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Urban soil infiltration rates on different land use types in southwest Nigeria: actual versus model estimates

Adelana A. O.

Institute of Agricultural Research and Training, Obafemi Awolowo University, P.M.B. 5029 Ibadan, Nigeria.

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Corresponding Author:
aadelana@gmail.com

ABSTRACT

As urban development increases and rainfall patterns become more highly variable, rainwater management issues are becoming increasingly prevalent. Because urban soils may experience greater compaction than non-urban soils due to disturbances, infiltration models may not accurately predict disturbed urban soils, compromising computations based on these models. Therefore, the objective of this research was to quantify the rates of soil infiltration on different urban land use types and assess the applicability and effectiveness of Horton and Green-Ampt infiltration models in urban soil environments. At 88 locations (23 commercial, 15 institutional, 36 residential, and 14 urban agricultural locations) spread across Akure metropolis, southwest Nigeria, soil infiltration rates and other soil characteristics (texture, compactness, and moisture content) were examined. The highest infiltration rates were found in institutional (16.20 ± 9.73 cm hr^{-1}) and urban agricultural (17.51 ± 10.38 cm hr^{-1}) soils; nevertheless, the data showed that Akure soils can infiltrate most rainfall episodes irrespective of urban land use types. The modeled and measured infiltration rates compared poorly with both the Horton and Green-Ampt models, underestimating the rates of infiltration of urban soil. Both models performed better in estimating infiltration capacities in moist than dry soils, and in loamy compared to sandy soils. The prediction accuracy of infiltration in loamy soils was more precise for non-compacted soils than compacted soils using both models, whereas the reverse trend was observed for sandy soils. The below-average performance of the models in urban soils suggests that projections based on them may be less reliable. The results of this study highlight the need to develop more reliable and improved infiltration models specifically tailored for urban soils.

INTRODUCTION

Due to the effects of climate change and urbanization, human populations are becoming more vulnerable to urban flooding, in addition to associated property destruction and freshwater pollution (Bergeson *et al*., 2022). Urbanization significantly increases a region's impervious area and modifies the urban water cycle processes, which is likely to increase runoff and the danger of urban flooding. Water runs off impervious surfaces during rainfall episodes in urban areas, posing risks to human health and safety. For instance, flooding incidents and economic losses have recently been reported in Akure (Ibitoye *et al*., 2020), Ibadan (Olawuni *et al*., 2015), Lagos (Ajibade *et al*., 2015; Nkwunonwo *et al*., 2016), and other cities in Nigeria. This has been linked, in part, to the municipal drainage network's slow development and poor management, as well as the fact that urban soils have not entirely mitigated rainfall floods (Ibitoye *et al*., 2020). Nevertheless, soil infiltration is rarely considered in most urban flooding research or the models that simulate flood propagation. According to Ren *et al*. (2020), a 1% increase in urban areas can result in a 41% reduction in rainwater infiltration into soils and, consequently, double the runoff. Similarly, Olivera and Defee (2007) reported a 146% increase in annual runoff in a watershed in Texas, USA, when impervious areas reached 10%, with urbanization accounting for 77% of that increase.

Soil infiltration has been directly quantified using both field infiltrometer studies and laboratory soil core testing (Wang *et al*., 2017). Direct measurements, however, are limited due to the spatial variability of soil properties such as structure (Basset *et al*., 2023), texture and moisture (Phillips *et al*., 2019), organic matter content (Yang and Zhang, 2011), and degree of compaction (Alaoui *et al*., 2018), which only provide immediate values of infiltration under certain conditions. While using this direct data on infiltration, it is seldom possible to simulate the hydrologic processes in a region at a watershed scale (Rossmiller, 2014). Instead, infiltration models that can be used to model infiltration in a watershed have been developed and validated using minimal information (Wang *et al*., 2017).

Many infiltration models include estimates of soil infiltration parameters, but these parameters are typically based on relatively unaltered soils (Wang *et al*., 2017; Schifman and Shuster, 2019). The physically based Green and Ampt (1911) and semi-empirical Horton (1940) models are two of the most used methods for estimating infiltration rates while using infiltration models. These models have been assessed using information from infiltration studies on rural soils used for agriculture or river basin management. For instance, Zakwan (2019), working on some agricultural soils, reported that the Horton model best-estimated infiltration on the sandy soils in Lafia, central Nigeria, whereas the Green-Ampt model exhibited the poorest performance in estimating infiltration in the same area. In the same study, both the Green-Ampt and Horton models performed poorly on the sandy loam soils in Umahia, south-eastern Nigeria. The study concluded that the suitability of any infiltration model for estimating infiltration rates is a function of the soil texture. In another study, Eze and Musa (2022) reported that Kostiakov's model performed better than Horton's model when estimating infiltration on some sandy loam and loamy sand agricultural soils in Niger State, Nigeria. Elsewhere in Iran, Mirzaee *et al*. (2014) reported that the Green-Ampt and Horton models fared poorly compared to other models evaluated at 95 locations used for agriculture. According to the study, all the models typically performed better for clayey soils than for loamy soils, suggesting that the infiltration models have the potential to offer a more accurate estimation of infiltration capacities for clayey soils.

