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Evaluation of infiltration models in clay loam and laterite soils under field conditions

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ABSTRACT

The purpose of the investigation is to calculate soil infiltration rates with the help of infiltration models. The infiltration model helps to design and evaluate surface irrigation systems. The study calculated constant infiltration for two types of soils (clay loam soil and laterite soil) under field conditions (Unploughed and Ploughed). The double-ring infiltrometer has been implemented to experiment. The value of various constants of the models was calculated using the approach of averages counselled through a graphical technique. Fitting infiltration test data to prominent infiltration models such as Philip's, Horton's and Kostiakov's and The Nash- Sutcliffe efficiency (NSE), coefficient of determination (R^2) and root mean square error (RMSE) statistics are used to evaluate the effectiveness of the model. The results indicate that Philip's model is the most reliable, with R^2, NSE, and RMSE values ranging from 0.9044-0.9677, 0.294-0.957 and 1.2647-5.7129, respectively. Therefore, under identical circumstances and without any kind of infiltration information, the above model can be employed to artificially produce infiltration information.

Introduction

Rainwater catchment areas have shrunk as a result of fast development and settlement. Urban regions will experience increasing water runoff and flooding of the shrinking rainfall collection areas (Apollonio *et al.,* 2016). Water infiltration through soil occurs naturally. Significant contributions are made to the hydrological cycle by it. Infiltration is the process of movement of water from the ground surface into the earth's soil and increasing the overall amount of water present, which affects water partitioning and hydrological responses (Shakesby *et al.,* 2000; Walker *et al.,* 2007). Infiltration is crucial to hydrology because it limits the water reserves that can be used to fill groundwater wells and prevents water runoff and soil erosion (Angulo *et al.,* 2016). A Simple device known as a double-ring infiltrometer can be used to measure the infiltration of water into the soil Dagadu *et al.* (2012). Infiltration can be stated in two dimensions, the capability of infiltration and the rate is measured in mm/hr. The infiltration velocity depends on the type of soil and its characteristics. An individual type of soil's infiltration capacity is its maximum infiltration rate. Soil absorbs the water under specific conditions known as soil infiltration capacity (Dhalhar,1972). Eight different infiltration models were considered by (Mirzaee *et al.,*2014). These models were evaluated by least squares fitting to measure soil infiltration. For the NIT Kurukshetra campus, (Sihag *et al.,* 2017a) compared the infiltration models. In comparison to existing models, the novel model best matched the field infiltration data. The soil infiltration rate was predicted using various soft computing techniques (Singh *et al.,* 2017; Sihag *et al.,* 2017a, b; Sihag *et al.,* 2019). The current investigation's goal is to identify the model

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parameters and locate the most appropriate model for the soils of the research area specified below.

Material and Methods

Study Area

The current soil infiltration investigation is being performed at the Indira Gandhi Krishi Vishwavidyalaya in Raipur (C.G.) (Figure 1). It is in Chhattisgarh's East Central region at longitude 21^{0}13'59"N, longitude 81^{0}37'59"E and altitude 289.5 m above mean sea level. This region is sub-humid, with hot summers and cold winters. The rain is caused by the southwest monsoon. Based on an 80-year average, it receives 1312 mm of rain each year, with 85% of that falling between June and September. A few showers in the winter and a handful of showers in the summer are possible. The hottest month is May and the coldest month is December. While the winter minimum temperature dropped to 8°C, the weekly high temperature in the summer was 45.8°C. From June through October, relative humidity and wind speed are high, with a peak in June and July.

Measurement of infiltration rates

A Double ring infiltrometer (ASTM 2003) was used to determine the infiltration rates. The double-ring infiltrometer includes two rings. The outside ring is 30 cm in diameter and has a 60 cm outside diameter, driving the rings 8-9 cm into the ground. The hammer should strike the steel plate ring uniformly without disrupting the soil surface. The level of the water in both rings were same. Frequently measurements of the water depths in the infiltrometer were taken until a steady degree of infiltration was attained. The soil sample weighed between 100 and 150g as taken at a location near the experiment site to determine the amount of water present in the soil before estimation of infiltration rate.

Infiltration models and parameter

The three subsequent infiltration models were evaluated to decide which would most appropriately match the information on field infiltration rates.

