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Prediction of Infiltration Capacities by Field Measurement and Selected Empirical Models for Irrigated Agriculture

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Authors' contributions

This work was carried out in collaboration between both authors. Authors MOA and FFA designed the study. Author FFA performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors FFA and MOA managed the analyses of the study. Author FFA managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

The study compared the infiltration capacities by field measurement and some empirical models for irrigation agriculture.The field measurement was carried out at the Farm Site of the Agricultural Engineering Department, Federal University of Technology, Akure. A double ring infiltrometer with inside diameter of 30 cm and outside diameter of 60 cm with height 67 cm was used to measure the infiltration rate at the experimental site. Three locations were selected at the site while three runs were carried out at each location. Soil samples were collected on different soil type at various sample points and at varying depths ranging from 10- 30 cm. The infiltration rates of water through the soil were measured. Thereafter, four infiltration equations namely Kostiakov, Horton, Green & Ampt and Philip adapted to ponded conditions were evaluated for their ability to predict infiltration into the predominant soil. The prediction of infiltration by the selected models shows fair to good agreement with the observed values. The overall performance rating shows the Kostiakov equation

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performing best, followed by Philip, Horton and Green and Ampt in that order. Also, four equations were obtained to predict the infiltration capacities from these models. From this study, it can be inferred that the evaluated parameters of the selected models can be used for obtaining the infiltration capacities of comparable soil types which are required for irrigated agriculture in other locations.

Keywords: Infiltration capacities; infiltrometer; empirical models; irrigated agriculture.

1. INTRODUCTION

Infiltration is the process of water movement from the ground surface into the soil and is an important component in the hydrological cycle [1]. Soil and water scientists have given a great deal of attention to infiltration because of its fundamental role in land-surface and subsurface hydrology, irrigation and agriculture [2]. Cumulative infiltration is the total quantity of water that enters into the soil in a given time [3]. Thus infiltration rate and cumulative infiltration are two parameters commonly used in evaluating the infiltration characteristics of soil. Infiltration is a dynamic process variable in time and space and plays a vital role in the replenishment of soil water [4] which is responsible for the growth and development of crops. It is one of the most important soil parameters required in the design and evaluation of irrigation system, watershed modeling and prediction of surface run-off [5,6]. It is also used in planning water conservation techniques, and in land evaluation for liquids and effluent waste disposal [7].

In most cases, maintaining a high infiltration rate is desirable for a healthy environment. However, soils that transmit water freely throughout the entire profile or into tile lines need proper chemical management to ensure the protection of groundwater and surface water resources [8]. Soils that have reduced infiltration can become saturated at the surface during rainfall. Saturation decreases soil strength, increases detachment of particles, and enhances the erosion potential. In some areas that have steep slope, surface material lying above a compacted layer may move in a mass sliding down the slope because of saturated soil conditions.Decreases in infiltration or increases in saturation above a compacted layer can also cause nutrient deficiencies in crops [9]. Either condition can result in anaerobic conditions which reduce biological activity or fertilizer use efficiencies. The infiltration data of the soil in the experimental locations are vital for irrigated agriculture. To preserve the land areas from further degradation and loss of useful water for agriculture, there is need to study the prime cause of excessive runoff from rainfall [10].

Infiltration is an integral part of the rainfall - runoff process whose modelling is required for planning and design of water resource [11]. Quantification of infiltration characteristics of the soil is achieved when field infiltration data are fitted mathematically to infiltration models [12]. Surface irrigation practitioners still use empirical infiltration models despite advances in the estimation of infiltration from soil physical properties. However, not all models are applicable in all soils. It is not always evident as to which model is better and under what conditions, hence their suitability for real world data need to be tested by evaluating different models.