Urban soils, as opposed to those in rural or agricultural areas, are frequently subjected to various anthropogenic pressures brought on by impacts and static loads, which can cause significant and widespread soil compaction. Because of this, even if two soils have the same texture, the structure, compaction, and moisture characteristics associated with urban soils might be quite distinct from those of rural or agricultural soils (Markovič *et al*., 2014). The effectiveness of infiltration models in estimating infiltration rates in urban soils is currently poorly understood. The Green-Ampt and Horton models are incorporated in most urban hydrologic modeling tools that are currently employed, such as the widely used USEPA Storm Water Management Model (SWMM) (Rossman and Huber, 2016). The issue here is that the hydrology of urban soils complicates rainfall-runoff prediction and has yet to be thoroughly investigated systematically. Within the anthropogenic time scale, urban soils can be subjected to activities that drastically modify their hydrology, such as construction and demolition, which change soil conditions in less than a week. Similarly, variability in urban soil hydrology can vary within less than a meter (Schifman and Shuster, 2019), rendering even the most intensive mapping efforts insufficient. This raises the question of whether models such as the USEPA Storm Water Management Model are appropriate for predicting the rainfall-runoff of urban ecosystems. As a result, studies that will improve these underlying infiltration models are becoming more essential. To fill the gaps in knowledge about the significance of urban soils in hydrologic processes and the generation of rainfall-runoff, we recorded infiltration rates across the city of Akure in southwest Nigeria. The objectives of this study, therefore, were to determine the effectiveness of the Green-Ampt and Horton models in estimating infiltration rates on urban soils and to compare the measured infiltration rates from various urban land use types with estimations from infiltration models.

MATERIAL AND METHODS

Study location

This study was conducted in the city of Akure, in southwest Nigeria. Two different seasons characterize the humid tropical climate of Akure: a longer wet season spanning from March to November and a short dry season extending from December to February. In Akure, the average yearly temperature is 27 °C, with 1,600 mm of rainfall (Nigerian Meteorological Agency, 2020). Akure is characterized by rocks from the Precambrian Basement Complex, primarily granite and gneisses, which underlie the low-lying outcrops. The most prevalent soil types in the city are Aquic Dystrudept, Typic Kandiudalf, and Typic Kanhapludalf. According to Owoeye and Ibitoye (2016), Akure is a developing city that has witnessed substantial urban and demographic expansion in recent years. The National Bureau of Statistics (2016) projected that in 2020, the population of Akure would be 630,238 with a density of 4,945 persons per square kilometre.

Site selection

Within the boundaries of Akure's urban area, 88 sites were located using a stratified randomized sampling strategy while considering the main land use types. Based on the classification system developed by Anderson *et al*. (1976), four urban land use types were identified: residential, commercial, institutional, and urban agriculture. Using the protocols established by Pouyat *et al*. (2007), a total of 23 commercial, 15 institutional, 36 residential, and 14 urban agricultural sites were sampled.

Soil infiltration measurement

Using a single-ring infiltrometer, infiltration rates were determined at each site as saturated hydraulic conductivity (Ksat) (Xu *et al*., 2012). Infiltration was measured according to Díaz-Sanz *et al*. (2020). The ring has a diameter of 0.30 m and a length of 0.30 m, with one end sharpened to facilitate ground penetration. Compared to double-ring infiltrometers, single-ring infiltrometers have a lower leakage rate when employed in compacted urban soils (Díaz-Sanz *et al*., 2020). The ring was hammered around 0.05 m into the soil, the precise ring depth was measured, and the soil surface was maintained to prevent lateral flow. To reduce surface disturbance when pouring water into the ring, grass clippings were placed on the soil surface. For the duration of the measurements, a steady head of 0.10 m of water was retained in the ring. For the first ten minutes, the amount of water infiltrated was measured every minute, and thereafter five five-minute intervals for the duration of an hour. Within the measuring time, steady-state infiltration was achieved in every instance. At each site, three 1.5-meter-distance infiltrometer points were selected for measurements. The infiltration rate (cm hr^{-1}) was estimated and presented as a function of time for each replicate. Given the high variation in infiltration rates between the sites, $\log_{10}$ transformed infiltration indices were developed, ranging from 0 (the site with the least infiltration) to 1 (the site with the highest infiltration) using Equation 1.