Horton's model

The decline in infiltration capability over time was depicted in Horton's semi-empirical model as an exponential decay given by

$$I = f_c + (f_o - f_c)e^{-kt}$$

where,
I is Infiltration capacity or potential infiltration rate [cm/hr],
f_c is final constant infiltration rate [cm/hr],
f_o is initial infiltration capacity [cm/hr],
k is Horton's decay coefficient, which is dependent on soil characteristics and vegetation cover, and
t is the time after the start of infiltration (hr).

Kostiakov's model

The formula for cumulative infiltration expressed by Kostiakov's model is

$$F = at^{b}$$

where,
F is cumulative infiltration capacity (cm/hr)
t is time after infiltration starts, and
a and b are constants that depend on the soil and initial conditions.

Philip's model

The relationship shown below represents Philip's (1957) two-term model:

$$f_p = \frac{1}{2}st^{-\frac{1}{2}} + k$$

where,
f_p is infiltration capacity at any time step from the beginning
s is infiltration capacity at any time step from sorptivity of soil water,
k is the hydraulic conductivity of Darcy.

Estimation and inter-comparison of model parameter

Root mean square error (RMSE)

The root means the square error is abbreviated as RMSE. When using a statistical model to predict a numerical outcome, predicted values rarely match actual outcomes completely.

$$\text{RMSE} = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{n}(a_i - b_i)^2\right)}$$

where,
a is the calculated value of the infiltration rate
b is the value of the infiltration rate
N is the number of observations

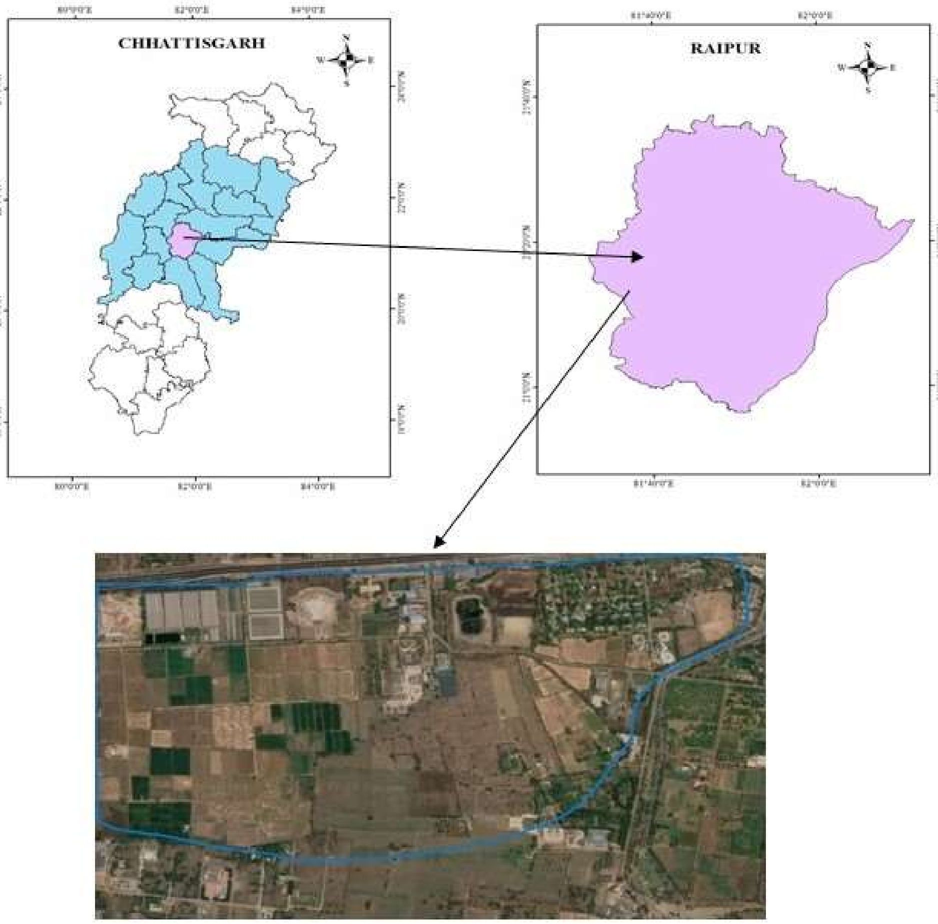

Figure 1: Location of the study area

Nash-Sutcliffe model efficiency coefficient

A normalized statistic called the Nash-Sutcliffe efficiency (NSE) measures how much residual variance there is in comparison to the variance of the measured data (Nash and Sutcliffe, 1970). A result of 80-90% shows moderately acceptable performance, a value of 80-90% indicates extremely good efficiency, while a value of less than 80% denotes an inadequate fit.