Using infiltration models, substantial reduction in time and cost of field measurement of infiltration can be achieved [13]. These models can be used in designing and optimizing irrigation projects [14]. Several studies have been conducted to evaluate the performances of different models or compare models' efficiencies and applicability for different soil conditions. Oku and Aiyelari [12] compared Philip and Kostiakov models and deduced that Philip's model was more suitable than Kostiakov's model from a study of the infiltration capacity of the soil (Inceptisols) of the humid forest in southern Nigeria using the two models. Musa and Adeoye [15] equally stated that Kostiakov's model showed a better performance over those of Philip's and Horton's models. in their study to adapt infiltration equations to the soil in the Guinea Savannah Zone of Nigeria.

Information on infiltration characteristics of soil is vital to irrigation agriculture while preservation of farmlands for agriculture requires that a thorough study be conducted on the hydraulic conductivity properties of soil and factors that may influence its occurence and alterations. Study of the infiltration characteristics usually leads to either high or low infiltration rates in soil and the provides a better insight into soil water management, runoff water harvesting, irrigation schelduling and soil conservation.Thus this study was conducted to determine and compare the infiltration capacity of the soil at the study area, as well as the infiltration capacities of the selected empirical models.

2. MATERIALS AND METHODS

The study was conducted at the experiment farm site of the Department of Agricultural and Environmental Engineering, Federal University of Technology, Akure (FUTA) between December and March for two consecutive years 2015 and 2016 respectively. Akure is located on Latitude 7° 10'N and Longitude 5° 05' E and lies within the humide region of Nigeria.Soil physical and chemical properties of the experimental site were determined using standard procedures. The particle size distribution of the samples was determined using the hydrometer method as described by Agbede and Ojeniyi [16].

Cylinderic infiltrometers, 6.7 cm high with an inner diameter of 30 cm and outer diameter of 60cm were designed and constructed for soil infiltration test. A total area of 60 m by 2 m was used forthe infiltration experiment performed at 20 m distance apart in three different locations. Water was gently poured into the installed infiltrometer until saturation was reached. The saturated soil was then left for 24 hours before the commencement of infiltration experiment.The outer cylinder was first ponded so as to prevent lateral movement of water level into the inner cylinder. Thereafter, a measuring cylinder was used to apply water into the inner cylinder for infiltration measurement while an installed metre rule in the inner cylinder was used to measure water intake into the soil at 30 seconds interval using a stopwatch. Measurement of water infiltration into the soil were conducted until the water level of the inner ring remained constant (i.e point where infiltration no longer takes place). This procedurewas followed three times in each location at the experimental site.

Four selected models were used for this study viz-a-viz Kostiakov, Horton, Green and Ampt and Philip.

2.1 Kostiakov Equation

The Kostiakov equation is mathematically expressed as:

$$F = at^{\propto} \qquad (1)$$

Where;

F is the infiltration capacity,

a and $\propto$ are constants ($0 < \propto < 1$) which can be predicted in advance but are usually fitted from test data.

Equation (1) can also be expressedas

$$F = at^{\propto} + b \qquad (2)$$

Where; b is a rectifying factor (a constant) and was determined by the equation:

$$b = \frac{t_1 t_2 - t_3^2}{t_1 + t_2 - 2t_3} \qquad (3)$$

Where t_1, t_2 are time of commencement and end of infiltration respectively, t_3 was estimated from the relationship;

$$t_3 = \sqrt{t_1 x\, t_2} \qquad (4)$$

However, it is not necessary to determine the valve of b. The logarithm of equation (1)

i.e $\text{Log}F = \log a + \propto \log t$ (5)

On substituting values for field data for infiltration F and elapsed time t into equation (5) would yield a number of infiltration equation which were solved simultanously to obtain valus for $\propto$ and a and there, the cumulative infiltration was calculated.

