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Comparison and Estimation of Four Infiltration Models

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Abstract

Infiltration is an important component of the hydrological cycle. It provides soil moisture in the vadose zone to support plant growth. This study was conducted to compare the validity of four infiltration models with measured values from the double ring infiltrometer. The parameters of the four models compared were estimated using the linear regression analysis. The C.C was used to show the performance of the predictability of the models. The RMSE, MAE and MBE were employed to check the anomalies between the predicted and the observed values. The results showed that, average values of the C.C ranged from 0.9294 - 0.9852. The average values of the RMSE were 4.0033, 17.489, 11.2400 and 49.8448; MAE were 3.1341, 15.9802, 10.6525, and 61.4736; and MBE were 0.0786, 9.5755, -0.0007 and 47.0204 for Philip, Horton, Green Ampt and Kostikov respectively for the wetland soils. Statistical results also from the Fisher's multiple comparison test show that the mean infiltration rate estimated from the Green Ampt's, Philip's and Horton's model was not significantly different ($p > 0.05$) from the observed. The results indicated that the Kostikov's model had the highest deviations as it overestimated the measured data in all the plots. Comparison of the statistical parameters C.C, RMSE, MAE, and MBE for the four models indicates that the Philip's model agreed well with the measured data and therefore, performed better than the Green Ampt's, Horton's and Kostikov's models respectively in that order for Besease wetland soils. Estimation of infiltration rate by the Philip's model is important in the design of irrigation schemes and scheduling. Therefore, in the absence of measured infiltration data, the Philip's model could be used to produce infiltration information for inland valley bottom

soils that exhibit similar characteristic as Besease wetland soils.

Keywords

Wetland, Infiltration Models, Irrigation, Philip's Model, Ring Infiltrometer

1. Introduction

Infiltration is the process by which water on the ground surface enters the soil. Infiltration plays a vital role in soil and water conservation as it determines the amount of runoff over the soil surface during irrigation and precipitation. The infiltration rate of a soil, thus ability of the soil to accept heavy rainfall or irrigation depends on the characteristics of the soil [1] [2]. Substantial reduction in time and cost of field measurement of infiltration can be achieved by using infiltration models [3]. Poor infiltration rate indicates potential of high runoff and erosion which affects the amount of water stored in the plant root zone [4]. This makes it difficult for the soil to meet the required water demand for crop production.

Design, operation and management of surface irrigation system rely greatly on the infiltration behaviour or characteristics of the soil, because the infiltration behaviour of the soil directly determines the essential variables such as inflow rate, length of run, application time and depth of percolation [5]. These infiltration characteristics of the soil are determined when fitted mathematically into infiltration models. But not all infiltration models can be applied to all soils [1]. Many researchers have compared the accuracy of the various models by comparing the computed and observed infiltration rates. Under different conditions, a particular model shows better predictions than others. But till date, it is not specifically mentioned which model gives the best prediction [6].

[7] estimated and compared Kostiakov, Novel and the Modified Kostiakov infiltration models in the Kurukshetra district of India. They concluded that, the Novel model was more accurate in predicting infiltration rate. [8] investigated the capability of the novel infiltration model in estimating the infiltration rate from actual field data in comparison to Philip, Kostiakov and Modified Kostiakov models in similar conditions. Findings from their research indicated that the novel model was the most suitable among three other models used for the estimation of infiltration rate of the study area. [9] also compared Philip's model, modified Philip's model, Horton's model, and Green Ampt's model in NIT Kurukshetra campus in India at ten different locations to predict infiltration rates and found out that, the infiltration rate versus time plot for the field data and predicted data did not accurately match; but the Modified Philip's model was much closer to the observed field data. [10] carried out infiltration studies of different soil under different soil conditions and compared the infiltration models with field data measured by Double-ring infiltrometer. They reported that the

Horton's model, and the Green Ampt's model were the best fitting to the observed field data to estimate infiltration rate at any given time with high degree of correlation coefficient and minimum degree of standard error. [11] also compared the Kostiakov's model, Modified Kostiakov's model, Philips model, and Horton's model on a sandy soil in Lafia, Southern Guinea Savana Zone of Nigeria. They observed that, although the other models produced good overall agreement with the field measured cumulative infiltration depth, the Horton's model gave the best fit to the measured cumulative infiltration. [1] reported that Philip's model was more suitable than Kostiakov's model under the Inceptisols in the humid forest zone of Nigeria.