$$\text{Model efficiency} = 1.0 - \frac{\sum_{i=1}^{n}(x-y)^2}{\sum_{i=1}^{n}(x-\bar{x})^2}$$

Coefficient of determination (R^2)

A statistical model's capacity to explain and predict future events is determined and evaluated using the coefficient of determination, often known as R^2.

The mathematical formula for computing R^2 is

$$R^2 = \left(\frac{z\sum ab-(\sum a)(\sum b)}{\sqrt{z(\sum a^2)-(\sum a)^2}\sqrt{z(\sum b^2)-(\sum b)^2}}\right)^2$$

Results and Discussion

Infiltration rates of clay loam and laterite soils under field conditions

Table 1 presents the observed infiltration rates for different field conditions. From the table, for unploughed clay loam soil, the initial infiltration rate varies 18.0-0.9 cm/hr. Similarly, for ploughed clay loam soil, the initial infiltration rate varies from 16.8- 1.2 cm/hr. In the case of unploughed laterite soil, the initial infiltration rate varies from 22.8-3.5 cm/hr. For ploughed laterite soil, the initial infiltration rate was 24.0-3.7 cm/hr.According to the information provided in Table 1, it can be observed that over time, the infiltration rate generally decreases with some rapid fluctuations. These fluctuations are due to factors like the presence of macro-pores such as rodent holes, earthworm channels, or root pathways in the soil, which facilitate increased water flow. The sudden increase in infiltration rates can also be caused by the release of trapped air from soil aggregates. This is supported by the observation of rodent holes and air bubbles during the infiltration tests. On the other hand, the sudden decrease in infiltration rates is attributed to the perching phenomenon, where water accumulates at different depths. It is important to note that these patterns are observed in both soil conditions (Garg *et al.,* 2005). The soil conditions affect the infiltration rate. The infiltration rate is higher in a ploughed condition of soils compared to unploughed conditions (Dagadu *et al.,* 2012). These fluctuations in the infiltration rate were due to soil profile (Mahapatra *et al.,* 2020). Ploughed soil can increase infiltration rates due to improved soil structure, increased porosity, reduced surface crusting and enhanced water pathways. However, the effects can vary depending on factors like soil type and ploughing technique. Proper ploughing practices are essential to optimize infiltration rates

Table 1: Infiltration rate (cm/hr) of soil under different field conditions

Time (min)	Infiltration rate (cm/hr)			
	Clay loam soil		Laterite soil	
	Unploughed	Ploughed	Unploughed	Ploughed
5	18	16.8	22.8	24.0
10	15.6	15.6	19.2	20.4
20	7.8	6	8.4	8.4
30	7.2	4.8	7.2	7.2
45	3.2	3.6	5.2	5.2
60	2.8	3.6	4.8	5.6
80	1.2	1.8	3.9	3.8
100	0.9	1.2	3.5	3.7
120	0.9	1.2	3.5	3.7

Computation of the model constants

Table 2 displays the values of several infiltration model parameters for various soil conditions for Horton's, Philip's and Kostiakov's infiltration models applied to clay loam soil under field conditions. For Horton's model, the empirical constant 'k' has values of 2.53 and 2.19. In Kostiakov's infiltration model, the empirical constants 'a' have values of 6.40 and 5.99, while 'b' has values of 0.50 and 0.51, respectively. In Philip's model, the constants 's' has values of 13.73 and 12.57 and 'k' has values of -3.95 and -3.41. Infiltration models applied to laterite soil under field conditions. For Kostiakov's infiltration model, the empirical constants 'a' have estimated values of 8.58 and 8.85, while 'b' has values of 0.56 and 0.55. In Horton's model, the empirical constant 'k' has estimated values of 2.98 and 2.85., respectively. In Philip's model, the constants 's' has estimated values of 15.36 and 16.29, and 'k' has values of -2.85 and -3.21. Observed infiltration data was utilized to study and analyze these models. The infiltration equations were evaluated using experimental data from the study area, to determine the numerical values for the parameters in the models. Based on the findings, it was discovered that different soil types and soils have different parameter values for infiltration models (Dagadu *et al.,* 2012). When fitting the Philip Two-Term model to infiltration data taken from real field conditions, several researchers have also reported negative values of K in the literature (e.g., Shukla *et al.,* 2003; Machiwal *et al.,* 2006). The negative values of K found in this study are likely caused by macropores and relatively impeded (low-permeability) layers at various depths. The input variables for various infiltration models were established. All the observation points infiltration equations for various types of soils and field circumstances were developed using these model constants.