2.2 Horton Equation

Horton equation used in the study to evaluate the accumulated infiltration of water into the soil can be expresed as:

$$f_t = f_c + (f_o - f_c)^{e^{-kt}} \qquad (6)$$

Equation (6) can be rewritten as:

$$f_t - f_c = (f_o - f_c)^{e^{-kt}} \qquad (7)$$

Where;

f_t = infiltration capacity at any time t, (mm/hr);
f_c = infiltration capacity at steady state (final infiltration rate), mm/hr;
t = time from onset of infiltration time (min);
f_o= infiltration at time t = 0, mm/hr;
k = is a constant and depends on soil type and initial moisture content;
$f_o - f_c$ can be denoted by Q and given by;

$$f_t - f_c = Q^{e^{-kt}} \quad (8)$$

Equation (8) can be rewritten as;

$$\log(f_t - f_c) = \log_e Q - kt \quad (9)$$

Equation (9) used in the study and solved similarly as the previous Kostiakov equation.

2.3 Green and Ampt Equation

The green and Ampt equation used in the study is expressed by;

$$f_t = k_s\left(1 + \frac{n_s}{f_t}\right) \quad (10)$$

Where;

n_s is the initial moisture content deficit i.e; $(\theta_S - \theta_j)$

f_t, is as defined previously;

$k_s$is a constant;

θ_S and θ_j are final and initial moisture content.

2.4 Philip Equation

Philip equation is expressend by;

$$f_t = St^{1/2} + A_t \quad (11)$$

Where;

S and A are constants depending the soil and its initial moisture content.

f_t and t are as previously defined.

2.5 Statistical Analysis

The measured values of cumulative infiltration were plotted versus the values obtained by each model. Using linear regression analysis, four equations were obtained to predict the infiltration capacities from these models. An equation for each model. Coefficient of determination and correlation coefficient statistical measures was used in evaluating the performance of each model.

3. RESULTS AND DISCUSSION

The entry of water into the soil is very crucial to crop survival and subsequent crop yield in any location. Thus for this study, the soil physical and chemical properties of the study area were determined to ascertain its suitability for irrigation agriculture.The soil textural classification of the study area is mainly sandy clay loam and the infiltration capacity was determined by a double ring infiltration at different soil sampling locations.

A statistic of the infiltration rate values for the various models' variables obtained by field measurement is presented in Table 1 while Table 2 showed the observed and predicted accumulated infiltration for the different models. The predicted cumulative infiltration values for Kostiakov, Green and Ampt, Philip and Horton were 6.65, 4.78, 5.98 and 3.39 cm respectively after 5 minutes of infiltration measurement. The values are soil dependent and site specific as equally observed by Smith and Parlange [17] and Musa and Adeoye [15].

Table 1. Determination of the variables of the selected empirical infiltration models by field measurements

Models	**Model equation**	**Variables**	**Obtained/adapted values**
Kostiakov	$F = at^{\propto} + b$	a	0.60 – 4.60 (cm/min)
		b	0.65 – 3.50
		$\propto$	0.40 – 0.49
Horton	$f_t = f_c + (f_o - f_c)^{e^{-kt}}$	K	0.58 – 585 (cm/min)
Green and Ampt	$f_t = k_s\left(1 + \frac{n_s}{f_t}\right)$	k_s	31.5 – 32.0 (cm/hr)
		n	8 - 10 (%)
		S	2.50 – 2.60 (cm/hr)
Philip	$f_t = St^{1/2} + A_t$	s	3.30 – 3.32 (cm/hr$^{1/2}$)
		A	-0.52 – 0.54 (cm/hr)

Adapted from Mbagwu [18]

Figs. 1-3 show the relationship between the depth of infiltration with time at the different locations. From the Figures, it can be seen that infiltration initial increases linearly with time and thereafter reaches steady and constant level.The coefficients of correlation (R^2) for the three locations were 67, 76, and 78% respectively, while (Figs. 2, 4 and 6) shows the convex shape graph of cummulative infiltration with time and the coefficient of infiltration being 99, 99 and 98% for the three locations. This implies that as time increases cummulative infiltration also increases until a ponded condition is obtained. It therefore means as irrigation water is increased with time, a level is reached when subsequent application of water no longer favours neither the crop growth nor yield in any location.

