	**0.034–0.1**
	θ_{ns} (-)	0.319	0.244	0.378	0.244	0.244	0.378	0.378
		0.327	**0.248**	**0.382**	**0.245**	**0.245**	**0.382**	**0.382**
	n (-)	0.479	0.479	0.479	0.398–0.479	0.398–0.479	0.408–0.479	0.479
		0.398	**0.412**	**0.453**	**0.398–0.479**	**0.398–0.479**	**0.398–0.479**	**0.398–0.479**
	ψ_b (mm)	3,130	3,130	3,130	3,129–3,130	1,133–3,015	3,130	3,130
		3,130	**3,130**	**3,130**	**1,818–3,130**	**1,350–3,130**	**3,130**	**910–3,130**
	K_s (mm h^{-1})	1.524	1.524	1.524	0.406–1.524	0.257–1.524	0.254–1.524	1.095–1.524
		1.524	**1.524**	**1.524**	**0.254–1.524**	**1.524**	**0.305–1.524**	**0.254–1.524**
	NS (cal.)	0.079	0.317	−0.008	0.258–0.618	0.047–0.506	−1.837–0.685	0.619–0.737
		− 0.062	**0.083**	**0.029**	**− 1.404–0.776**	**0.269–0.557**	**− 7.467– − 0.69**	**− 1.606–0.664**
	R^2 (cal.)	0.164	0.384	0.572	0.267–0.867	0.073–0.612	0.092–0.810	0.734–0.853
		0.096	**0.115**	**0.045**	**0.105–0.823**	**0.275–0.561**	**0.004–0.622**	**0.102–0.789**
	NS (val.)	0.001	0.371	−0.091				
		− 0.161	**0.257**	**− 0.009**				
	R^2 (val.)	0.444	0.444	0.052				
		0.078	**0.346**	**0.057**				
	PBIAS (cal)	8.8	7.5	8.9	4.1–7.4	5.8–8.0	4.4–9.1	3.6–10.0
		6.7	**7.4**	**8.7**	**2.4–7.6**	**4.2–6.2**	**4.3–27.0**	**3.7–8.8**
	PBIAS (val)	9.0	6.3	9.1				
		7.7	**5.6**	**8.0**				

[a]*NS*: Nash–Sutcliffe coefficient.
R^2: coefficient of determination.
PBIAS: percent bias.
cal.: calibration (2/3 of the experiments).
val.: validation (1/3 of the experiments).
See Table 2 for definitions of the parameters. The numbers in regular fonts are for new (i.e., <15-year) soils, while the numbers in bold fonts are for old (i.e., ≥15-year) soils.