Table 2: The values of various infiltration model parameters for various soil types under various field circumstances

Soil types	Horton's model	Kostiakov's model		Philip's model	
	k	a	b	s	k
Clay loam soil (Unploughed)	2.53	6.40	0.50	13.73	-3.95
Clay loam soil (Ploughed)	2.19	5.99	0.51	12.57	-3.41
Laterite soil (Unploughed)	2.98	8.58	0.56	15.36	-2.85
Laterite soil (Ploughed)	2.85	8.85	0.55	16.29	-3.21

Comparison of observed and estimated infiltration rates for clay loam soil

Table 3 and Figure 2 show the comparison of observed and model-estimated infiltration rates under unploughed conditions in Clay loam soil. The initial infiltration rate predicted by Philip's model was 19.84 cm/hr, which was near to observed infiltration rate 18.00 cm/hr. Similarly, it was predicted by Horton's model as 14.74 cm/hr and the Kostiakov's model as 22.05 cm/hr differentiating highly from the observed value. The infiltration rates were decreased from 18.00 to 0.90 in observed value, in the case of Philip's 19.84 to 0.91 cm/hr, 22.05 to 4.53 cm/hr for Kostiakov's and 14.74 to 0.90 cm/hr for Horton's model respectively. The computed values of infiltration rates by different models for ploughed Clay loam soil are presented in Table 4 and Figure 3. The initial infiltration rate predicted by Philip's model is 18.37 cm/h, which was close to the observed infiltration rate 16.80 cm/hr. Similarly, this was predicted by Horton's model as 14.20 cm/hr and the Kostiakov's model as 21.27 cm/hr both, deviated significantly from the observed value. The infiltration rates were decreased from 16.80 to 1.20 in observed value, 18.37 to 1.04 cm/hr in the case of Philip's, 21.27 to 4.21 cm/h for Kostiakov's and 14.20 to 1.20 cm/hr for Horton's model respectively. In this study, derived infiltration rates of clay loam soil were compared with three different models: Kostiakov's, Horton's and Philip's models. Observed and estimated infiltration rates were examined under field conditions (ploughed & unploughed). Upon analyzing the data in the results, found that Kostiakov's model exhibited the largest variation compared to the measured data at every sampling point. This indicates that Kostiakov's model consistently overestimated the infiltration rates. The poor performance of Kostiakov's model could be attributed to its limitations in accurately representing the behaviours of infiltration in clay loam soil. Horton's model performed poorly but less than Kostiakov's model, possibly due to inconsistent physical interpretation of parameters and errors in estimating initial and steady-state infiltration rates, leading to an inadequate fit to the measured data. Philip's model outperformed the others, fitting the measured data well and showing suitability for estimating infiltration rates in clay loam soil.

Table 3: Comparison of observed and estimated infiltration rates for unploughed Clay loam soil

Infiltration rate (cm/hr)				
Time(min)	**Observed infiltration**	**Horton's model**	**Kostiakov's model**	**Philip's model**
5	18.00	14.74	22.05	19.84
10	15.60	10.54	15.61	12.87
20	7.80	3.86	11.06	7.95
30	7.20	2.67	9.03	5.76
45	3.20	1.24	7.38	3.98
60	2.80	1.05	6.40	2.92
80	1.20	0.91	5.54	2.00
100	0.90	0.90	4.96	1.37
120	0.90	0.90	4.53	0.91