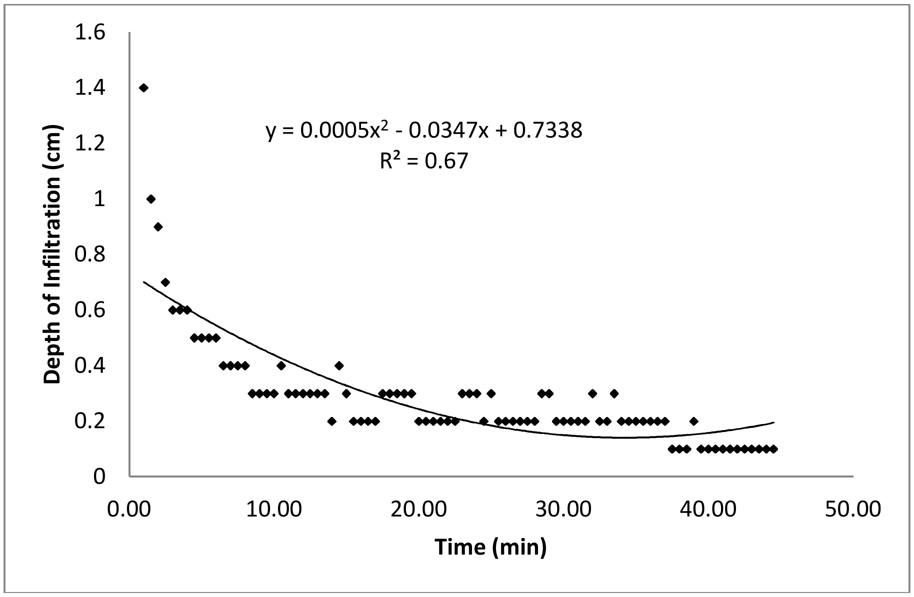


Fig. 1. Infiltration depth versus time in Plot A

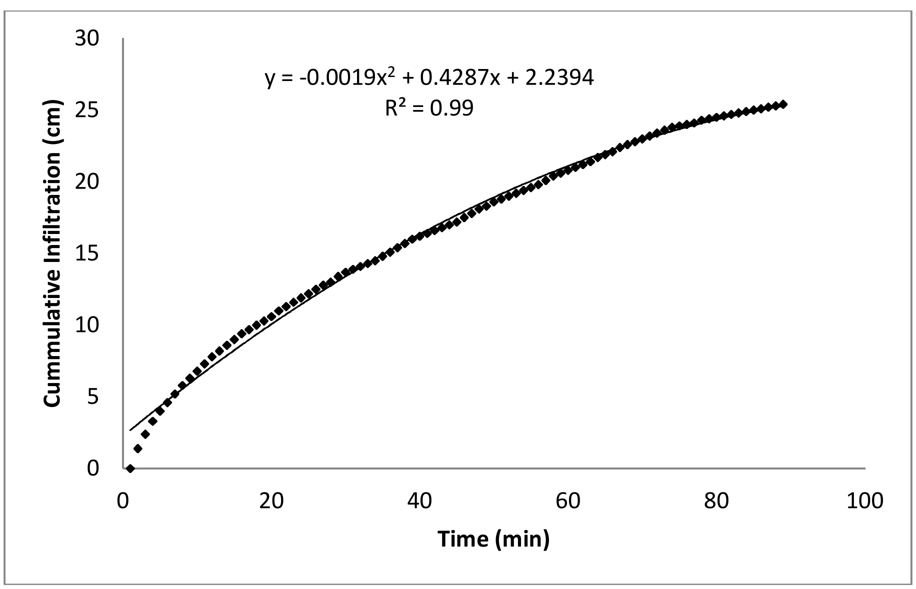


Fig. 2. Cumulative infiltration depth versus time in Plot A

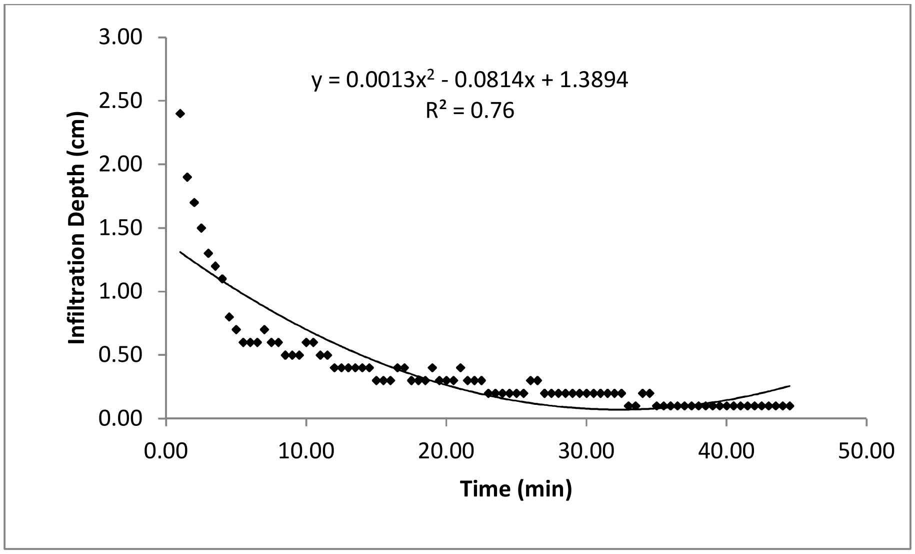


Fig. 3. Infiltration depth versus time in Plot B

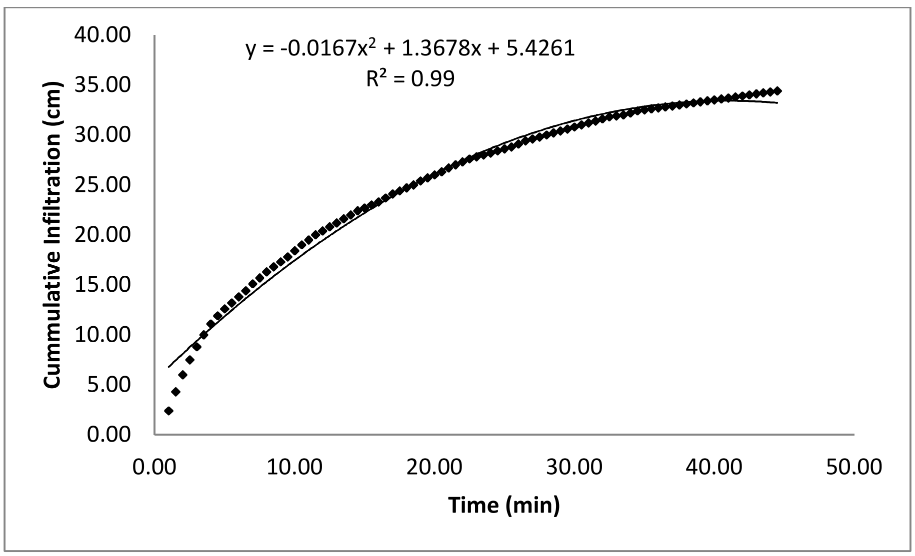


Fig. 4. Cumulative infiltration depth versus time in Plot B

Table 2. Measured and predicted accumulated infiltrationof selected models

Time (Sec.)	Time (min)	Observed accumulated infiltration (cm)	Predicted accumulated infiltration (cm)			
			Kostiakov	Philip	Green & Ampt	Horton
60	1.0	1.4	1.15	2.77	2.65	1.07
90	1.5	2.4	2.16	3.25	3.36	1.36
120	2.0	3.3	3.00	3.62	3.72	1.65
150	2.5	4.0	3.75	3.90	3.82	1.94
180	3.0	4.6	4.42	4.15	4.08	2.23
210	3.5	5.2	5.04	4.35	4.54	2.49
240	4.0	5.8	5.61	4.51	5.21	2.82
270	4.5	6.3	6.15	4.65	5.56	3.10
300	5.0	6.8	6.65	4.78	5.98	3.39

