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Prediction of infiltration rates of fallow and cultivated soils in Minna, Southern Guinea Savanna zone of Nigeria

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ABSTRACT

Measurement and modelling of soil water infiltration under field condition are crucial to management of water resources, design and execution of drainage and irrigation projects for sustainable agricultural productivity and food security. This study was carried out to determine the time required to attain equilibrium or final infiltration rate of soils of Gidan-Kwano (a sandy loam) and Shintako (a loamy sand) sites around Minna, and reduce the tedium, time and cost associated with the measurement of soil infiltration rate. Three infiltration models (Kostiakov, Horton and Philip models) were evaluated. A double-ring infiltrometer was used to measure the infiltration rates of the soils at the two sites subjected to two land use management practices (fallow and cultivated soils) in Minna, Southern Guinea savanna zone of Nigeria. Infiltration runs were conducted at 0, 4, 8 and 12 weeks after cultivation. Results showed that the equilibrium infiltration rate of the tested soils was attained between 1 and 2 hours. The equilibrium infiltration rates of the fallow and cultivated soils were 21.54 and 7.62 cm hr^{-1}, respectively, at the Gidan-kwano site, while the values at the Shintako site were 30.59 and 24.50 cm hr^{-1}, respectively for the fallow and cultivated soils. Generally, the soils under fallow exhibited higher infiltration rates than cultivated ones. Curvefitting was done on Kostiakov's, Horton's and Philip's infiltration models. Infiltration data generated using Kostiakov's model were not significantly different from field-measured values at 5 % level of probability. The Kostiakov model was the most suitable for the prediction of infiltration rates of the soils investigated compared to Philip and Horton models. It is therefore, recommended for the soils tested, in the Southern Guinea savanna zone of Nigeria.

Key words: Infiltration rate, Kostiakov, Philip and Horton infiltration models, Fallow and cultivated soils

INTRODUCTION

Measurement of soil water under field condition to ensure sustainable yields in agricultural production is particularly concerned with conserving water from inadequate rainfall in the Nigerian sub-humid, semi-arid and arid zones (Guinea savanna, Sudan savanna and Sahel savanna, respectively), and the application of irrigation water to supplement insufficient rainfall. The techniques employed are directed towards increasing the amount of water that goes into the soil from the surface, and to ensure that plants make efficient use of this water. This movement of water downwards into the soil through the surface is termed infiltration. Adequately high rate of infiltration would result in: (i) an increase in the root zone water storage, (ii) reduction in the amount of runoff and flooding and (iii) control of soil erosion. Both water conservation and erosion control involve basically runoff control by enhancing infiltration. Estimation and modelling of soil water infiltration characteristics are vital tools for the quantitative evaluation of water storage capacity of catchments, control and assessment of runoff processes, scheduling of irrigation and planning for water-crop yield (Davidsen *et al.*, 2018).

Infiltration rate decreases with time during an irrigation or rainfall event. The rate of decrease is rapid initially, but in the long-term it approaches a constant value termed equilibrium or final infiltration rate (Eze *et al.*, 2006) which is loosely related to saturated hydraulic conductivity (Karuku *et al.*, 2012). Accumulated infiltration refers to the total quantity of water that enters the soil in a given time. Infiltration rate and accumulated infiltration are two parameters that are commonly used to evaluate the infiltration characteristics of the soil. Management of water resources and the design of hydraulic structures for irrigation purpose will require an evaluation and modelling of soil water infiltration according to Dahak *et al.* (2022). It then entails that realistic planning of water management activities, such as erosion control and irrigation, will

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require simple information on the rate at which different soils take up water under varying conditions and soil management practices. Eze *et al.* (2006) noted that some soils in Minna, Southern Guinea savanna zone of Nigeria, left fallow for about five years had significantly higher infiltration rates than the cultivated ones. These workers reported that these results so observed was due to the undisturbed condition of the soils under fallow. The presence of earthworms that are larger than 2 mm in diameter facilitate water infiltration by forming vertical burrows and creating larger continuous pores that are greater than 1.5 mm (Fischer *et al.,* 2014). Data on rates of infiltration of water into soils can be used to supplement other soil information which could help soil scientists, engineers, hydrologists and others to deal more effectively with a wide spectrum of water resource management and conservation problems.

Land use is one of the key factors that affect soil water infiltration (Thornleya and Cannell, 2010). It can influence the amount of runoff and increase soil degradation. The implication is that changes in land use could result in soil quality reduction and increase soil degradation as reported by Aghasi *et al.* (2010), and also, give rise to variability in soil infiltration rates (Dahak *et al.,* 2022). In similar study, it has been widely reported that land use significantly influenced soil infiltration rates (Sun *et al.,* 2018; Suryoputro *et al.,* 2018). However, soil infiltration capacity variation among different land use types appears to be less clear (Sun *et al.,* 2018).

