Predictability of Philip and Kostiakov Infiltration Models under Inceptisols in the Humid Forest Zone, Nigeria

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ABSTRACT

Knowledge of the infiltration of water into a soil is very important for efficient soil and water management and conservation, especially when the water supply is through rainfall. For efficient irrigation water management, once field infiltration values are constant and the curve established for a particular soil, it is possible to determine during irrigation how long it will take to infiltrate a certain amount of water. Ring infiltrometer measurements were carried out at 10 m intervals down a 5% Inceptisol toposequence of 100 m length in a humid forest in southern Nigeria. The aim was to determine the infiltration capacity of the soil with slope positions and to fit the infiltration data into the Philip and Kostiakov infiltration models in order to quantify the hydrological behavior of the soil and the ability of these models to predict infiltration into the Inceptisols of a humid forest. The nonlinear least square procedure was employed to determine the parameters of the models—namely, the transmissivity and sorptivity of Philip's model and the initial infiltration and the index of soil sorptivity reflecting the rate of declining infiltration capacity of Kostiakov's model. The results indicated that the initial infiltration and cumulative infiltration ranged from 2.0 to 7.50 cm min^{-1} and from 84.90 to 555.20 cm after 6 h of elapsed time, respectively. The coefficient of determination was near unity indicating the models were a good fit for data and could be used to predict infiltration for the studied soil. Transmissivity values ranged from 0.14 to 1.29, putting the soil conductivity class between 'very slow' and 'slow'. Sorptivity was very high with values in the range 1.20 to 8.08. The index of sorptivity of soil ranged from 0.65 to 0.88 indicating fairly high soil sorptivity and the initial infiltration of Kostiakov's model ranged from 0.03 to 1.09. Goodness of fit was used to compare the measured and predicted infiltration values and showed that 10% and 50% disparities existed for initial infiltration and 30% and 70% disparities for cumulative infiltration under Philip's and Kostiakov's models, respectively. It can be deduced that Philip's model was more suitable than Kostiakov's model for predicting water infiltration in Inceptisols of the humid forest zone of Nigeria.

Keywords: infiltration models, Inceptisol, humid forest zone, Nigeria

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INTRODUCTION

Infiltration is the downward entry of water from the surface into the soil profile (Lal, 1990). It is the key to soil and water conservation because it determines the amount of runoff over the soil surface during rainstorms. The relation between the rate of water supply to the soil and the rate of infiltration through it determine the distribution of such water between runoff and storage in the root zone (Pla, 2007). Thus the ability of the soil surface to accept continuous heavy rainfall or irrigation depends on the infiltration behavior or characteristics of the soil. According to Ogban *et al*. (2000), low values of the infiltration characteristics indicate a potentially high runoff (erosion) on such toposequences or slopes. These will invariably affect the water economy of the rooting zone of plants. Such soil will have difficulty in meeting the water needs for crop production where water is a major limiting factor (Wuddivira and Abdulkadir, 2000). The dry months in the humid forest zone of Nigeria are from November to March which result in green and fruit vegetables being very scarce and expensive. Irrigation holds the key to reversing the decline in crop production and sometimes even total crop failure during dry period. Tube and hand-dug wells have been constructed in the valley bottoms to remedy the lack of water and to encourage farmers, enabling them to pump water and irrigate their fields along the slope and on upper slopes. On the other hand efforts are being made to improve surface irrigation, irrigation efficiency and also to design affordable irrigation sets for use in crop production.

According to Hume (1993), to effectively design and operate surface irrigation systems to meet the water needs for crop production, the infiltration behavior of the soil must be accurately known and accurately quantified. For instance an infiltration curve can be used to determine the amount of water required for irrigation over time.

Infiltration behavior or characteristics of the soil are quantified when field infiltration data are fitted mathematically to infiltration models. However, not all models are applicable in all soils. Morgan (1995) reported that the Green and Ampt (1911) infiltration model described well the infiltration behavior of soils in southern Spain (Sconging and Thornes 1979) and in Arizona (Sconging *et al*.,1992) but Bork and Rohdenburg (1991) also working in southern Spain, obtained better results with the infiltration model proposed by Philip (1957) (Philip's model). Furthermore Gifford (1976) found neither models satisfactory for semi-arid rangeland in northern Australia and in Utah in the United States of America. Mbagwu (1997) reported that Philip's model would always fail to predict measured infiltrations when the assumptions of the model were not met during the infiltration process. Earlier, Kutilex *et al*. (1988) and Sir *et al*. (1988) observed poor predictive ability with Philip's model for some soils.