The study sought to evaluate the performance of four infiltration models (Kostiakov's, Philips, Horton's and Green Ampt) to determine their suitability for predicting infiltration rates for Besease wetland soils.

2. Study Area

Besease is a predominantly farming area in the Ejisu Municipal District of the Ashanti Region in Ghana. The site lies within Latitude 1°15'N and 1°45'N and Longitude 6°15'W and 7°00'W. The study area covers about 72 ha of the valley bottom lands at Besease (Figure 1). The climate of the study area is mostly related to the semi-humid type. The region is characterised with two distinct seasons, the wet season which begins from April and ends in October while the dry season extends from the month of November to March. The wet seasons can be categorised less than two rainy seasons. The major rainy season which ranges from mid-March to July and the minor rainy season starts from September to mid-November. The mean annual rainfall is 1420 mm; mean monthly temperature is 26.5°C, the relative humidity ranges from 64% in January to 84% in August. The average monthly maximum and minimum evapotranspiration (ET_o) for the study area were 127.5 mm and 64.7 mm and has an annual ET_o of 1230 mm. The area is drained by the Oda River which is seasonal and whose basin is about 143 km² [12].

The study area is located in the moist semi-deciduous forest zone. Grass species prominently found in the valley bottom are *Santrocema trifolia*, *Chromolaena odorata*, *Imperata cylindrical*, *Mimosa pigra*, *Ceiba patendra*, *Centrosema pubescens* and *Mariscus flabelliformis*. Plant species like *Raphia hookeri* (*Raphia palm*), *Alstonia boonei*, *Malotus oppositifolius* and *Pseudospondias microcarpa* extends along the margins of the Oda River. Soils of the Ejisu-Besease can be found in the soil map of Kumasi area. The study area lies in the Offin soil series which are grey to light brownish grey, poorly drained alluvial sands and clays developed within nearly flat but narrow valley bottoms along streams. The series have very slow internal drainage, very slow runoff, rapid permeability and moderate water holding capacity. The geology of the watershed is relatively heterogeneous and mainly composed of Phyllites, quartzite, shale, Tarkwain and Voltaian-sandstone and limestone. The Phyllites which underlie 59% of the area