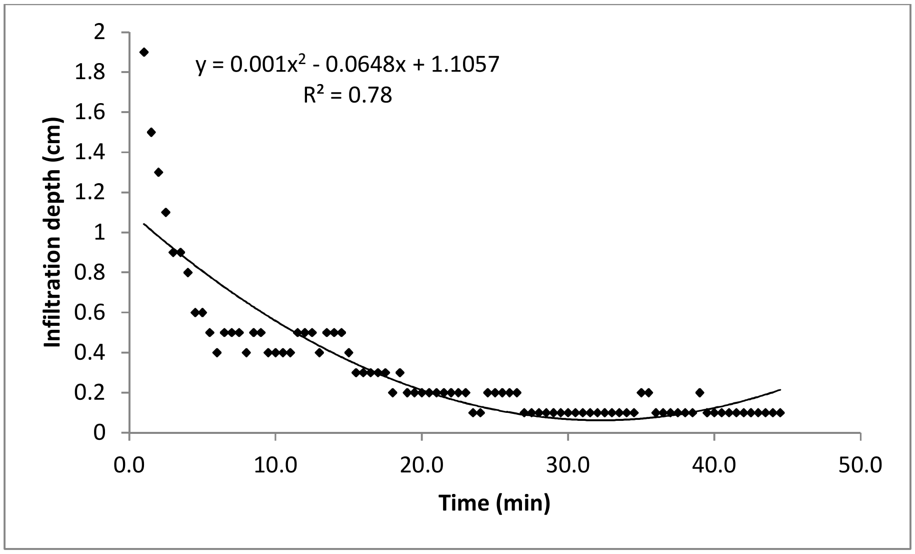


Fig. 5. Infiltration depth versus time in Plot C

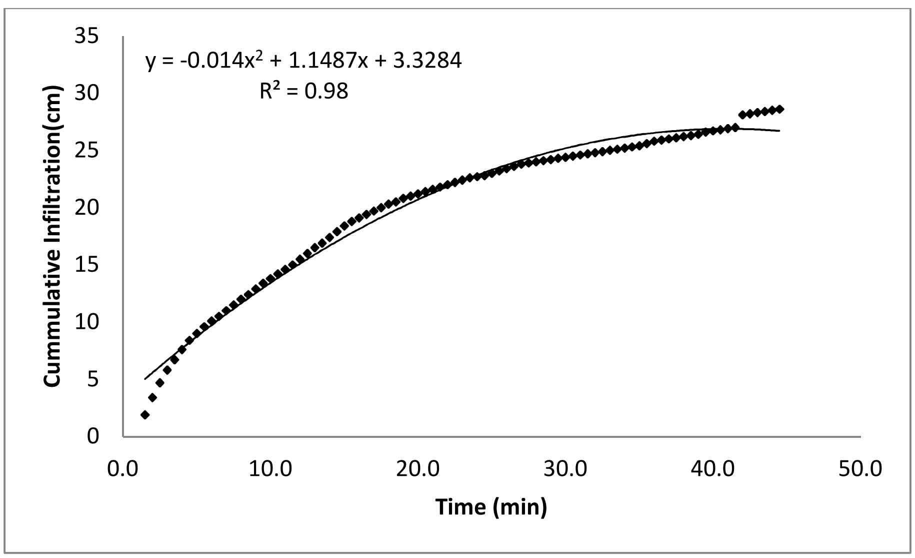


Fig. 6. Cumulative infiltration depth versus time in Plot C

Fig. 7 shows the combination of the field relationship with the empirical models, it compares the field values of infiltration rate with those of models. The figure gives the performance of the infiltration equation and rates in the order Kostiakov>Green and Ampt>Philip > Horton, with Kostiakov equation being the best followed by Green and Ampt, Philip and Horton when compared with the field measurement.