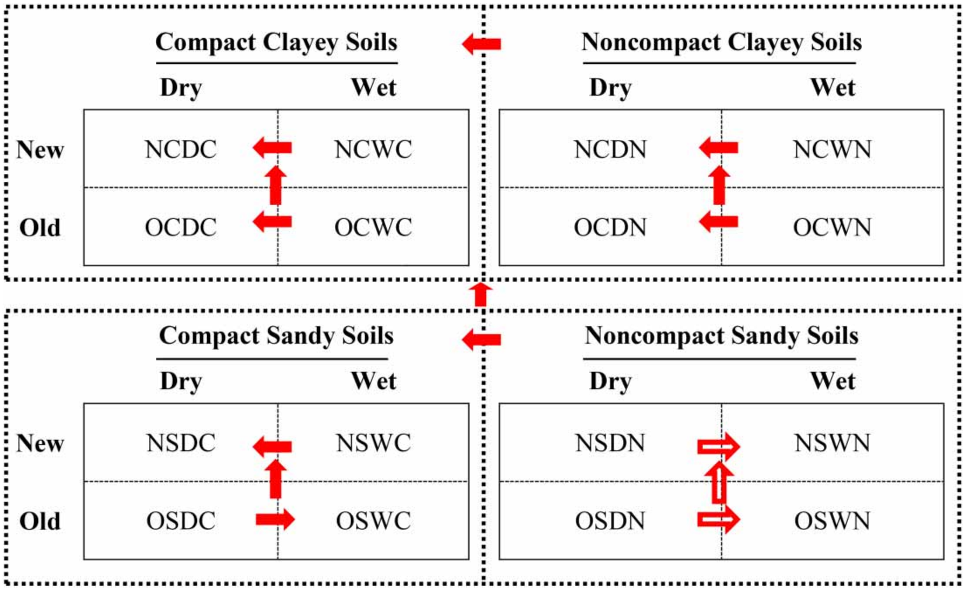

Figure 2 | Relative accuracies in reproducing the experiment infiltration capacities of the soils defined in Table 2. A solid arrow points to the soil(s) with an obviously higher accuracy, while a hollow arrow points to the soil(s) with a slightly higher accuracy.

Infiltration capacity of sandy soils by both Horton and G-A models

As with the clayey soils (Table 3), for a new compact sandy soil (Table 4), its infiltration capacity was better estimated when it was dry ($NS = 0.43–0.81$; $R^2 = 0.43–0.83$) than when it was wet ($NS = -0.51–0.93$; $R^2 = 0.001–0.93$), whereas for an old compact sandy soil, its infiltration capacity tended to be less accurately estimated when it was dry ($NS = -0.84–0.84$; $R^2 = 0.001–0.86$) than when it was wet ($NS = -0.11–0.73$; $R^2 = 0.097–0.85$). Regardless of being dry or wet, the experimental data for the new soils were better reproduced than those for the old soils. For the new soils, more than 58% of the experiments were reproduced at an acceptable accuracy ($NS \geq 0.36$), while for another 34% of the experiments, the estimated infiltration capacity was more accurate than the average of the experimental data ($NS > 0$). In contrast, for the old soils, about 53% of the experiments were reproduced at an acceptable accuracy, but for about 20% of the experiments, the estimated infiltration capacity was less accurate than the average of the experimental data. Overall, the models performed better for the compact sandy soils than for the compact clayey soils, as indicated by the values of NS and R^2.

Regardless of being new or old and being dry or wet, most of the sandy-soil experiments could not be reproduced, as indicated by the fact that more than 83% of the new-soil experiments and more than 72% of the old-soil experiments had a negative NS value. Totally, only 11% of the 75 sandy-soil experiments were reproduced at an acceptable accuracy ($NS \geq 0.36$), while for another 11% of the experiments, the estimations of infiltration capacity were slightly more accurate than the averages of the responding experimental data. Nevertheless, regardless of being dry or wet, the experimental data for the new noncompact soils were slightly better reproduced than those for the old noncompact soils because the models explained more variations presented in the new- than old-soil experimental data. Similarly, regardless of being old or new, the models explained more variations presented in the wet- than dry-soil experimental data, indicating that the wet-soil experiments were better reproduced, albeit slightly (Figure 2).

Regardless of being new or old, for both calibration and validation, the experiments for the compact sandy soils were better reproduced than those for the noncompact sandy soils, as indicated by the fact that the values of NS and R^2 for the compact sandy soils ($NS = 0.053–0.27$; $R^2 = 0.073–0.27$) are mostly larger than those for the noncompact soils ($NS = -2.70– -0.10$; $R^2 = 0.01–0.28$) (Table 4). Most

Table 4 | Performance and calibrated parameters of the models for sandy soils[a]