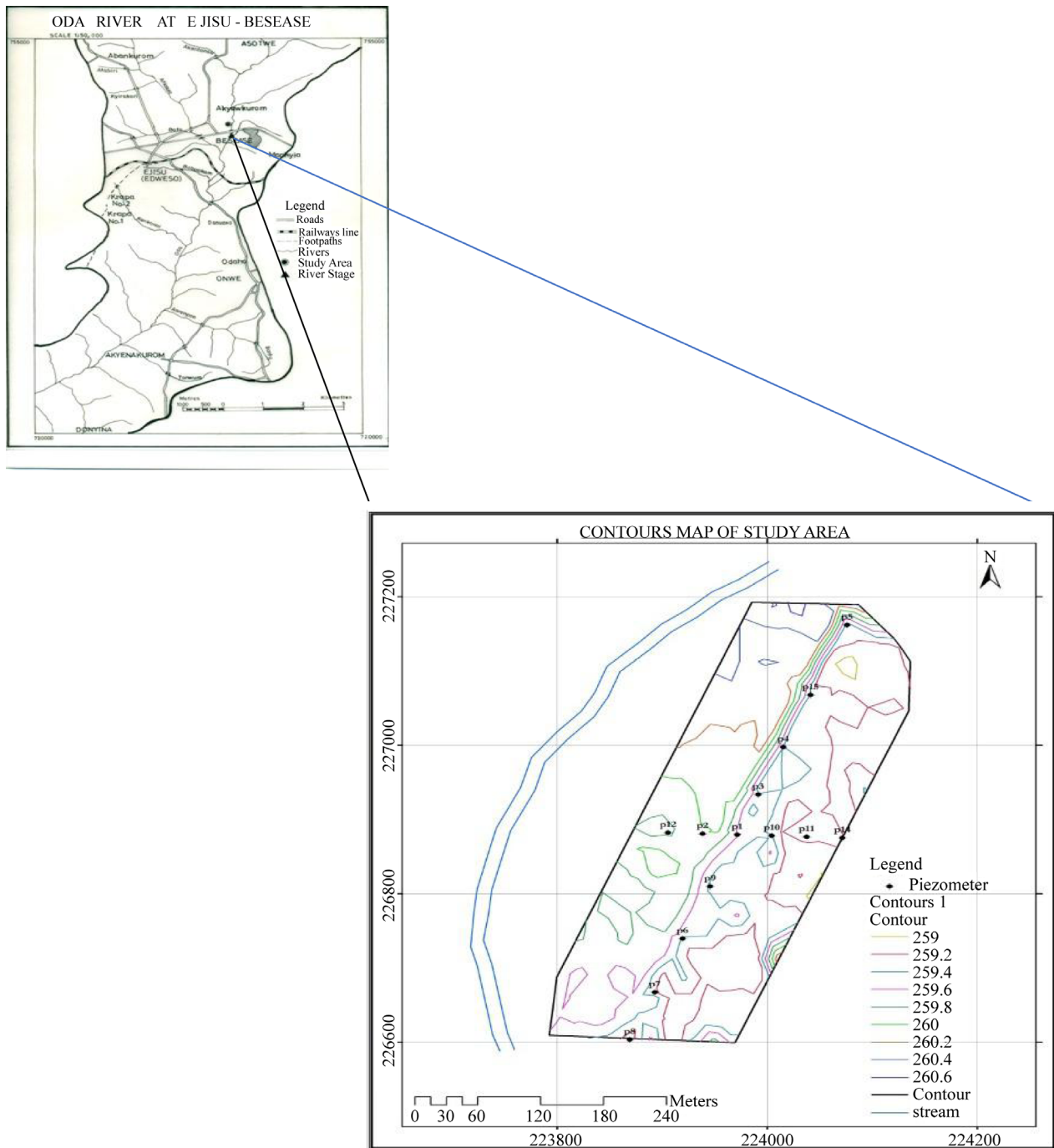


Figure 1. Map of Besease project site showing piezometric network.

consist of upper and lower Birimian rocks. Very few rock outcrops were encountered in the survey as the rocks are deeply weathered. The weathered phyllite is soft and easily broken, recognizable pieces and is typically found at 2 - 3 m below surface. Soils found within the Oda River catchment are grouped as those derived from granites, sandstones, alluvial materials, greenstone, andesite, schist and amphibolites. Specifically, the soils are Orthi-ferric Acrisol, Eutric Fluvisol, Gleyic Arenosols, Eutric Gleysols and Dystric-Haplic Nitisol. The Besease aquifer

is composed of heterogeneous sequence of layers which is dominated by sand, clayey sand and silts. The valley bottom is developed by small holder farmers who cultivate rice in the wet season and also grow vegetables like cabbage, lettuce, bell pepper, cauliflower, cucumber and okra. Other cereals like maize are cultivated at the dry season when the water table is low.

3. Materials and Methods

3.1. Sample Collection

Soil samples were collected with core samplers of height 10 cm to an average depth of 100 cm (**Figure 1**). Disturbed soil samples were taken from the field at site P1 - P2, P1 - P9, P6 - P9, P7 - P8, P11 - P14, and P13 - P4 and air dried, ground and passed through the 2 mm sieve to obtain the soil fractions for the determination of soil texture.