Measurement of infiltration rate is labour-intensive, tedious, cumbersome and it could be quite expensive especially where water supply is limited. Hence, it may be necessary to device a means of predicting cumulative infiltration and infiltration rate over a given period of time without necessarily carrying out measurements in the field. This can be achieved through the application of certain common time-dependent infiltration models. Furthermore, infiltration rate is a complex parameter of the soil to estimate because it is influenced by multiple physical and hydrologic factors, which include rainfall variability (Tsai and Yeh, 2019), surface and deep soil properties (Barbosa *et al.,* 2018), slope morphology (Biswas, 2019), vegetation and land use (Kalhoro *et al.,* 2019), and soil moisture (Schoener and Stone, 2019). Well-established and widely accepted theoretical infiltration models based on regression analysis are the simplest and most effective tools utilized for the evaluation of infiltration rates (Sihag *et al.,* 2021).

The theory and process of infiltration have been reviewed by Philip (1969) and Hillel (1971) amongst other soil scientists. A number of infiltration equations and models may be found in literature. They include infiltration models by Green and Ampt (1911), Kostiakov (1932), Horton (1939, 1940), Philip (1957), Holtan (1961), Modified Kostiakov (Smith, 1972), Smith and Parlange (1978), and Kostiakov-Lewis (Walker and Skogerboe, 1987). These infiltration equations and models may be generally grouped into two broad categories: (i) those which are empirical in nature and/or require fitted parameters, and (ii) those which are derived from the theory of flow in porous media and utilize measured parameters. Equations in the first category have often involved simplified concepts, which permit the infiltration rate or cumulative infiltration volume to be expressed algebraically as a function of time (t) and empirical constants or soil parameters. Some of the equations in the first category mentioned above were used in this study because of they are quite user friendly, and they included models by Kostiakov (1932), Horton (1939, 1940) and Philip (1957). It would be necessary to carry out tests on the applicability and accuracy of these infiltration models because some of the available ones may not be applicable under all conditions of soil and climate. Suryoputro *et al.* (2018) evaluated five infiltration models (Green-Ampt, Kostiakov, Kostiakov-Lewis, Philip and Horton) under different land use types (settlements, plantations, rice fields and forests). Results from this study indicate that among the infiltration models evaluated, Kostiakov model was the most suitable for mineral soils with rapid infiltration rate (the final infiltration rate higher than 0.42 mm min^{-1}). In contrast, Mbagwu (1993) reported that modified models of Kostiakov and Philip were more suitable. Dahak *et al.* (2022) noted that Horton model is the most suitable (compared with Kostiakov and Philip models) to assess the infiltration rate over an Algerian catchment. Similar to the reports of Suryoputro *et al.* (2018), Mahapatra *et al.* (2020) concluded that the Kostiakov model exhibited a higher accuracy for predicting soil infiltration characteristics over an Indian catchment compared to Philip model. In another study conducted over the Nigerian humid forest catchment, (Oku and Aiyelari, 2011) noted that the Philip model was more suitable than the Kostiakov model for predicting soil water infiltration. Apart from land use, the geology of soils affects the choice of reliability of a given infiltration model (Utin and Oguike, 2018). These authors concluded that the

Kostiakov model performed better for predicting infiltration rates in soils developed from sandstone and alluvial soils, whereas, the Philip model was more reliable for coastal plains. (Zakwan *et al.,* 2016) opined that Kostiakov and Horton models provided better estimation of infiltration data than Philip model. The superiority of the performance of the Kostiakov model over other infiltration models has been widely reported on a global scale in Iran (Jagani *et al.,* 2018), India (Igbokwe and Adindu, 2014), China (Lei *et al.,* 2020), and Nigeria (Thomas *et al.,* 2020). The Kostiakov, Philip and Horton models simulated cumulative infiltration equally well and the results were close to field measurements on a sandy soil according to Ogbe *et al.* (2011). The objectives of the present research were: (1) To measure the infiltration rates of two selected soils under two land use management practices in order to determine the time required for the attainment of equilibrium infiltration rate, (2) To predict cumulative infiltration and infiltration rates using three time-dependent infiltration models, and (3) To determine the most applicable infiltration model for the tested soils and the management of similar soils.