Equation	Parameter or measure	Sandy soil						
		All	Compact	Noncompact	Dry compact	Wet compact	Dry noncompact	Wet noncompact
Horton	f_0 (mm h^{-1})	656.488	194.107	1,014.07	126.26–519.152	42.333–204.747	632.242–1,693.464	857.38–1,271.079
		419.049	**245.542**	**810.997**	**114.576–1,194.962**	**42.333–1,616.209**	**85.994–1,292.336**	**461.343–1,062.284**
	f_c (mm h^{-1})	60.198	33.249	60.198	3.219–60.198	5.440–27.977	60.198	60.198
		60.198	**53.035**	**60.198**	**4.033–60.198**	**1.651–60.198**	**7.99–60.198**	**60.198**
	k (h^{-1})	2	7	2	3.808–7	2.213–7	2	2
		2	**6.617**	**2**	**2–7**	**2–7**	**2–4.076**	**2**
	NS (cal.)	−0.194	0.273	−1.270	0.522–0.808	−0.508–0.931	−10.914–0.724	−11.791– − 3.254
		− 0.041	**0.073**	**− 0.917**	**− 0.836–0.796**	**− 0.038–0.732**	**− 13.455–0.724**	**− 43.452– − 2.069**
	R^2 (cal.)	0.069	0.273	0.256	0.590–0.828	0.003–0.931	0.128–0.937	0.558–0.789
		0.052	**0.073**	**0.184**	**0.001–0.796**	**0.113–0.783**	**0.047–0.937**	**0.001–0.731**
	NS (val.)	−0.167	0.166	−1.153				
		− 0.020	**0.071**	**− 0.605**				
	R^2 (val.)	0.065	0.175	0.263				
		0.059	**0.113**	**0.065**				
	PBIAS (cal)	−6.9	−6.5	−5.5	−4.6–2.8	−10.1–1.8	−5.9–2.2	−5.5–4.9
		− 7.4	**− 8.5**	**− 5.6**	**− 6.7–2.9**	**− 8.5–3.8**	**− 6.0–2.2**	**− 6.7–4.7**
	PBIAS (val)	−7.1	−7.6	−5.6				
		− 7.5	**− 8.3**	**− 6.5**				
G-A	λ (-)	0.29	0.29	0.29	0.29–0.386	0.29–1.97	0.29	0.29
		0.29	**0.38**	**0.29**	**0.29–1.97**	**0.29–1.97**	**0.29–1.968**	**0.29–1.968**
	θ_r (-)	0.035	0.035	0.035	0.035–0.082	0.035–0.082	0.035	0.035
		0.035	**0.082**	**0.035**	**0.035–0.082**	**0.035–0.082**	**0.035**	**0.035**
	θ_{ns} (-)	0.123	0.062	0.284	0.062	0.062	0.284	0.284
		0.136	**0.082**	**0.295**	**0.082**	**0.082**	**0.295**	**0.295**
	n (-)	0.501	0.501	0.501	0.437–0.501	0.437–0.501	0.501	0.501
		0.501	**0.437**	**0.501**	**0.437–0.501**	**0.437–0.501**	**0.501**	**0.501**
	ψ_b (mm)	600	600	600	600	54.991–600	600	600
		600	**600**	**600**	**98.949–600**	**54.991–600**	**600**	**589–600**
	K_s (mm h^{-1})	120.396	17.17	120.396	3.509–93.938	3.474–43.97	120.396	120.396
		120.396	**50.749**	**120.396**	**6.040–120.396**	**3.302–120.396**	**4.627–120.396**	**4.627–120.396**
	NS (cal.)	−0.301	0.262	−2.701	0.432–0.772	−0.108–0.798	−13.678–0.145	−19.274– − 8.393
		0.000	**0.074**	**− 1.613**	**− 0.728–0.840**	**− 0.111–0.609**	**− 21.539–0.492**	**− 21.539–0.492**
	R^2 (cal.)	0.078	0.262	0.277	0.432–0.796	0.001–0.866	0.419–0.930	0.793–0.935
		0.062	**0.074**	**0.211**	**0.004–0.859**	**0.097–0.854**	**0.055–0.930**	**0.055–0.930**
	NS (val.)	−0.281	0.159	−1.031				
		− 0.095	**0.053**	**− 0.095**				
	R^2 (val.)	0.069	0.168	0.122				
		0.010	**0.086**	**0.010**				
	PBIAS (cal)	−7.2	−6.5	−7.0	−6.0–2.7	−8.6–3.0	−7.9–4.0	−7.3–6.2
		− 7.3	**− 8.5**	**− 6.6**	**− 6.9–2.5**	**− 8.0–4.4**	**− 7.5–4.0**	**− 7.0–6.2**
	PBIAS (val)	−7.5	−7.6	−7.3				
		− 7.8	**− 8.4**	**− 7.0**				