3.2. Measurement of Infiltration Rates

Double ring infiltrometers, consisting of two concentric rings, were used to measure the infiltration rate. Rings were 250 mm deep and were made from 12-gauge steel with sharpened bottom edges. They were driven into the ground to 50 mm depth. Grass was cut to near soil level and a pad was placed inside the inner ring to prevent puddling. The inner and outer edges were tamped to seal possible cracking. Generally, the water level was kept at or above 50 mm depth. The difference in height between the inner and outer rings was kept to a minimum. The rate of fall of water was measured in the inner ring while a pool of water was maintained at approximately the same level in the outer ring to reduce the amount of lateral flow from the inner ring. The rate of fall of the water level in the inner cylinder was measured at 2, 3, 5, 10, 15, 20, 30, 45 and 60 minutes and at 30-minute intervals thereafter. The accumulated volume of water entering the soil was converted to the infiltration rate (mm/h) and was plotted against elapsed time whereby a declining slope was obtained. Fifty-five (55) samples (replicates) were used for the measurement of soil infiltration rate. The field infiltration rate measurement was considered as observed. The aim of the measurements was to obtain a steady-state infiltration rate. This is achieved when the amount of infiltrated water was constant in time, i.e. when the infiltration curve (instantaneous infiltration against time) levels out. To estimate the infiltration rate at steady state, the terminal infiltration rate (*i.e.* the infiltration rate obtained at the end of the experiment in about 2 h), was used as an approximation of the steady state infiltration rate.

3.3. Infiltration Models and Parameters

In this study, Kostiakov's, Philip's, Horton's and Green Ampt's infiltration models were fitted to the infiltration data.

3.3.1. Kostiakov's Model [13]

Kostiakov's model, an empirical model expresses cumulative infiltration equa-

tion as

$$F_p = at^b \quad (1)$$

where F_p = cumulative infiltration (cm), t = time from start of infiltration (min), and a and b are constants that depends on the soil initial conditions. Where, $a > 0$ and $0 < b < 1$.

The parameters in the Kostiakov equation are obtained from the plot of $\ln(F_p)$ versus $\ln(t)$ and the best fit straight line through the plotted points gives $\ln a$ as the intercept and b as the slope.

3.3.2. Philip's Model [14]

Philip's physical based model expresses infiltration rate as

$$f_p = \frac{1}{2}St^{-1/2} + K \quad (2)$$

where f_p = Infiltration capacity (cm/h) at any time t (min) from the start, S = soil water sorptivity which is a function of initial soil water content and K = Darcy's hydraulic conductivity. The observed infiltration rate, f_p values are plotted against the reciprocal square root of time, $t^{-1/2}$. The best fitting straight line through the plotted points gives K as the intercept and $\frac{S}{2}$ as the slope of the line.

3.3.3. Horton's Model [15]

Horton's semi-empirical model expressed the decay of infiltration capacity with time as an exponential decay given by

$$f_p = f_c + (f_0 - f_c)e^{K_h t} \quad \text{for } 0 \leq t \leq t_c \quad (3)$$

where f_p = infiltration capacity (cm/h) at any time t (min) from the start of the rainfall

f_0 = initial infiltration capacity (cm/h) at $t = 0$

f_c = final steady state infiltration capacity (cm/h) at $t = t_c$.

K_h = Horton's decay coefficient which depends upon soil characteristic and vegetation cover. The parameters of the Horton's equation are determined by plotting the values of $\ln(f_p - f_c)$ against t to obtain the best fit straight line through the plotted points. $\ln(f_0 - f_c)$ depicts the intercept and the decay constant, K_h represent the slope.