$$Infiltration\ index = \frac{log_{10}(infiltration\ rate)}{highest(log_{10}(infiltration\ rate))} \qquad 1$$

To find out if infiltration capacity could accommodate local rainfall events, hourly rainfall data for Akure were obtained from the Nigerian Meteorological Agency and compared to the infiltration capacity of the sites. A rainfall event was considered partially infiltrated if, over an hourly period, rainfall rates were higher than the site's capacity for infiltration.

Other soil physical variables

Using a modified Boyoucos hydrometer technique (Gee and Or, 2002), the sample site's soil texture was examined to establish a relationship between infiltration and variations in soil type. The penetration resistance (PR) of the soils was measured using a field penetrologger (Eijkelkamp Agrisearch Equipment, Netherlands) to evaluate their compactness. Sites with PR ≥ 2.0 MPa are classified as compact, whereas those with PR < 2.0 MPa are classified as non-compact. Volumetric moisture content (θ) was measured using a soil moisture sensor Theta Probe (Eijkelkamp Model 06.15.50, Netherlands) to account for the inherent soil moisture when infiltration readings were made. It was assumed in this study that a specific soil was moist when θ ≥ FC/2, where FC is the field capacity, and dry when θ < FC/2. Based on the inherent soil moisture, compaction, and soil texture, eight categories were identified for the urban soil infiltration measurement scenarios, as indicated in Table 1.

Infiltration models

According to Salvadore *et al*. (2015), there is no generalized approach for modelling rainfall-runoff; rather, there are numerous models that may be used. The research focus, data accessibility, and expertise regarding the model all influence the choice of models. The Horton and the Green-Ampt models are two of the most widely used methods for calculating infiltration in rainfall-runoff models, so they were considered as an unbiased representation of current models.

Horton's semi-empirical infiltration model may be stated as:

$$f_t = f_c + (f_o - f_c)e^{-k_d t} \qquad 2$$

where f_t is the infiltration capacity into the soil at time t, f_c is the minimum infiltration rate capacity, f_o is the maximum infiltration rate capacity, k_d is the decay constant, and t is the time from the start of rainfall. Another widely used rainfall-runoff model is the physically based Green-Ampt model, which can be stated as:

$$f_t = \frac{K_S}{2}\left[1 + \frac{\Psi_f(\theta_{ns} - \theta_\alpha)}{F_t}\right] \qquad 3$$

where f_t is the infiltration capacity into the soil at time t, K_s is the saturated hydraulic conductivity, F_t is the cumulative infiltration until time, θ_α is the initial/antecedent soil moisture, θ_{ns} is the volumetric water content, and Ψ_f is the capillary pressure at the wetting front. Equation 3 can be written as:

$$f_t = K_s + \frac{A}{F_t} \quad 4$$

where A is a constant accounting for the initial soil moisture, matric suction potential, and the pressure at the wetting front. About seventy per cent of the field data was utilized for calibration for both the Horton and the Green-Ampt calibrated models, and thirty per cent was used for validation. Each of the mean infiltration datasets was used to calculate the model parameters, resulting in 88 sets of parameter values for each model. By looking at differences across sets of parameter values for a particular soil combination, the performance of the model was evaluated.

Table 1. Site code and number of sites sampled based on soil properties

Soil properties[a]	Loamy[b]	Sandy[c]
Moist non-compact	LMN (n = 11)	SMN (n = 10)
Moist compact	LMC (n = 11)	SMC (n = 9)
Dry non-compact	LDN (n = 12)	SDN (n = 10)
Dry compact	LDC (n = 13)	SDC (n = 12)

[a] Soil is compacted when PR ≥ 2.0 MPa and non-compacted when PR < 2.0 MPa; when moisture ≥ FC/2 site is moist and when moisture < FC/2 site is dry. [b]Loamy soils had sand 50–60%, silt 11–20%, and clay 20–30%. [c]Sandy sols had sand ≥ 70%, 5–10% silt, and clay ≤ 12%. LMN is loamy moist non-compact, SMN is sandy moist non-compact, LMC is loamy moist compact, SMC is sandy moist compact, LDN is loamy dry non-compact, SDN is sandy dry non-compact, LDC is loamy dry compact and SDC is sandy dry compact.