Fig. 8(a), (b), (c) and (d) show the linear relationships between the predicted values accumulated infiltration capacity as well as values obtained by field measurement. The coefficient of determination between the model prediction of accumulative infiltration and those obtained by measurement was highest in the Kostiakov model (0.99), followed by Philip (0.98), Horton model (0.98) and lastly, Green and Ampt (96%). From these findings, it can be seen that infiltration rates for sandy clay loam soil can be deduced for irrigation system designs which are crucial for agricultural production.

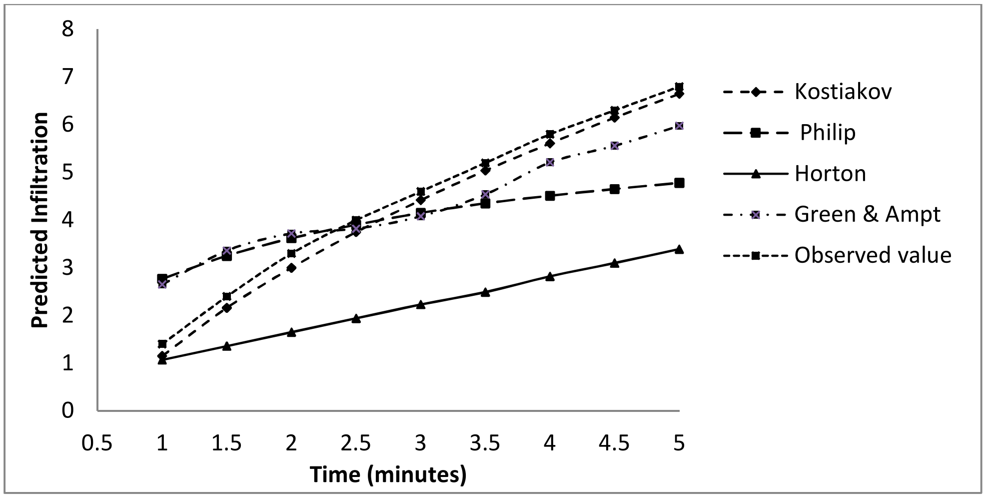
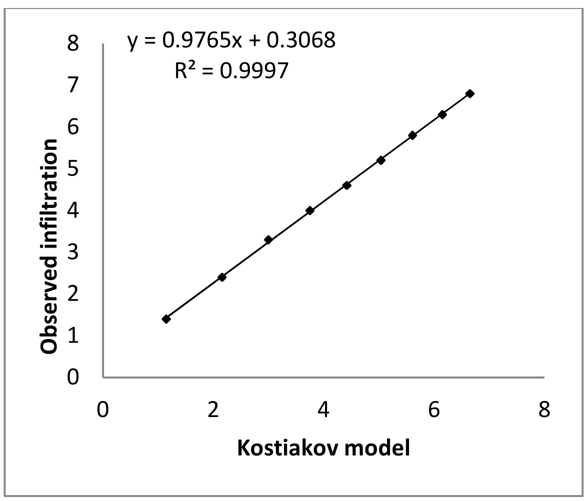
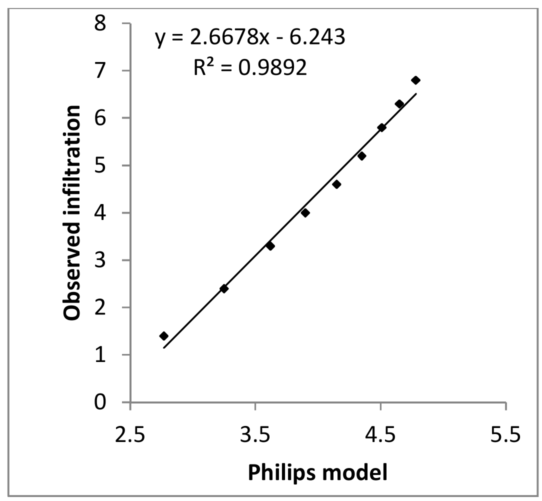