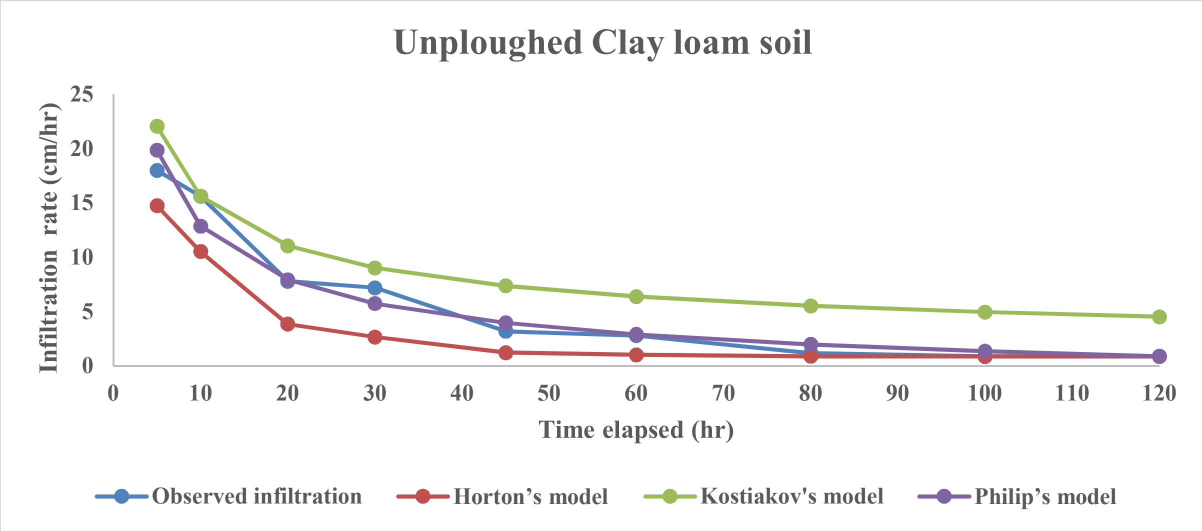

Figure 2: Observed and estimated infiltration rates for unploughed Clay loam soil

Table 4: Comparison of observed and estimated infiltration rates for ploughed Clay loam soil

	Infiltration rate (cm/hr)			
Time(min)	**Observed infiltration**	**Horton’s model**	**Kostiakov’s model**	**Philip’s model**
5	16.80	14.20	21.27	18.37
10	15.60	11.19	14.93	11.99
20	6.00	3.51	10.49	7.48
30	4.80	2.40	8.53	5.48
45	3.60	1.66	6.93	3.85
60	3.60	1.47	5.99	2.88
80	1.80	1.23	5.17	2.04
100	1.20	1.20	4.61	1.46
120	1.20	1.20	4.21	1.04