For example, in the Green-Ampt or Horton model, the soil combination LDC had thirteen sets of parameter values, whereas the soil combination SMC had nine sets (Table 1). When there were fewer parameter differences for the former combination than the latter, the model was more appropriate for that combination of soil. This decision is supported by the observation that models with soil combinations that could provide reasonably consistent parameter values tend to be more reliable. Likewise, the infiltration datasets for sandy and loamy soils were combined into separate datasets for either moist or dry, as well as compact or non-compact conditions. Consequently, two datasets for sandy soils and two more for loamy soils were created. Following that, each dataset was split into two separate datasets: one for model validation and the other for model calibration. For the four soil combinations – dry compact, moist compact, dry non-compact, and moist non-compact, the model's performance was evaluated.

Statistical analyses

The R statistical tool, version 4.2.1 (R Core Team, 2022), was used for parameter estimation, data analysis, and graphical presentation. The statistical method followed Díaz-Sanz et al. (2020). To ascertain the effect of urban land use types (ULUTs) on soil infiltration rate, a significance test was performed using the Kruskal-Wallis multiple comparison test ($p \leq 0.05$) and a post-hoc Dunn’s test using the

Bonferroni method to correct for the p-values. The Shapiro-Wilk test was used to check for normality before the significance test.

The match between the modeled and measured infiltration rates was assessed using the Nash-Sutcliffe efficiency coefficient (NSE). Although NSE is often used to assess the overall effectiveness of rainfall-runoff models, in this study, the methodology of Wang *et al*., (2017) was employed to assess the infiltration elements within the models. The study determined that the modeled infiltration rates were deemed acceptable for NSE values between 0.36 and 0.75 and good for NSE values over 0.75. To further confirm the effectiveness of the model, the coefficient of determination (R^2) was also calculated. A better model performance is indicated by a higher R^2 value, which varies from 0 to 1.0.

RESULTS

Rainfall events infiltrated

Rainfall rates of more than 0.1 cm hr^{-1} averaged around 183 hourly rainfall events a year, whereas historical rainfall within Akure varied from 0 to 36.4 cm hr^{-1} between 2001 and 2020. Over the course of the 20-year period, around 12% of the direct rainfall incidents within the urban limits of the city would not have entirely infiltrated; the proportion of rainfall events that were partially infiltrated was highest on commercial land use (20.2%) and lowest on urban agricultural sites (4.5%) (Fig. 1).

Infiltration on urban land use types

With an average of 10.43 cm hr^{-1} and a median of 7.49 cm hr^{-1}, the measured infiltration rates from all the sites vary from 2.55 to 40.57 cm hr^{-1}. Comparing the ULUTs, the infiltration rates for residential (8.06 ± 4.76 cm hr^{-1}) and commercial (6.08 ± 3.48 cm hr^{-1}) sites were significantly ($p < 0.001$) lower than those for agricultural and institutions. However, infiltration on agricultural (17.51 ± 10.38 cm hr^{-1}) sites was higher than that of institutions (16.20 ± 9.73 cm hr^{-1}) but the difference was not statistically significant (Table 2).

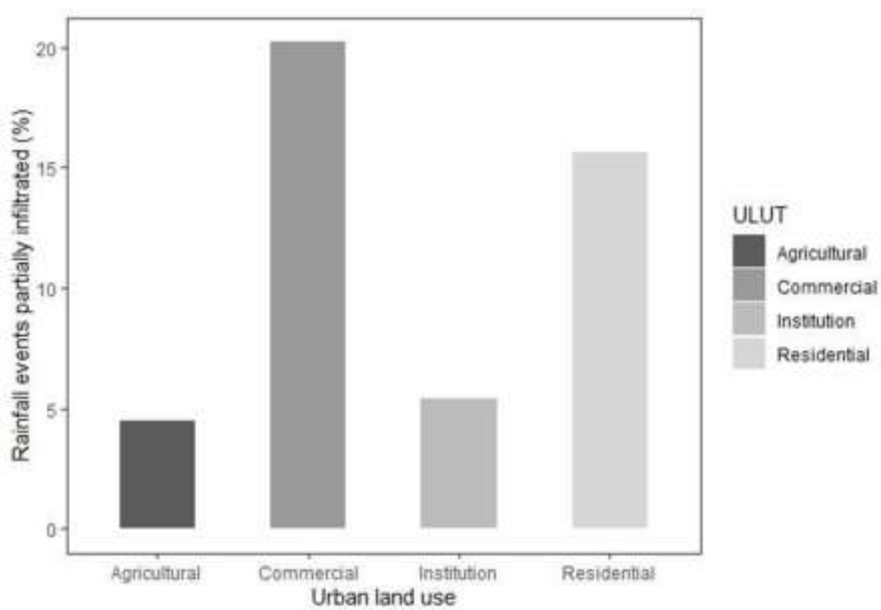

Fig. 1: Percentage of rainfall events in Akure when rainfall exceeds infiltration rates on ULUTs using hourly rainfall data for 20 years (2001–2020)