[a]*NS*: Nash–Sutcliffe coefficient.
R^2: coefficient of determination.
PBIAS: percent bias.
cal.: calibration (2/3 of the experiments).
val.: validation (1/3 of the experiments).
See Table 2 for definitions of the parameters. The numbers in regular fonts are for new (i.e., <15-year) soils, while the numbers in bold font are for old (i.e., ≥15-year) soils.

of the experiments for the new compact soils could somewhat be reproduced ($NS \geq 0.16$; $R^2 \geq 0.10$), whereas the experiments for the noncompact soils could not be reproduced, as indicated by the negative NS values. In consequence, if the data for the compact and noncompact soils were analyzed together, the estimations of infiltration capacity were not better than the averages of the pooled data. This indicates that the compact soils might have distinctly different infiltration characteristics from the noncompact soils. Again, Figure 2 summarizes the relative performances of the models in reproducing the experiments of the sandy soils. Moreover, the models performed better in mimicking the infiltration processes of the most clayey-soil experiments than those of the sandy-soil experiments because the former experiments have overall larger values of NS and R^2 than the latter experiments.

Parameters of the Horton model

For a given clayey or sandy soil, the replicate experiments gave very different values of f_0 in the Horton model (Tables 3 and 4). In general, the variation of f_0 between the sandy-soil experiments was found to be much larger than that between the clayey-soil experiments. For instance, for the dry compact clayey soils, f_0 was determined to vary from 18.98 to 76.2 mm h^{-1}, whereas for the dry compact sandy soils, f_0 was determined to vary from 114.58 to 1,194.96 mm h^{-1}. This indicates that for the same (in particular sandy) soil, the calibrated value of f_0 using a set of experimental data of one rainfall event was likely not good for predicting the infiltration of another rainfall event. In addition, the variation of f_0 was also dependent on the soil age, dryness and wetness, and compactness. For both the clayey and sandy soils, the variation of f_0 for a new soil tended to be smaller than that for an old soil, while the variation for a compact soil tended to be larger than that for a noncompact soil. The variation for a dry clayey soil was either larger or smaller than that for a wet clayey soil, depending on the age and compactness of the soil, whereas the variation for a dry sandy soil was consistently smaller than that for a wet sandy soil.

For parameter f_c, its variation between the sandy-soil experiments was found to be much larger than that between the clayey-soil experiments. The clayey-soil (except for OCWN) experiments gave a constant value of $f_c = 0.76$ mm h^{-1}, whereas the sandy-soil (except for NSDN, NSWN, and OSWN) experiments gave f_c values ranging from 1.65 to 60.2 mm h^{-1}. The OCWN experiments gave f_c values ranging from 0.13 to 0.76 mm h^{-1}, the NSDN, NSWN, and OSWN experiments, on the other hand, gave a constant value of $f_c = 60.2$ mm h^{-1}. Similarly, for parameter k, its variation between the sandy-soil experiments was larger than that between the clayey-soil experiments. For the clayey soils, the variation of k between the experiments of a compact soil was smaller than that between the experiments of a noncompact soil, whereas for the sandy soils, the variation of k between the experiments of a compact soil was larger than that between the experiments of a noncompact soil. Overall, the variation of k between the experiments of a new clayey soil was either larger or smaller than that between the experiments of the responding old soil, the variation of k between the experiments of a new sandy soil, in contrast, was consistently smaller than that between the experiments of the responding old soil. Regardless of being clayey or sandy, k tended to have a larger value for a new soil than the responding old soil, indicating that the infiltration capacity of the new soil declined more quickly with time.

Parameters of the G-A model

For parameter λ, its variation between the experiments of a clayey soil tended to be smaller than that between the experiments of a sandy soil (Table 3 versus Table 4), indicating that ψ_f (i.e., capillary pressure head at wetting front) of the clayey soils is more stable than that of the sandy soils. As expected, the λ value of a clayey soil was smaller than that of a sandy soil because clayey soils usually have a larger capillary pressure head (Equation (3)). In general, a new soil tended to have a smaller variation of λ than an old soil, and the variation was independent of dryness and wetness. Regardless of being clayey or sandy, the λ variation between the experiments of a noncompact soil was smaller than that between the experiments of a compact soil, with constant λ values for the new noncompact clayey ($\approx$0) and sandy (=0.29) soils.