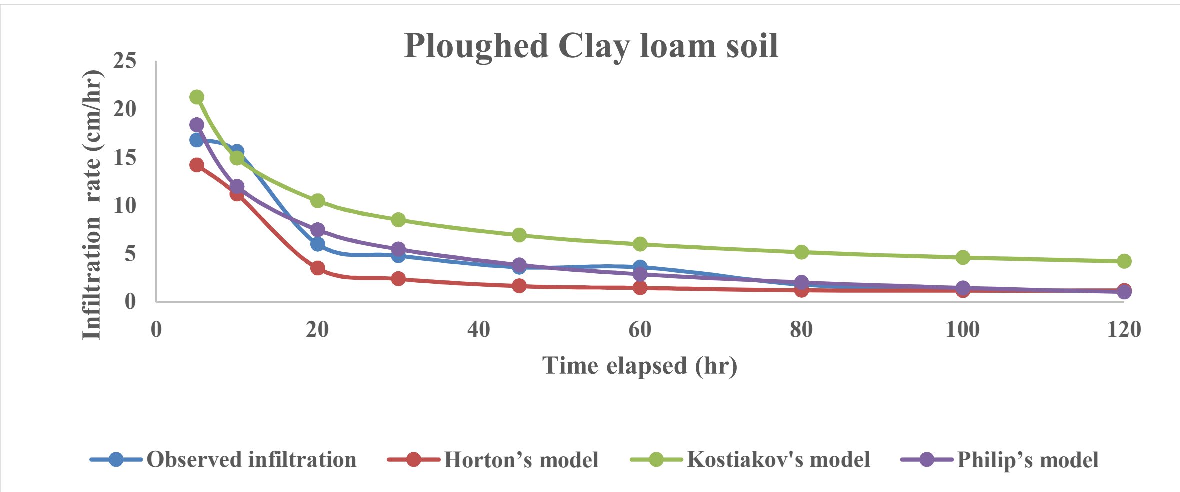

Figure 3: Observed and estimated infiltration rates for ploughed Clay loam soil

This result collaborates with the findings (Thomas et *al.,* 2020; Saadi *et al.,* 1985) who used the six-infiltration model in textured soil and found that Philip's model gave a good representation of the infiltration model while Kostiakov's, modified Kostiakov's, Green Ampt and Holtan Overton performed in that order respectively as adduced by Igbadun *et al.,* (2016). However, the most successful prediction of accurately matched test data was an estimation of the infiltration rate made by Philip's model. Additionally, its performance in the absence of field data suggests its potential for practical applications without direct measurements.

Comparison of observed and estimated infiltration rates for laterite soil

Table 5 and Figure 4 show the comparison of observed and model-estimated infiltration rates under unploughed conditions in Laterite soil. The initial infiltration rate predicted by Philip's model was 23.75 cm/hr, which was near to observed infiltration rate 22.80 cm/h. Similarly, it was predicted by Horton's model as 18.56 cm/hr and the Kostiakov's model as 34.17 cm/hr differentiating highly from the observed value. The infiltration rates decreased from 22.80 to 3.51 in observed value, 23.75 to 2.58 cm/hr in the case of Philip's, 34.17 to 5.84 cm/hr for Kostiakov's and 18.56 to 3.51 cm/hr for Horton's model respectively. The computed values of infiltration rates by different models for ploughed Laterite soil are presented in Table 6 and Figure 5. The initial infiltration rate predicted by Philip's model is 25.00 cm/hr, which was close to the observed infiltration rate 24.00 cm/hr.

Table 5: Comparison of observed and estimated infiltration rates for unploughed laterite soil

Infiltration rate (cm/hr)				
Time(min)	**Observed infiltration**	**Horton's model**	**Kostiakov's model**	**Philip's model**
5	22.8	18.56	34.17	23.75
10	19.2	13.06	23.24	15.96
20	8.4	5.32	15.81	10.45
30	7.2	4.34	12.62	8.01
45	5.2	3.69	10.07	6.02
60	4.8	3.58	8.58	4.83
80	3.9	3.52	7.31	3.80
100	3.51	3.51	6.46	3.10
120	3.51	3.51	5.84	2.58

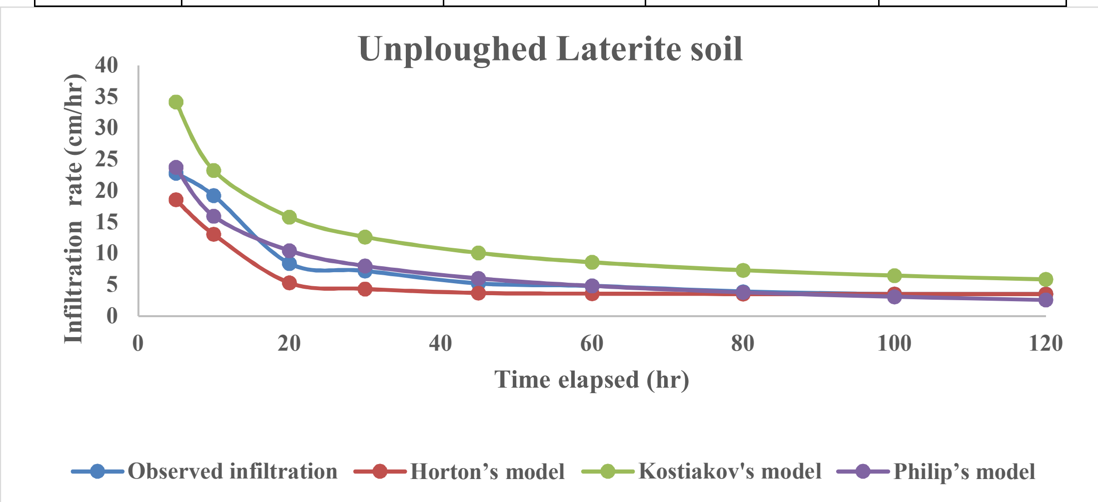

Figure 4: Observed and estimated infiltration rates for unploughed Laterite soil

Table 6: Comparison of observed and estimated infiltration rates for ploughed laterite soil