Table 2: Mean infiltration rates under different ULUTs in Akure

Urban land use type	**Number of sites**	**Infiltration rates (cm hr^{-1})**
Agricultural	14	17.51 ± 10.38a
Commercial	23	6.08 ± 3.48c
Institutional	15	16.20 ± 9.73a
Residential	36	8.06 ± 4.76b

Means with different letters are significantly different at $p < 0.05$, numbers after ± are standard deviations

The infiltration index values in Akure metropolitan area had a mean of 0.56 and a median of 0.54, ranging from 0.25 to 1.00. The index values ranged most widely among residential sites, from 0.30 to 0.82, while the least was on commercial sites, with a range of 0.25 to 0.69 (Fig. 2).

Estimated model parameters

Tables 3 and 4 show that the model produced significantly varying values of f_o according to the Horton model for loamy or sandy soils. Generally, it was discovered that significantly greater variability in f_o across the estimates for sandy soil as compared to loamy soil exists. For example, f_o varied between 2.05 and 10.22 cm hr^{-1} for LMC soils and between 16.10 and 38.49 cm hr^{-1} for SDN soils. Furthermore, the inherent moisture and compaction all had an impact on the variations in f_o. The difference in f_o for compacted soil was generally greater when compared to non-compacted soil, regardless of soil texture. While the difference in f_o for dry sandy soil was always less compared with that of moist sandy soil, the difference for dry loamy soil varied based on the soil compaction.

The difference in f_c between the infiltration conducted on sandy soil (4.15 to 38.40 cm hr^{-1}) compared with those conducted on loamy soil (1.04 cm hr^{-1}) was high. Likewise, the difference in k_d was found to be greater among the infiltrations in sandy soil compared to.

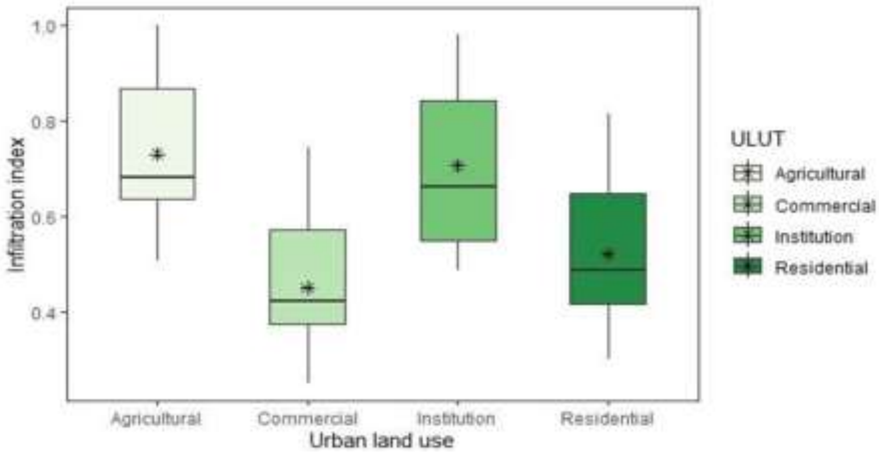

Fig. 2: Infiltration index in different ULUTs

Table 3: Green-Ampt and Horton models' calibrated parameters and performance on loamy soils