For parameter θ_r, its variation between the experiments of a clayey soil was much larger than that between the experiments of a sandy soil. The new clayey wet noncompact (NCWN) (Table 1) soil had a constant $\theta_r = 0.034$, while the wet noncompact sandy soils had a constant $\theta_r = 0.035$. Regardless of being clayey or sandy, the variation of θ_r was almost independent of dryness/wetness and age. For parameter θ_{ns}, it was mainly dependent on soil texture and compactness while slightly influenced by soil age. As expected, for a given soil, θ_{ns} was independent of wetness or dryness. For parameter n, its variation for either the clayey or sandy soils was small and independent of age, compactness, and dryness/wetness.

For parameter ψ_b, its variation for a compact soil was much larger than that for the responding noncompact soil, but it was independent of age and dryness/wetness. For the compact clayey soils, ψ_b varied from 1,818 to 3,130 mm, while for the compact sandy soils, ψ_b varied from 54 to 600 mm. For either the noncompact clayey or sandy soils, ψ_b was determined to be constant. In contrast, saturated hydraulic conductivity, parameter K_s, had large variations for most of the soils except for OCWC, NSDN, and NSWN. These three exceptional soils were determined to have constant K_s values.

The Horton versus G-A model

Overall, the Horton and G-A models had a comparable performance in predicting the cumulative infiltration for a given soil, as indicated by the similar *PBIAS* values between the two models (Tables 3 and 4). Both models consistently underestimated the cumulative infiltrations of the clayey soils ($PBIAS = 3.5$ to 27.0%), whereas the models underestimated the cumulative infiltrations of some sandy soils while overestimating the cumulative infiltrations of the others ($PBIAS = -10.1$ to 6.2%). For a mixture of clayey and/or sandy soil, the prediction error of the cumulative infiltration could be become larger, as indicated by the relatively larger absolute *PBIAS* values for the soils signified by 'All,' 'Compact,' and 'Noncompact' in the tables.

In terms of predicting infiltration process, both models had an acceptable performance ($NS > 0.36$) for the NCWN and NSDC soils (Tables 3 and 4). However, the large variations of the parameters from one experiment to another could make it uncertain to parameterize either of the two models for the NSDC soil. This means that neither of the models could be applicable for the compact soils and soils with moisture of less than θ_{fc}. For the NCWN soil, the two models had a comparable performance (Figure 3), as indicated by their similar values of *NS* and R^2. However, for an area with the mixture of new, old, wet, and dry noncompact soils, regardless of being clayey or sandy, it is highly unlikely that either of the models would accurately estimate the areal infiltration. It was logically reasoned that for an area with the mixture of compact/noncompact clayey and sandy soils, the infiltration models would not be expected to predict the areal infiltration well. In contrast, for an area with the mixture of new, old, wet, and dry compact clayey soils, the models would likely provide more reliable/reproducible predictions of the areal infiltration. In summary, the Horton and G-A models were almost equivalent in reproducing the infiltration experiments of the disturbed urban soils listed in Table 1. The models could rarely be used for the sandy soils, but they might perform fairly well for the clayey soils (in particular for the NCWN soil).

DISCUSSION

Both Horton and G-A model performed better in estimating the infiltration capacity of the clayey soils than that of the sandy soils. This is consistent with Mishra *et al.* (2003) and Mirzaee *et al.* (2013), whose studies were conducted for rural soils, and Pitt (1987) and Pitt *et al.* (1999, 2000), whose studies were conducted for urban soils. For a given soil, its infiltration capacity is closely related to its pore size and connectivity, which in turn are dependent on the soil structure (Charbeneau 2006). In general, external loadings, including periodically wetting and drying, can more easily change the structure of a sandy soil than that of a clayey soil (Eash *et al.* 2015). As a consequence, the pore size and connectivity of a sandy soil could vary largely from one experiment to another and during an experiment, which can be the reason that a same model parameter was determined to have more different values between experiments for a sandy soil than those for a clayey soil. Pitt *et al.* (1999, 2000) reported that 'compaction had dramatic effects on infiltration rates through sandy soils, while compaction was generally just as important as soil moisture at