Infiltration rate (cm/hr)				
Time(min)	**Observed infiltration**	**Horton's model**	**Kostiakov's model**	**Philip's model**
5	24	19.71	34.47	25.00
10	20.4	14.09	23.59	16.74
20	8.4	5.53	16.15	10.89
30	7.2	4.56	12.93	8.31
45	5.2	3.89	10.36	6.19
60	5.6	3.83	8.85	4.93
80	3.3	3.71	7.56	3.84
100	3.72	3.72	6.69	3.10
120	3.72	3.72	6.06	2.55

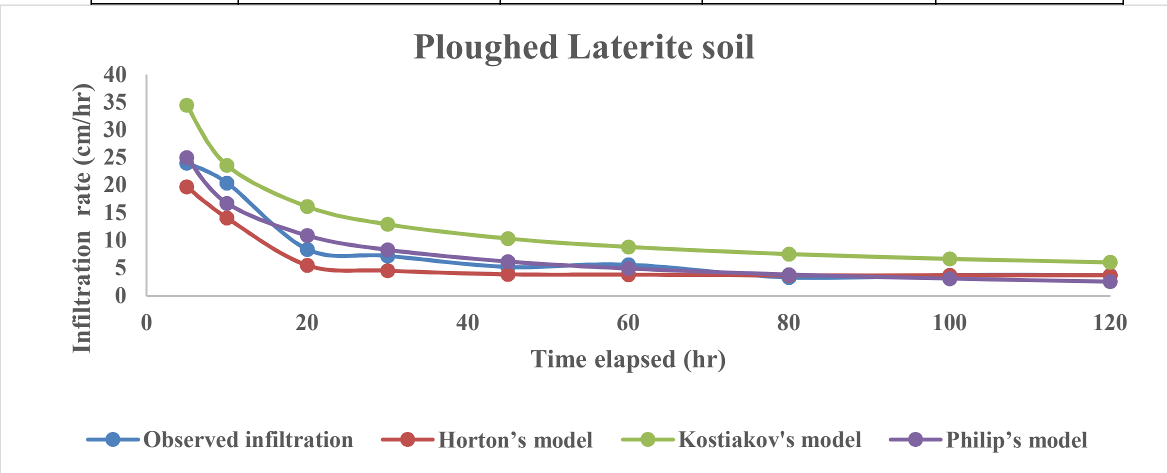

Figure 5: Observed and estimated infiltration rates for ploughed laterite soil

This was estimated by Horton's model as 19.71 cm/hr and Kostiakov's model as 34.47 cm/hr, both deviated significantly from the observed value. The infiltration rates were decreased from 24.00 to 3.72 in observed value, 25.00 to 2.55 cm/hr in the case of Philip's, 34.47 to 6.06 cm/hr for Kostiakov's and 19.71 to 3.72 cm/hr for Horton's model respectively. The same models (Kostiakov's, Horton's and Philip's) were also used for laterite soil. These models were tested by comparing their results with observed and estimated levels of infiltration rate in field conditions, particularly in the case of ploughed and unploughed. The models of Kostiakov's have shown the highest variation, according to these results. This suggests that the model consistently overestimated the measured data at each sample location. This overestimation shows that the model predictions are not compatible with the observed field measurements. Thus, the model Kostiakov's did not provide an accurate representation of infiltration rates in the laterite soil studied. Horton's model did not perform as poorly as Kostiakov's, perhaps due to a lack of physical interpretation of the parameters and incorrect estimation of initial and continuous state infiltration rates which resulted in an inadequate fit with measured data. Philip's model performed well. This result agrees with research (Thomas *et al.,* 2020; Saadi *et al.,* 1985) that used six infiltration models in textured soil and discovered that Philip's model provided a good representation of the infiltration model while Kostiakov's, modified Kostiakov's, Green Ampt and Holtan Overton performed in that order, as suggested by Igbadun *et al.,* (2016). incorporating the measured data and indicating suitability for predicting infiltration of Laterite soils. In addition, its potential for practical use without direct measurements is shown by its ability to work in the absence of field data. However, the most successful prediction of accurately matched test data was an estimation of the infiltration rate made by Philip's model.