MATERIALS AND METHODS

Study Area

The experiment was carried out at two locations, Gidan-kwano and Shintako villages, around Minna in Niger State, Nigeria. Each of the study sites had been under about five years of fallow after which a portion of the land was cultivated during the period of the experiment. Minna is located between latitude 6°00′ and 7°00′ North and between longitude 9°30′ and 9°45′ East in the Southern Guinea savanna zone of Nigeria. It has a mean annual rainfall of 1,300mm and a daily temperature range of 27 to 34°C. The Gidan-kwano soil is a sandy loam classified as Plinthustalf, while the Shintako soil is loamy sand classified as Paleustalf (Eze, 2000; Eze *et al.,* 2006) following the procedures outlined in Soil Survey Staff (2014) and FAO (2014).

Experimental Design

The experiment consisted of two treatments; namely, fallow and cultivated soils, each replicated four times. Each treatment plot was 2 x 2 m in size. The cultivated plots were marked out, tilled manually and levelled (to obtain a flat soil surface) using a hand-hoe with a blade size of 20 cm cutting width and 30 cm long. The hand-hoe has a total weight of 2 kg. Yellow maize (TZR-Y) was grown on the cultivated plots. Recommended fertilizer rate was applied using NPK (15:15:15) at 2 and 6 weeks after emergence. Manual weeding was carried out on the cultivated plots thrice (at 2, 6 and 12 weeks after planting) with the aid of a smaller hand-hoe.

Infiltration rates were measured on the fallow and cultivated plots with the aid of a double-ring infiltrometer (Ahuja *et al.,* 1976; Eze *et al.,* 2006). The double-ring infiltrometer consists of two rings, inner and outer rings. The inner ring was constructed with a 5 mm thick metal sheet, and was 26 cm in diameter and 34.7 cm in height. The outer ring was made of a 3 mm thick metal sheet, whose diameter and height were 55 and 30 cm, respectively. The two rings were carefully driven 15 cm deep into the ground with minimal soil disturbance in the inner ring. For this purpose, a heavy wooden block was placed on top of the rings upon which moderate blows of a heavy hammer were applied. The heavy wooden block was moved around the edges of the top of the rings after every two to three blows so that the rings could penetrate the soil uniformly, without damage. After the rings were driven into the soil, the disturbed soil adjacent to the rings was made firm by gently tapping the soil with the hand. Four runs each, of infiltration rate measurements were carried out on the fallow and cultivated soils during each measurement interval or period. Infiltration rate measurements were taken before cultivation (0 week after planting), and subsequently at intervals of 4, 8 and 12 weeks after planting.

The process of infiltration was initiated by ponding water in the outer ring. The ponded water was maintained at a shallow depth, to provide a buffer so as to discourage lateral flow and ensure one-dimensional vertical flow. Immediately after applying water into the outer ring, water was applied into the inner ring. The soil surface within the rings was covered with a thin layer of dry grass to prevent direct impact of applied water and a consequent disturbance of surface soil. The fall in water level (in cm) in the inner ring was read at intervals of 1, 2, 5, 10, 15, 20, 30, 45, 60, 75, 90, 100 and 120 minutes as a measure of cumulative infiltration (cm). To achieve this, a metal plate was placed over the outer ring to stabilize a ruler. The ruler was attached to a float in order to keep the ruler standing upright on the surface of the water ponded in the inner ring. Whenever the water level in the inner ring dropped to about 7 cm, more water was supplied to raise the water level to a desired height and maintain the head which may interfere with water transmission. Infiltration rate (cm/min) was determined as cumulative infiltration over a specified time (t) period.

Infiltration Modelling

Three infiltration models were selected to determine their degrees of fitness; namely, the Kostiakov (1932), Horton (1939, 1940) and Philip (1957) models. The models are represented by the following equations:

(i) Kostiakov's Equation

$$I = Mt^n + b$$

$$i = Mnt^{n-1}$$

(ii) Horton's Equation

$$I = i_c t + ((i_0 - i_c)/k) [i - e^{-kt}]$$

$$i = i_c t + (i_0 - i_c)e^{-kt}$$

(iii) Philip's Equation

$$I = St^{½} + At$$

$$i = ½St^{-½} + A$$

where,

I = cumulative infiltration (cm)

i = infiltration rate (cm hr^{-1})

e = natural logarithm

i_0 = infiltration rate at time t = 0 or initial infiltration rate (cm hr^{-1})

i_c = final infiltration rate after prolonged wetting or steady state infiltration rate (cm hr^{-1})

t = time (mins) since infiltration started

A, b, M, n, k and S = constants

The soil parameters in each of the infiltration models were obtained after curve-fitting using average values (Eze, 2000). Chi-square test was carried out at 0.05 level of significance in order to determine the goodness-of-fit of the selected infiltration models in relation to the field-observed (experimental) infiltration values.