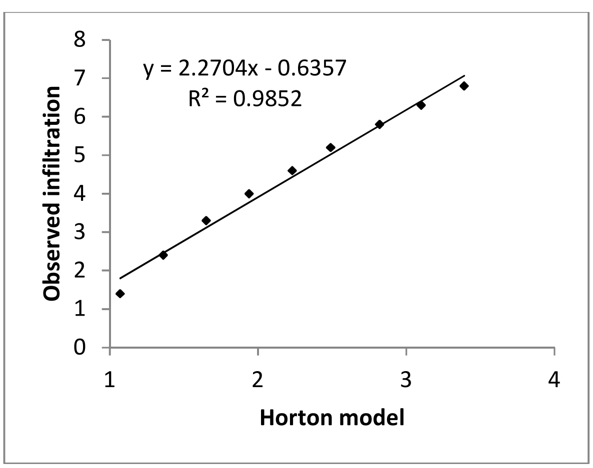
Fig. 7. Graph of the predicted accumulated infiltration (cm) of the various models



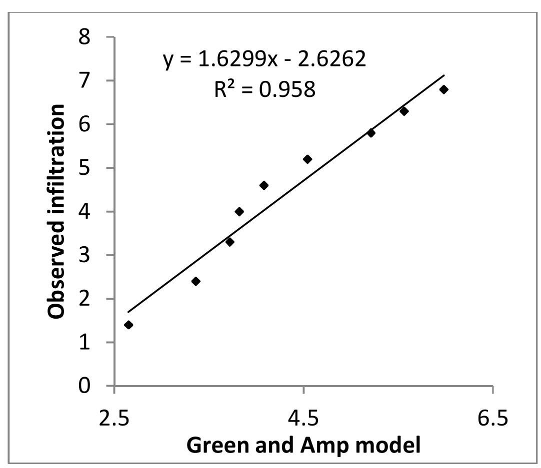
(a)



(b)



(c)



(d)

Fig. 8(a), (b), (c) and (d). Graph of predicted accumulated infiltration (cm) versus observed values

The obtained equations to predict the infiltration capacity as a function of the empirical infiltration models are stated below:

Infiltration capacity = 0.9765$\beta1$ + 0.3068 (1)

Infiltration capacity = 2.6678$\beta2$ - 6.243 (2)

Infiltration capacity = 2.2704 $\beta3$ - 0.6357 (3)

Infiltration capacity = 1.6299 $\beta4$ - 2.6262 (4)

Where $\beta1$, $\beta2$, $\beta3$ and $\beta4$ are kostiakov, Philips, Horton and Green & Ampt models respectively.

4. CONCLUSION

A double ring infiltrometer was used to carry out the infiltration capacity of the soil at the experimental site and the infiltration data obtained on the field were used in evaluating the parameters of the empirical models of Kostiakov, Horton, Green and Ampt and Philip. The evaluated parameters for these models agreed comparatively with the values obtained by Idike and Ejieji [19] and Mbagwu [18] for the same soil type in their study areas.The performance rating of these infiltration equations shows that Kostiakov’s equation performed best followed by Philip, Green and Ampt and Horton equations in that order. Also, four equations were obtained to predict the infiltration capacities from the empirical infiltration models. The study gives that the evaluated parameters can be used for the infiltration equations in the study area and other areas with similar soil properties for irrigated agriculture.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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