Model	Parameter	All	Compact	Non-compact	Moist compact	Dry compact	Moist non-compact	Dry non-compact
Horton	*fc* (cm hr^{-1})	1.04	1.04	1.04	1.04	1.04	1.04	1.04
	fo (cm hr^{-1})	10.22	10.22	11.35	2.05–10.22	6.12–10.22	9.33–11.35	8.09–11.35
	kd	2.60	2.60	2.60	2.60–3.75	2.60–3.11	2.60–2.82	2.60–4.89
	NSEcal.	0.07	0.51	-0.07	-0.03–0.73	0.21–0.79	0.60–0.84	-3.05–0.77
	NSEval.	-0.07	0.47	-0.21				
	R^2ca	0.25	0.64	0.22	0.09–0.84	0.41–0.88	0.77–0.89	0.11–0.74
	R^2val	0.06	0.50	0.05				
G-A	*Ks* (cm hr^{-1})	6.10	6.10	6.10	3.03–6.10	2.07–6.10	4.38–6.10	1.01–6.10
	A	2.70	0.83	7.64	0.07–0.62	0.13–0.79	1.66–6.66	2.55–6.00
	NSEcal.	0.12	0.48	-0.01	0.07–0.60	0.39–0.93	0.65–0.70	-2.76–1.03
	NSEval.	0.002	0.57	-0.14				
	R^2cal.	0.25	0.58	0.62	0.11–0.70	0.37–0.89	0.73–0.84	0.14–0.70
	R^2val.	0.66	0.67	0.08				

cal. is calibration, val. is validation, NSE is the Nash-Sutcliffe efficiency coefficient, R^2 is the coefficient of determination, G-A is the Green-Ampt model

Modeled infiltration rate on loamy soil

The infiltration on the compacted soils, irrespective of the inherent moisture condition, was more precisely simulated when using the calibration as well as the validation data compared with the non-compacted soils. This is evident in the NSE and R^2 values obtained from both Horton and Green-Ampt models for compacted soils (NSE = 0.47–0.57 and R^2 = 0.50–0.67), which are generally higher than those for non-compacted soils (NSE = -0.21–-0.01 and R^2 = 0.05–0.62) (Table 3). When the non-compacted and compacted data sets were combined for analysis, the infiltration rate estimates did not outperform the means of the combined data. Furthermore, Table 3 shows that the infiltration rate of the compacted loamy soil was more accurately predicted by both models when the soil was dry (NSE = 0.21–0.93 and R^2 = 0.37–0.89) than when in a moist condition (NSE = -0.03–0.73 and R^2 = 0.09–0.84). Conversely, for non-compacted loamy soils, the models correctly predicted infiltration in moist conditions (NSE = 0.60–0.84; R^2 = 0.73–0.89) than in dry conditions (NSE = -3.05–1.03; R^2 = 0.11–0.74), unlike what was observed for compacted loamy soils.

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Modeled infiltration rate on sandy soil

Like loamy soils, the infiltration rate of compacted sandy soil was more accurately predicted when dry (NSE = 0.60–0.81 and R^2 = 0.23–0.89) compared to when moist (NSE = - 0.76–0.83 and R^2 = 0.02–0.95) (Table 4).

Most of the infiltration on the sandy soils, irrespective of the inherent moisture condition, was unable to be accurately modeled, as shown by over 80% of the infiltrations having negative NSE values.

Table 4: Green-Ampt and Horton models' calibrated parameters and performance on sandy soils

Model	Parameter	All	Compact	Non-compact	Moist compact	Dry compact	Moist non-compact	Dry non-compact
Horton	*fc* (cm hr^{-1})	4.11	2.20	4.11	0.89–1.90	0.40–4.11	4.11	4.11
	fo (cm hr^{-1})	16.22	11.20	29.31	4.15–10.22	10.12–14.25	19.10–30.11	16.10–38.40
	kd	2.60	3.75	2.60	2.70–3.75	3.10–3.75	2.60	2.60
	NSEcal.	-0.29	0.41	-1.91	-0.76–0.83	0.60–0.81	-17.68–-4.88	-16.37–0.79
	NSEval.	-0.25	0.25	-1.73				
	R^2cal.	0.10	0.51	0.36	0.10–0.92	0.25–0.89	0.29–0.38	0.09–0.70
	R^2val	0.11	0.36	0.40				
G-A	*Ks* (cm hr^{-1})	11.50	2.58	11.50	0.53–6.60	0.54–10.08	11.50	11.50
	A	4.05	1.24	11.46	0.11–0.93	0.20–1.19	11.46	11.46

NSEcal.	-0.45	0.39	-4.05	-0.16–0.80	0.65–0.79	-28.91	-20.52
NSEval.	-0.42	0.24	-1.55				
R^2cal.	0.12	0.39	0.42	0.02–0.95	0.23–0.89	0.08	0.06
R^2val.	0.10	0.25	0.18				

cal. is calibration, val. is validation, NSE is the Nash-Sutcliffe efficiency coefficient, R^2 is the coefficient of determination, G-A is the Green-Ampt model

Just 10% of the infiltrations conducted on sandy soil could be predicted with an adequate level of accuracy (NSE > 0.39). The compacted soils exhibited higher NSE and R^2 values (NSE = 0.24–0.41 and R^2 = 0.25–0.51) compared to the non-compacted soils (NSE = -4.05–-1.55 and R^2 = 0.18–0.42), indicating more accurate predictions of infiltration for both calibration and validation in the compacted sandy soils than in the non-compacted sandy soils (Table 4). The negative NSE value showed that while the infiltrations on the non-compacted soils were unable to be predicted, most of the infiltrations on the compacted soils were capable of being significantly predicted. Consequently, the estimates of the infiltration rate did not seem more reliable compared with the means of the combined compacted and non-compacted datasets.