Estimation and inter-comparison of model parameter

The statistics shown in Table 7 clearly shows that all infiltration models accurately estimate the infiltration rate. The model that provided the best fit was selected based on the criteria of minimizing RMSE and maximizing NSE and R^2. The results of this evaluation are summarized in Table 7. Table 7 shows that all the models perform effectively with very low errors (RMSE) ranging from 1.2647 to 5.7129, extremely high values of R^2 (0.9044-0.9677), and moderate to very good values of model efficiency (NSE: 0.294-0.957), all of which show that these infiltration models are excellent at predicting infiltration rates. In terms of the RMSE criteria, Horton's (mean RMSE=2.5375) and Kostiakov's (mean RMSE=4.5147) models come in second and third, respectively, with Philip's model having the lowest mean RMSE (1.3758). According to the RMSE values, the Philip Two-Term performs approximately equally in estimating infiltration. Philip's model has the highest mean NSE value of 0.948, according to the measured NSE values (Table 7). From Table 7, it is evident that Horton's models' efficacy is excellent, with an NSE value of 0.824, respectively. Kostiakov's models, on the other hand, perform poorly with an NSE value of 0.40, respectively. Despite having very high R^2 values (>0.94) in a variety of situations, all the models had comparable rankings to model efficiency (NSE) in terms of R^2 values.

Table 7: Inter-comparison parameter of infiltration models

Soil conditions	Horton's model	Kostiakov's model	Philip's model
Root mean square error (RMSE)			
Clay loam soil (Unploughed)	2.9660	3.4850	1.2647
Clay loam soil (Ploughed)	2.2793	3.3879	1.4484
Laterite soil (Unploughed)	2.9319	5.7129	1.4133
Laterite soil (Ploughed)	1.9729	5.4731	1.3767
Average	**2.5375**	**4.5147**	**1.3758**
Nash-Sutcliffe efficiency (NSE)			
Clay loam soil (Unploughed)	0.836	0.638	0.934
Clay loam soil (Ploughed)	0.814	0.294	0.957
Laterite soil (Unploughed)	0.814	0.294	0.957
Laterite soil (Ploughed)	0.834	0.403	0.946
Average	**0.824**	**0.407**	**0.948**
Coefficient of determination (R^2)			
Clay loam soil (Unploughed)	0.9044	0.9624	0.9624
Clay loam soil (Ploughed)	0.9435	0.9476	0.9491
Laterite soil (Unploughed)	0.9666	0.9569	0.9568
Laterite soil (Ploughed)	0.9677	0.9470	0.9464
Average	**0.9456**	**0.9535**	**0.9537**

These infiltration models were chosen based on how well they performed in most field situations as measured by R^2, RMSE, and NSE. Based on the analysis of parameters RMSE, NSE and R^2, it can be concluded that Philip's model demonstrated a strong agreement with the measured data, indicating superior performance compared to Horton's and Kostiakov's models. This result corroborates the findings of Thomas *et al.* (2020), who evaluated four infiltration equations on silt and sandy soils. They concluded that Philip's model provided a highly accurate representation of infiltration, followed by Kostiakov's, Green Ampt, and Horton's models followed in that respective order, as indicated by Igbadun *et al.* (2016). Similarly, Oku & Aiyelari (2011) predicted cumulative infiltration in Inceptisols within humid forest zones and found that Philip's model outperformed Kostiakov's model. These studies imply that certain infiltration models are more suitable for specific site conditions (Machiwal *et al.* 2006), this implies that not all infiltration models can be universally applied to all types of soils. Different models may have varying levels of applicability depending on the soil characteristics and conditions of a particular site.

Conclusion
The study shows that the infiltration rate is influenced by the soil properties. Infiltration rates started high and fell over time until they reached a constant level, according to graphs showing infiltration rates vs time. One of the main fields of study in hydrology is infiltration, a crucial part of the hydrological cycle. Planning and developing water resource systems and comprehending the rainfall-runoff process depend on data on infiltration rates for different soil types. The infiltration rate vs time graphs for field data and model data do not match exactly, but Philip's model is substantially closer to the observed field data. This is discovered while comparing infiltration models to field data. Based on the mean values of RMSE, NSE, and R^2, Philip's model had the lowest RMSE and highest NSE and R^2 values, indicating that it accurately represented the infiltration rate. Thus, it can be used to create infiltration data artificially in the absence of infiltration data that have been detected. So, in any further research work prefer Philip's model

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Conflict of interest
The authors declare that they have no conflicts of interest.

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