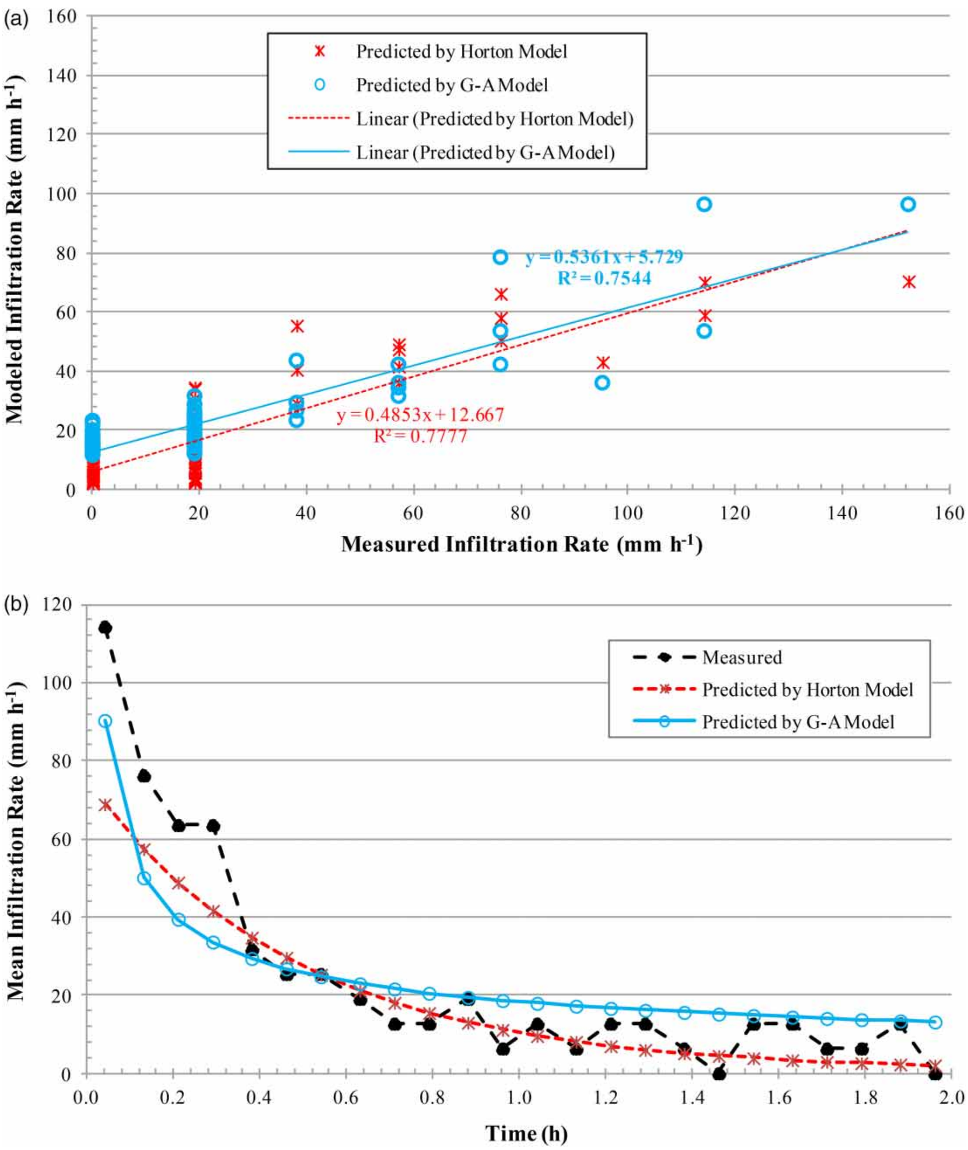

Figure 3 | Plots showing: (a) modeled versus measured and (b) measured and modeled mean, infiltration rates for the NCWN soils.

sites with predominately clay rich soils. Moisture levels had little effect on infiltration rates at sandy sites.' Those authors suggested that 'because of the large amounts of variability in the infiltration rates found, it is important that engineers obtain local data to estimate the infiltration rates associated with local development practices.'