DISCUSSION

Nearly all rainfall incidents from the recent climatic record could be infiltrated according to infiltration rates across Akure (Fig. 1). This suggests that permeable urban soils in Akure could infiltrate substantial quantities of runoff from impervious surfaces. Although some of the infiltration rates reported in the literature are higher than those reported in this study, they still align with the wide range reported by Fasinmirin *et al*. (2018) and Elemile *et al*. (2020). It has been demonstrated that the type of urban land use has a major impact on the infiltration rate. Infiltration rates were found to be significantly higher on institutional and agricultural sites, especially those with more aboveground biomass, compared to commercial sites with sparse to bare land cover. The higher compaction levels on commercial sites could have resulted in poor soil structure and subsequently lower infiltration rates. Surprisingly, greater infiltration rates were observed in Akure metropolis, contrary to the initial expectations based on the model estimates. As demonstrated in Fig. 3, both the Horton and Green-Ampt models often tended toward underestimating infiltration rates on the urban soils. In many instances, there was a significant disparity between the estimated and observed infiltration rates.

The infiltration rate of loamy soils in Akure was estimated more accurately using the Horton and Green-Ampt models than sandy soils. This is in line with Wang *et al*.'s (2017) research on urban soils; however, it differs from Zakwan's (2019), whose study was carried out on rural agricultural soils. The infiltration rate of any soil is directly proportional to the size and connectedness of its pores, both of which are influenced by the soil structure. According to Lal and Shukla (2004), external loadings often have a greater ability to modify the structure of sandy than loamy soils. Consequently, the size and connectedness of pores in sandy soil may fluctuate significantly between infiltration tests. This could be the cause of the observed variation in values of any single model parameter for sandy soils over loamy soils. While the models might work rather well for loamy soils, they could be of limited use for sandy soils. Pitt *et al*. (2008) showed that infiltration rates on sandy soils were significantly impacted by compaction, irrespective of the antecedent soil moisture content.

Additionally, regardless of soil texture, both models estimated the soil's infiltration rate better on the non-compacted soils compared to the compacted soils. A soil's structure tends to become more stratified after it has been compacted, creating a complex vertical profile, and this can inhibit water flow (Lal and Shukla, 2004). Furthermore, according to Yang and Zhang (2015), compacted soil frequently develops macropores and fissures in its top layer. Since the top layer is typically more compact compared to the subsurface layers, water may initially infiltrate more slowly, but as time passes and the layer gets wet, the rate of infiltration gets higher. Thus, the assumptions of the rainfall-runoff models are more likely to be invalidated in compacted soil (Gribbin, 2014). In their study, Wang *et al*. (2017) also reported that both the Horton and Green-Ampt models were able to more