3.3.4. Green Ampt's Model [16]

Green Ampt proposed a model for infiltration capacity based on Darcy's law and expresses the physical model as

$$f_p = m + n/F_p \quad (4)$$

where m and n are Green Ampt's parameters of infiltration model. Values of infiltration capacity, f_p are plotted against $\frac{1}{F_p}$ on an arithmetic graph. The in-

tercept on the ordinate axis is m and n serves as the slope when the best fit straight line is drawn through the plotted points.

3.4. Statistical Analysis

3.4.1. Coefficient of Correlation (C.C)

Coefficient of correlation is a statistical measure that calculates the strength of the relationship between the relative movements of two variables. The coefficient of correlation is calculated as

$$CC = \frac{z \sum ab - (\sum a)(\sum b)}{\sqrt{z(\sum a^2) - (\sum a)^2} \sqrt{z(\sum b^2) - (\sum b)^2}} \quad (5)$$

3.4.2. Root Mean square Error (RMSE)

The root mean square error exaggerates the prediction error, thus the difference between the predicted value and the actual value. This is evaluated by

$$RMSE = \sqrt{\frac{1}{N} \left(\sum_{i=1}^n (a_i - b_i)^2 \right)} \quad (6)$$

where a is the calculated and b is observed values of the infiltration rate and N is the number of observations.

3.4.3. Mean Bias Error (MBE)

This is the average difference between the predicted values and the observed values of the infiltration models. The mean bias error is estimated by

$$MBE = \frac{1}{N} \sum_{i=1}^n (a_i - b_i)^2 \quad (7)$$

where a is the calculated and b is observed values of the infiltration rate and N is the number of observations.

3.4.4. Mean Absolute Error (MAE)

The absolute error is the absolute value of the difference between the predicted value and the observed value. The absolute error is estimated by

$$MAE = \frac{1}{N} \sum_{i=1}^n |a_i - b_i| \quad (8)$$

where a is the calculated and b is observed values of the infiltration rate and N is the number of observations.

3.4.5. One-Way Analysis of Variance

Kostiakov's, Philip's, Horton's and Green Ampt's infiltration models were used to predict soil infiltration rate using the 55 (replicates) observed field infiltration rate. The replicates were used to compute means and standard deviation for each model and the observed in IBM SPSS version 23. One-way analysis of variance (ANOVA) was used to determine whether there are any statistically significant differences in the infiltration rates among the four different infiltration rate models and the observed at $\alpha = 5\%$ significance level. Fisher Multiple compari-

son post hoc test was used to separate the means.

4. Results and Discussion

Results from **Table 1** shows that the final infiltration rate for the studied site ranged from 1.2 to 42 cm/h. The final infiltration rate was higher in silt loam soil with least value of 2.8 cm/h at site P6 - P9 and the highest value of 42 cm/h at site P10 - P1 compared to sandy loam soil which has least value of 1.2 cm/h and the highest value of 9 cm/h. Variations in infiltration rates are facilitated by extensive root system and animals burrowing in the soil, inadequate prewetting, and soil disturbance by the infiltration ring. The parameters of the four equations estimated using the line of best fit from the regression analysis are summarized in **Table 2**. The values of Kostiakov's parameter **b** estimated ranged between 0.55 and 0.92 (**Table 2**), which is in accordance with the theory of infiltration that puts the value to be positive and always less than one (Ogbe *et al.*, 2011). The best fit model was selected on the basis of Maximum of coefficient of correlation (C.C.), minimum of Root Mean Square Error (RMSE), minimum of Maximum Absolute error (MAE) and Minimum of Mean Bias error criteria. Comparing the predicted and measured infiltration rate, the average values of C.C shown in **Table 3** were computed for the four different models. The higher average values of the C.C (0.9294 - 0.9852) implies that the model accounted for almost all of the variability in the data and indicating that Philip's Green Ampt's, Kostiakov's and Horton's model provided a very good fit to the data in that order respectively.