In addition, both models performed better in estimating the infiltration capacity of a noncompact soil than that of a compact soil, regardless of whether the soil is clayey or sandy. Once compacted, a soil tends to have a more layered structure (Wang *et al.* 2000; Eash *et al.* 2015). That is, the vertical profile of a compact soil is more probably heterogeneous and anisotropic than a noncompact soil. Also, a compact soil tends to form cracks and macropores in its surface layer (Yang & Zhang 2011). The surface layer, which is usually more compacted than the underlying layers, may restrict water penetration at the beginning but its penetration rate can increase with the lapse of time as a result of soaking. Thus, a compact soil is more likely to violate the aforementioned models' assumptions (Viessman & Lewis 2003). Based on the laboratory tests of soil columns with different compaction levels, Sajjadi *et al.* (2016) also found that the Horton model performed better for the columns with a lower compaction level than those with a higher compaction level.

Further, both models performed better in estimating the infiltration capacity of a new soil than that of an old soil, regardless of being clayey or sandy and compact or noncompact. One possible reason is that in comparison with a new soil, an old soil is more likely to be compacted to have a layered structure and violate the homogeneous and isotropic assumptions of the G-A model. Another possible reason is that in comparison with a new soil, an old soil is more likely to have macropores (USDA-NRCS 2008; Yang & Zhang 2011), which cannot be taken into account by the models.

Moreover, organic matter (OM) contributes to the stability of soil aggregates and pores through the bonding or adhesion properties of organic materials (Bot & Benites 2005). As a result, a soil with a higher OM content generally has a more stable soil structure and thus the infiltration mechanism closer to what the models assume than a soil with a lower OM content. Although this study could not consider OM as an additional categorical variable because the OM contents were not measured and reported in Pitt *et al.* (1999), a number of studies reviewed by Vodyanitskill (2015) found that OM may decrease (as compared to the background values) in some parts of a city but increase in other parts. In an urban environment, clayey soils tend to have a higher OM content than sandy soils; OM content decreases with increase of compactness, decrease of bulk density, and increase of soil age. This may partially explain the better performances of the models for the clayey than sandy soils, the noncompact than compact soils, and the new than old soils. Nevertheless, the possible variations of OM contents from site to site and from experiment to experiment at a given site can contribute to the different model performances, as indicated by the *NS* and R^2 values in Tables 3 and 4.

However, the models could perform either better or worse for a dry than a wet soil, depending on the soil's age and compactness and the interactions thereof. For the new compact soils, the air trapped in the voids of a wet soil is harder to be removed than that trapped in the voids of a dry soil; for the old soils, on the other hand, the air trapped in the voids of a dry soil may be harder to be removed than that trapped in the voids of a wet soil (Pan & Bassuk 1985). The trapped air can cause the occurrence of hysteresis phenomena (van Genuchten 1980; Ghanbarian-Alavijeh *et al.* 2010), which neither model considers. In contrast, for the noncompact soils, regardless of being new or old, the air trapped in the voids of a dry soil tends to be harder to be removed than that trapped in the voids of a wet soil. The trapped air could affect the rate and path of water movement in the soils. Also, the wetting process of infiltration could result in secondary soil-water properties (e.g., porosity and hydraulic conductivity) (Eash *et al.* 2015), depending on the soil's age, compactness, texture, and structure. Such effects could not be accounted for by the models.