RESULTS AND DISCUSSION

Data presented in Table 1 indicate that infiltration rates in the study exhibited a common trend of very high initial values, which reduced sharply within the first 15 minutes. Only a slight decrease in the rate of water intake was observed after 45 minutes. Consequently, the rate between 1 and 2 hours is taken as the equilibrium infiltration rate. This conclusion is similar to the reports of Yimer *et al.* (2008), Jagdale *et al.* (2012) and Suryoputro *et al.* (2018). These workers concluded that the time taken to attain final infiltration rate was 1 hour. Dahak *et al.* (2022) reported a range between 1 and 4.5 hours for the attainment of final infiltration rate. The researchers mentioned above noted that soil type (mainly soil texture), land use and soil condition gave rise to differences in the initial and final infiltration rates of the soils investigated. The findings in this study are in contrast with the report of Okai *et al.* (2000), who noted that final infiltration rate of a sandy loam to fine sandy clay loam soil in Kadawa, Kano State, Nigeria could not be attained even after six hours. This observation was attributed to deep penetration

Table 1. Average infiltration rates (cm hr^{-1}) of fallow and cultivated soils at Gidan-kwano and Shintako sites

Elapsed time	Gidan-kwano site		Shintako site	
(mins)	Fallow	Cultivated	Fallow	Cultivated
1	52.62	32.31	72.43	70.50
2	48.69	26.31	66.86	60.50
5	38.86	19.57	58.37	49.00
10	33.69	15.83	50.91	41.60
15	30.74	14.06	45.94	37.83
20	29.19	12.92	43.37	35.80
30	26.86	11.29	40.44	33.02
45	24.78	10.02	37.41	29.73
60	23.82	9.01	35.56	28.34
75	23.09	8.54	33.90	27.06
90	22.66	8.17	32.98	26.25
100	22.23	7.97	32.16	25.58
120	21.54	7.62	30.59	24.50

of wetting front and decrease in suction potential gradient over a long period of time. The fallow soils generally exhibited higher infiltration rates than those under cultivation. The equilibrium infiltration rates of the fallow and cultivated soils were 21.54 and 7.62 cm hr^{-1}, respectively, at the Gidan-kwano site, while the values at the Shintako site were 30.59 and 24.50 cm hr^{-1}, respectively for the fallow and cultivated soils. Cultivation may have destroyed the granular nature of the soils, compacted them and reduced the proportion of macro-pores (Eze *et al.*, 2006), while fallowing promoted earthworm activity, penetrating and decaying roots, and continuity of pore channels from the surface down the profile in the soils (Chan, 2014; Fischer *et al.*, 2014).

Curve-fitting was done on the infiltration models of Kostiakov (1932), Horton (1939, 1940) and Philip (1957). Table 2 shows the estimated soil parameters for the three models. It also displays the Chi-square values of expected infiltration data calculated using soil parameters and field-measured (observed) values for cultivated and fallow soils of Gidan-kwano and Shintako sites. The average infiltration rates obtained using the soil parameters of both Horton and Philip models showed significant differences ($p \leq 0.05$) from experimental results in all cases tested, with the former showing a higher deviation. The Chi-square values obtained from observed and expected infiltration data were higher than the table value (21.03) at p=0.05 level of probability, indicating that there is a significant difference between the field-observed infiltration data and the expected values calculated using the soil parameters, A and S in Philip's infiltration model, and i_o, i_c, e and k in that of Horton, and in all the soils under study (Table 2). In contrast to this finding in the current study, Adindu *et al.* (2015) reported that Philip's infiltration model adequately predicted the infiltration rate of some soils in Aba, Abia State, Nigeria. Suryoputro *et al.* (2018) and Dahak *et al.* (2022) reported that soil infiltration rate is influenced by several factors

Table 2. Estimated soil parameters for infiltration model equations from curve fitting for Gidan-kwano and Shintako sites