A comparison between the measured and estimated infiltration rates as calculated from the four models is shown in **Figure 2**. The Kostiakov's model had the highest deviations as it overestimated the measured data in all the sampling points. The Horton's model was the next to Kostiakov model in terms of poor performance. This may be due to the fact that their parameters lack a consistent physical interpretation and also the process involved in the evaluation of the parameters might be very sensitive to approximation errors and errors due to parallax while determining the initial and steady state infiltration rates from the graph as inputs for the prediction of cumulative infiltration [17]. However, the

Table 1. Initial final and moisture contents of the study area.

Site	Soil type	Initial infil. rate (cm/h)	Final infil. rate (cm/h)	Moisture Cont. (%)
P7 - P8	silt loam	270	37.5	18.3
P6 - P9	silt loam	36	2.8	17.5
P1 - P9	sandy loam	24	3.3	16
P13 - P14	sandy loam	45	9	11.5
P1 - P2	sandy loam	24	1.2	11.8
P10 - P1	silt loam	270	42	20

Table 2. Estimated infiltration model parameters.

Test Site	Philip's model		Green Ampt's model		Kostiakov's model		Horton's model		
	s	k	m	n	b	a	k	f_0	f_c
Site: P7 - P8	103.92	-23.68	40.76	305.1	0.84	205.02	2.42	231.68	37.5
Site: P6 - P9	14.97	-9.26	-2.43	47.68	0.67	15.08	5.65	37.67	2.4
Site: P1 - P9	10.94	-5.7	1.97	20.02	0.8	16.35	3.28	21.57	2.2
Site: P13 - P4	15.16	-0.27	8.88	57.43	0.92	40.84	2.03	33.15	9
Site: P1 - P2	10.03	-6.9	-4.21	23.17	0.55	6.68	6.68	23.06	1.2
Site: P10 - P11	104.78	-10.63	59.43	2217.8	0.85	224.17	2.16	212.85	46.8

Table 3. Performance evaluation parameters of the various infiltration models.

Test Site	Philip's model	Horton's model	Green-Ampt's model	Kostiakov's model
coefficient of correlation (C.C)				
P10 - P11	0.993	0.9477	0.8986	0.9838
P1 - P2	0.9663	0.9079	0.9833	0.9255
P13 - P4	0.9863	0.8941	0.985	0.9242
P1 - P9	0.9921	0.9597	0.9139	SS0.9789
P6 - P9	0.9783	0.9289	0.9833	0.9789
P7 - P8	0.9955	0.9378	0.9536	0.9746
Average	0.9852	0.9294	0.9529	0.9522
Root means square error (RMSE)				
P10 - P11	9.5465	39.8549	35.3858	127.1988
P1 - P2	1.9409	3.5617	1.3734	4.3387
P13 - P4	1.91	7.3604	1.9929	25.0485
P1 - P9	0.967	4.354	3.1239	10.687
P6 - P9	2.215	5.7666	1.942	9.6733
P7 - P8	7.4405	44.0367	23.6221	122.1226
Average	4.0033	1.7489	11.24	49.8448
Mean absolute error (MAE)				
P10 - P11	7.1456	35.2567	32.7114	121.52
P1 - P2	1.6478	2.7967	1.1234	3.9711
P13 - P4	1.3022	6.6778	3.9716	23.7778
P1 - P9	0.7733	4.0167	2.8773	9.9289
P6 - P9	1.746	5.041	1.5755	93.573
P7 - P8	6.19	42.0922	21.6556	116.0711
Average	3.1341	15.9802	10.6525	61.4736
Mean bias error (MBE)				
P10 - P11	0.1944	14.6522	-0.0034	121.52
P1 - P2	0.0189	1.6278	0.0033	2.3867
P13 - P4	0.0267	3.6978	0.0015	23.7778
P1 - P9	0.02	3.0344	-0.003	9.9289
P6 - P9	0.026	4.175	-0.003	8.438
P7 - P8	0.1856	30.2656	0	116.0711
Average	0.0786	9.5755	-0.0007	47.0204