Although the G-A model is physically based while the Horton model is semi-empirical (Mishra *et al.* 1999), they had an almost identical performance in reproducing the experimental data in this study. Previous studies (e.g., Mishra *et al.* 2003; Mirzaee *et al.* 2013) even showed that the Horton model is superior to the G-A model for rural soils. As mentioned above, the G-A model, a direct directive of the Darcy's law for unsaturated soil (Charbeneau 2006), assumes that the soil profile is homogenous and isotropic, has a uniform water content at the beginning, and becomes naturally saturated above, while maintaining the initial water content below the wetting front. The first assumption is probably invalid because of the soil heterogeneity and existence of macropores or secondary porosity represented by the experimental data. The other two assumptions are also unlikely true because the initial soil moisture was not uniform throughout the soil vertical profile and the wetting front might not have a rectangular shape. In contrast, the Horton model, which fits an exponential function experimental data, does not have such assumptions as the G-A model and thus is not affected by any violations of them. The fitting could adapt the function to the experimental data as much as possible, making the Horton model have a performance similar with or even better than the G-A model. However, the assumptions that infiltration exponentially decreases with time at a constant decay rate might not be always true, as indicated by the different k values from experiment to experiment (Tables 3 and 4). This is consistent with Pitt *et al.* (1999, 2000).

In reality, because the soils in an urban drainage area of interest likely consist of multiple types with various soil-water properties, ages, and compaction levels, for practical applications, large uncertainties can be caused by selecting an inappropriate infiltration model for urban catchment hydrologic modeling because the model can be either good or bad, depending on the site-specific properties of urban soils (Pitt 1987; Sajjadi *et al.* 2016). Such uncertainty can propagate through to the runoff and/or water quality predictions of urban hydrologic models (Salvadore *et al.* 2015), potentially lowering the confidence in their predictions. That is, it is always necessary to accurately model infiltration for any hydrologic analysis and design. Thus, our study can potentially benefit the entire (i.e., both academic and practical) hydrology community and urban stormwater managers.

Our current study has three major limitations. First, the study was conducted using data measured at a limited number of sites in just one city, Birmingham, Alabama, USA. The extrapolation of the results to other urban areas, where the wetting/drying cycles and compaction levels are distinctly different from those of the study city, may need further verification using local data. Precautions should be made to generalize the results to those areas with predominantly sand-rich soils, whose infiltration rates can be dramatically affected by compaction, as pointed out by Pitt *et al.* (2000). Second, the study simply assessed the performance of the Horton and G-A models without an intention to improve them. Finally, the study did not examine how the uncertainty of infiltration prediction would propagate from site to catchment level. That is, the study did not examine how to scale up the site-level results. To overcome these limitations, in subsequent research, we will use/collect more data from various urban environments with different climate conditions to not only assess the performance of existing models but also develop more robust infiltration algorithms for disturbed urban soils. Also, we will develop the procedure of scaling up site-level results to determine/correct the uncertainty of catchment runoff prediction resulting from the uncertainty of infiltration estimation in urban environments.

CONCLUSIONS

This study assessed the performance of the Horton and G-A models in modeling infiltration of disturbed urban soils. These two models were selected because they have been mostly used in existing urban hydrologic modeling software packages, including the widely used SWMM program. The data were measured by Pitt *et al.* (1999) through 153 experiments at ten sites (16 different soil combinations) across the city of Birmingham, Alabama, USA. The assessment was implemented by examining how accurately the models could reproduce the measured data as well as the models' robustness. The results indicated that the models performed better for the clayey than sandy soils, the new than old soils, and the wet than dry soils. For the clayey soils, the models performed better for the noncompact than compact soils, but for the sandy soils, the models performed better for the compact than noncompact soils. Overall, the models had a poor performance for most of the soils, except for the NCWN soils. Thus, for disturbed urban soils (in particular sandy soils), infiltration models can have distinctively different performances and large uncertainties (Pitt 1987; Lassabatere *et al.* 2010; Di Prima *et al.* 2016; Sajjadi *et al.* 2016). This performance variability is a critical factor that subsequently can propagate through to the runoff and/or water quality predictions made by most urban hydrologic models, thus potentially lowering the confidence in their predictions. It is recommended that future research should be directed at improving infiltration algorithms for disturbed urban soils using a wide variety of selected field experiments in various urban environments with different climate conditions.

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