Site	Land use Management	Estimated soil parameters		
		Kostiakov	Horton	Philip
Gidan-kwano	Cultivated soil	M = 0.5343	i_0 = 24.24 cm hr^{-1}	A = 5.93
		n = 0.69	i_c = 6.00 $cmhr^{-1}$	S = 27.83
		b = 0.02	e = 2.7182	X^2 = 28.95*
		X^2 = 0.06 Ns	k = 0.0036	
		X^2 = 57.40*		
Gidan-kwano	Fallow soil	M = 0.8651	i_0 = 44.37 cm hr^{-1}	A = 19.91
		n = 0.81	i_c = 19.95 $cmhr^{-1}$	S = 36.55
		b = 0.03	e = 2.7182	X^2 = 23.92*
		X^2 = 0.09 Ns	k = 0.0036	
		X^2 = 54.25*		
Shintako	Cultivated soil	M = 1.1378	i_0 = 56.71 cm hr^{-1}	A = 22.46
		n = 0.78	i_c = 22.50 $cmhr^{-1}$	S = 51.68
		b = 0.07	e = 2.7182	X^2 = 37.98*
		X^2 = 0.14 Ns	k = 0.0036	
		X^2 = 83.37*		
Shintako	Fallow soil	M = 1.3944	i_0 = 63.26 cm hr^{-1}	A = 30.56
		n = 0.79	i_c = 29.95 $cmhr^{-1}$	S = 47.98
		b = -0.19	e = 2.7182	X^2 = 31.02*
		X^2 = 0.04 Ns	k = 0.0036	
		X^2 = 67.99*		

M, n, b, A, S, i_0, i_c, e and k: Constants under a given soil condition

X^2: Chi-square value

Ns: Not significantly different

*: Significantly different at 0.05 level of probability

Table X^2 value (P = 0.05) = 21.03

Degree of freedom (n - 1) = 12

such as soil physical characteristics (texture and structure), hydraulic properties, vegetation cover and land use. Also, they noted that the hydraulic relationship between soil characteristics and infiltration rates is quite complex. Therefore, the applicability of models to different soil types and conditions will require advanced field studies. The reliability and suitability of infiltration models have been reported, with particular reference to the variability of infiltration rates resulting from changes in land use (Suryoputro *et al.*, 2018). Over an Indian catchment, Mahapatra *et al.* (2020) concluded that the Kostiakov model predicted infiltration characteristics with a higher degree of accuracy and lowest parameter uncertainty compared to the Philip model. However, in the humid forest catchment of Nigeria, Oku and Aiyelari (2011) noted that the Philip model performed better than the Kostiakov model for prediction of soil water infiltration. Utin and Oguike (2018) concluded that the choice of reliability of any infiltration model is a function of the geology of a given soil type. These workers noted that the Kostiakov model was more suitable for predicting infiltration rates of soils derived from sandstone and alluvial soils, whereas, Philip model was more reliable for coastal plains. Suryoputro *et al.* (2018) reported that the Kostiakov model was most suitable for mineral soils with rapid infiltration rate (greater than 0.42 mm min^{-1}), compared to Kostiakov-Lewis, Horton, Philip and Green-Ampt models.

When field-observed infiltration data were compared with the expected values calculated using the soil parameters (b, m and n) in Kostiakov's infiltration model, no significant difference was observed. It is therefore evident that Kostiakov's model adequately fitted the field experimental data compared to the Horton and Philip models. This clearly indicates the superior performance of Kostiakov's model. This finding is similar to those of numerous workers (Adindu *et al.*, 2014; Zakwan, 2017; Suryoputro *et al.*, 2018; Utin and Oguike, 2018; Mahapatra *et al.*, 2020; Thomas *et al.*, 2020), who used similar models for related soils. Therefore, Kostiakov's infiltration model can be used to adequately predict infiltration rates of the sandy loam and loamy sand soils in Minna and similar ones in the Nigerian Southern Guinea savanna zone.

It is noteworthy to mention that the Kostiakov model, like others, is a theoretically derived equation. Therefore, even though it may be found to be significant in soil water management, care must be taken because certain assumptions may be made that may constitute notable deviations from field conditions. The applicability of this model must also be tested for given soil conditions.

CONCLUSION

The purpose of this study was to measure infiltration rates of selected soils under two land use management practices in order to determine the length of time required for the attainment of equilibrium infiltration rate. This information will be useful especially in areas where erosion control and irrigation projects are being carried out. This study involved the use of a double-ring infiltrometer to measure infiltration rates of soils subjected to two different land management practices (fallow and cultivated soils) located around Minna in the Southern Guinea savanna zone of Nigeria. Three infiltration models (Koatiakov, Philip and Horton) were evaluated. The Kostiakov model was the most suitable for the prediction of infiltration rates of the soils investigated compared to Philip and Horton models.

The Kostiakov model is thus recommended for the soils tested and for similar soils elsewhere in the Nigerian Guinea savanna zone. The usefulness of this infiltration model can be employed in the design and careful planning of erosion control and irrigation projects, especially in this zone where soils are fragile, and short spells of dryness and water shortages result from high rainfall variability. This will ensure the availability of food crops, particularly vegetable crops all year round.

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