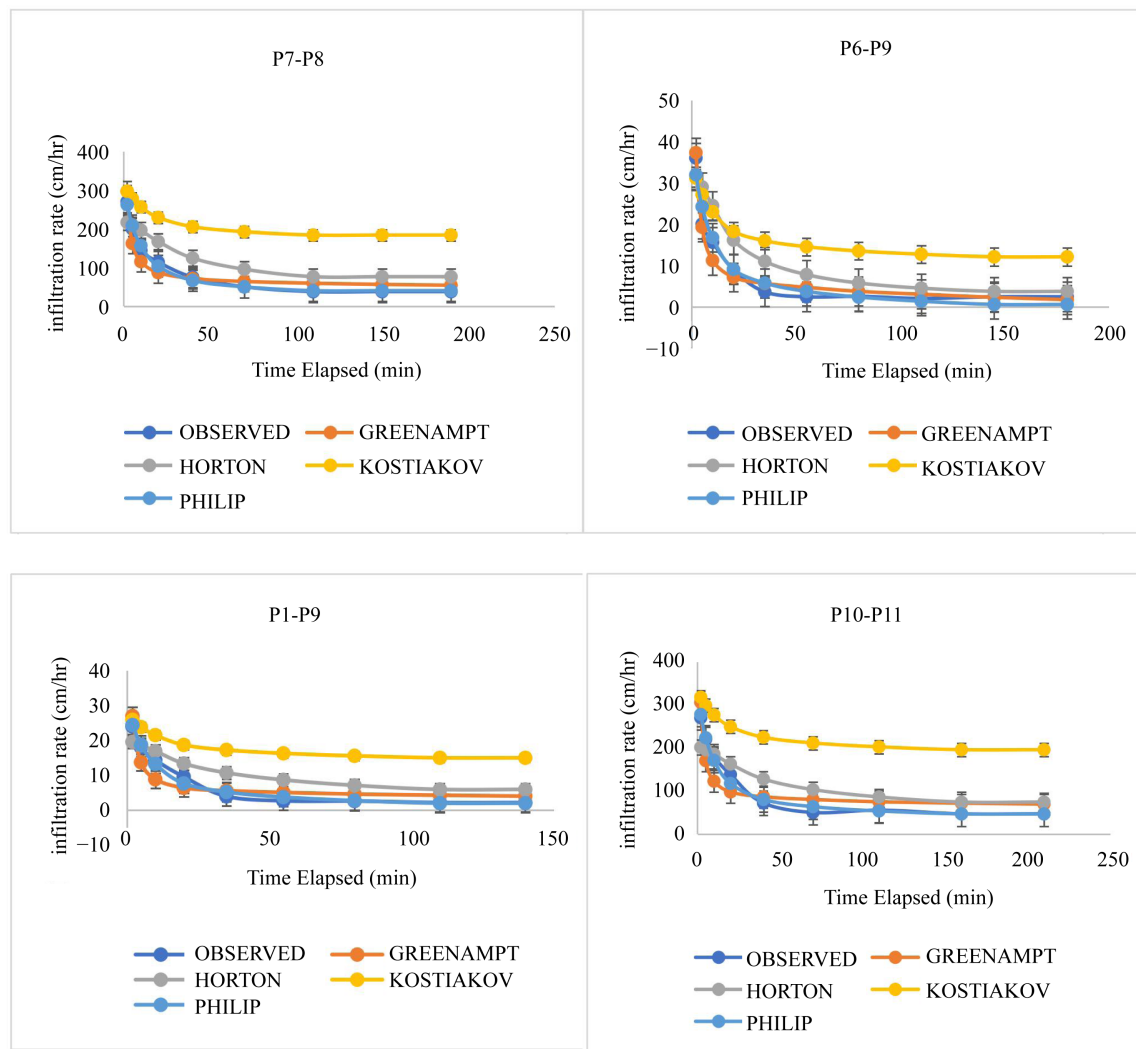


Figure 2. Comparison of measured infiltration rate with various models estimated infiltration rate for the study area.

infiltration rate estimated by the Philip's model was the most successful in predicting fitting measured experimental data.