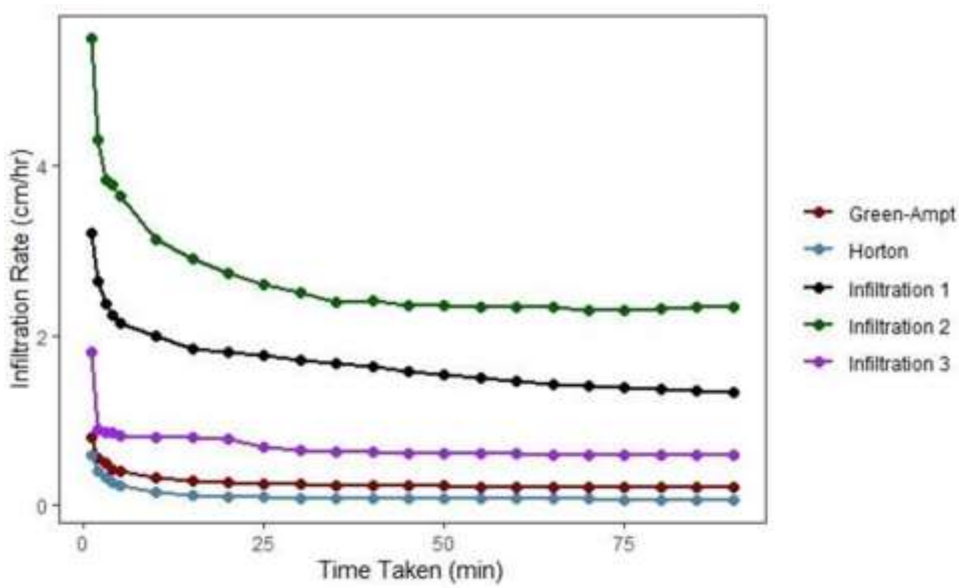

Fig. 3: Comparison between highly variable measured and modeled infiltration rates at LMC site

accurately predict infiltration rates on non-compacted soils when compared with compacted soils.

Another factor that might have influenced the model's performance is the organic matter (OM) content. Due to the binding qualities of organic materials, organic matter helps to stabilize soil aggregates and pores (Zhou *et al*., 2022). Therefore, compared to soil with a lower OM content, soil with a greater OM content typically has a more stable soil structure and an infiltration pathway that is more in line with the model's assumptions. While OM was not considered as a factor in this study, Brown *et al*. (2012) reported that OM could increase in certain locations in an urban area but reduce in others when in comparison with baseline levels. Loamy soils typically contain more organic matter than sandy soils in an urban setting; OM concentration falls with increasing compaction and decreasing bulk density. This explains why the non-compacted and loamy soils perform better in the

Horton and Green-Ampt models than the compacted and sandy soils. However, as the NSE and R^2 values in Tables 3 and 4 show, differences in OM contents across locations, as well as between infiltration tests at a certain location, may account for some of the variances in model performances.

While the Horton model is semi-empirical and the Green-Ampt model is physically based, both models performed quite similarly in terms of simulating urban infiltration rates in Akure. However, it has been observed in earlier studies that for rural agricultural soils, the Horton model performs better than the Green-Ampt model (Mirzaee *et al*., 2014; Zakwan, 2019). According to the Green-Ampt model, the soil is assumed to be homogeneous down the profile, with constant antecedent moisture through the profile that naturally becomes saturated above the wetting front and retains its antecedent moisture content below the wetting front. The model's earlier premise can be considered invalid due to the variability of the soil throughout the profile and the presence of macropores, as indicated by the infiltration results. It is unlikely that the wetting front had a rectangular shape, and the antecedent soil moisture was not consistent across the soil horizons in the profile, making the validity of the other two premises equally doubtful. However, unlike the Green-Ampt model, the Horton model is independent of the same assumptions and therefore unaffected by any breaches of them. Instead, it fits the infiltration results in the form of an exponential function. By fitting the function as closely as feasible to the infiltration results, the Horton model was capable of matching or surpassing the Green-Ampt model's performance. However, as demonstrated by the various k_d values across infiltration measurements in this study, the hypothesis that infiltration reduces exponentially over time at a steady decay constant may not necessarily remain valid (Wang *et al*., 2017).

Since the soils in an urban watershed are likely to be diverse in terms of their soil water characteristics and degree of compaction, choosing the wrong rainfall-runoff model for urban watershed hydrologic modeling can lead to major challenges. This is because the model's performance can vary greatly based on the location-specific characteristics of urban soils. Urban rainfall-runoff models may see a decline in reliability in their runoff projections because of this variability (Salvadore *et al*., 2015). In other words, precise modeling of infiltration is a prerequisite for all hydrologic analyses and designs.

CONCLUSIONS

The effectiveness of the Horton and Green-Ampt models in simulating the infiltration of urban soils was evaluated in this study. At 88 locations throughout the Nigerian city of Akure, 264 infiltration tests were conducted to determine the soil's infiltration rates. This evaluation was carried out by looking at the reliability of the two models and their ability to replicate the measured infiltration rates with accuracy. Results show that urban soils may function effectively in providing hydrological services and that, in general, the models performed poorly in simulating the highly variable infiltration rates of urban soils. Specifically, the models fared better on moist soils than on dry soils and better on loamy soils than on sandy soils. Therefore, infiltration models may operate very differently and have a significant degree of uncertainty for urban soils, especially those with sandy textures. Many hydrological models estimate rainfall-runoff relationships, and the variability in their performance is a key factor that could reduce the reliability of such projections. Further studies could focus on the

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development of infiltration algorithms for urban soils through a series of carefully selected infiltration trials conducted in diverse urban settings under varying climates.

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