Statistical results from **Table 4** indicates that the infiltration rate differed significantly ($F(4) = 3.89$, $p < 0.01$) across the different models. The Fisher's multiple comparison test revealed that the mean infiltration rate estimated from the Green Ampt's (44.44 ± 8.81), Horton's (53.92 ± 8.9), and Philip's (44.52 ± 9.11) model were not significantly different ($p > 0.05$) from the observed (44.44 ± 9.12). However, the mean infiltration rate predicted by the Kostiakov's (90.76 ± 13.95) model was significantly higher than the other models (**Table 4**).

The average values of the RMSE were 4.0033, 17.489, 11.2400 and 49.8448, MAE were 3.1341, 15.9802, 10.6525, and 61.4736, and MBE were 0.0786, 9.5755, -0.0007 and 47.0204 for Philip, Horton, Green Ampt and Kostiakov respectively for the entire study area (**Table 4**). Comparison of the statistical parameters RMSE, MBE, and MAE indicates that the Philip's model agreed well with the

Table 4. Mean and standard error of observed and predicted infiltration rate.

Methods	Mean Infiltration rate (cm/h)	Std. Error of Mean (cm/h)
Observed	44.44b	9.12
Green Ampt	44.44b	8.81
Horton	53.92b	8.90
Kostiakov	90.76a	13.95
Philip	44.52b	9.11
<i>F-ratio</i>	3.89	
<i>df</i>	4	
<i>P-value</i>	0.004	

Means that do not share a letter are significantly different by Fisher's multiple comparison test.

measured data and therefore, performed better than the Green Ampt's, Horton's and Kostiakov's models respectively in that order for Besease wetland soils. This result corroborates with the findings of [18], who assessed six infiltration equations on a homogeneous coarse textured soils and found out that the Philip's model gave a very good representation of the infiltration while Kostiakov, modified Kostiakov, Green Apmt and Holtan Overton performed in that order respectively as adduced by [17]. [1] also predicted cumulative infiltration under the Inceptisols in the humid forest zones. The result showed that Philip's model was more suitable than the Kostiakov model. However, the results of this study is in contrast to the research conducted by [19] who reported that Kostiakov model related closely to the measured data than Philip's model for a hydromorphic soil at Samura, Nigeria. Thus, infiltration models should be tested for their ability to estimate the final infiltration rate for each location and should be documented at each site [20]. One or few of the infiltration models are better and for a specific site condition [21], [1] which presupposes that not all models are applicable in all soils. Consequently, the application of these models under verified field conditions leads to the determination of the appropriate infiltration characteristics for the equations that would optimize infiltration simulation, irrigation performance and minimize water wastage [12].

5. Conclusions

The prediction accuracy of four infiltration models was validated with measured values using the double ring infiltrometer. Comparison of the field and predicted infiltration rate indicated that the infiltration rate predicted by the Philip's model was much closer to the observed data. The statistical results of C.C show that infiltration rate can be predicted by the Philip, Green Ampt, Horton and Kostiakov models, respectively.

Statistical results also from the Fisher's multiple comparison test show that the mean infiltration rate estimated from the Green Ampt's, Philip's and Horton's model was not significantly different ($p > 0.05$) from the observed.

Based on the mean values of RMSE, MAE and MBE values, the Philip's model provided the lowest values and could be deduced that infiltration rate was well described by this model. Quantification of infiltration rate by this model will be of importance in the design of irrigation schemes and scheduling of irrigation. Therefore, in the absence of measured infiltration data, the Philip's model could be employed to generate infiltration information for inland valley bottom soils that exhibit similar characteristics of Besease wetland soils.

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Conflicts of Interest

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