Infiltration behavior of a soil is determined by field point-to-point measurements of infiltration using a ring infiltrometer. However point-to-point field measurement is laborious, tiresome, time consuming and could be a very serious problem and expensive where water is limited (Ahmed and Duru 1985; Haverkamp *et al*., 1988; Hume, 1993; Wuddivira and Abdulkadir, 2000). These researchers called for a method to predict the infiltration rate without actual point-to-point measurements.

If information is available on the fall of the water depth in the ring of the infiltrometer and the rate of fall (cm hr^{-1}) but there is no other information about the soil involved, it is possible to characterize the water infiltrating from irrigation. Using this knowledge and considering the criticism over the poor predictive ability of Philip's model on some soils and sites, the aims of the present study were: 1) to determine the infiltration capacity of the soil with slope positions; 2) to fit the infiltration data into Philip's and

Kostiakov's (Kostiakov, 1932) infiltration models in order to quantify the hydrological behavior of the soil and the ability of these models in predicting infiltration into the Inceptisols of the humid forest zone in Nigeria; and 3) to generate information on the use of these models on toposequences in the soils of this region and similar soils elsewhere.

MATERIALS AND METHODS

The experiment was carried out in February 2008 along a 5% slope sustaining newly established *Tectona grandis* in southern Nigeria (Figure 1). The soil of the site is classified as an Inceptisol (Periaswamy *et al*., 1983). The mean annual rainfall for the study location ranged from 2000 to 2250 mm (CRADP, 1992). Soil samples were collected to a depth of 0–15 cm at all infiltration points. The samples were bulked to obtain composite samples as previous research had shown low variability for soil properties at this location (data not shown). The samples were subjected to analysis of routine soil phyisco-chemical properties. In total, 10 infiltration tests each replicated twice were made at 10 m intervals down the slope. A double ring infiltrometer using the falling head method described by Mbagwu (1997) and Gabriels (2007) was used. The dimensions of the inner ring used were 50 cm high and 30 cm inner diameter whereas the outer ring
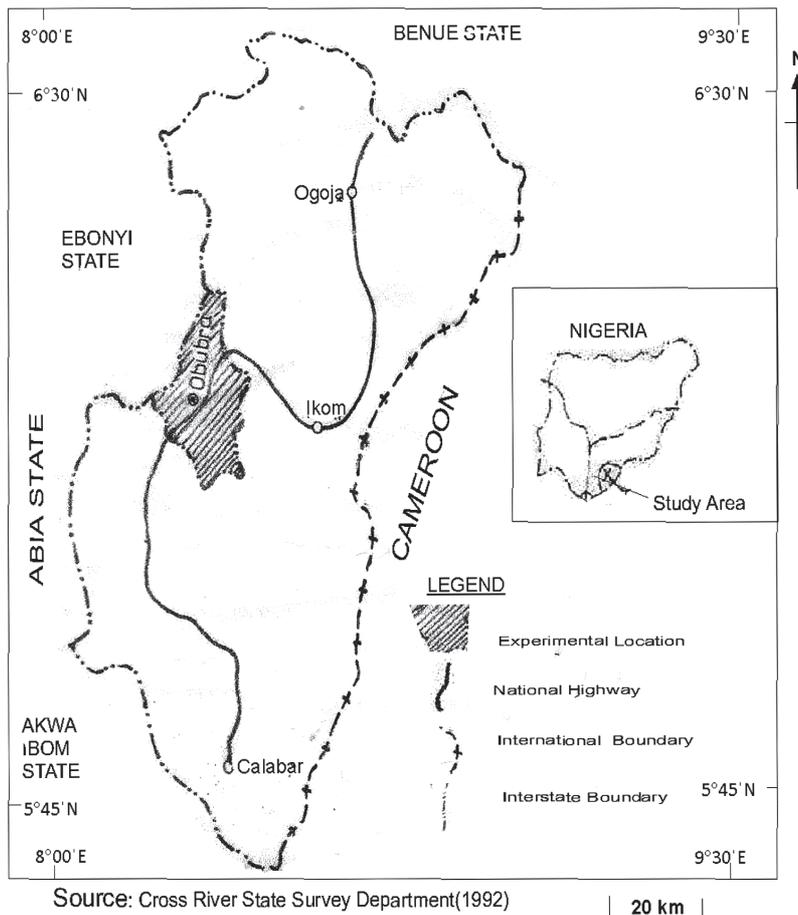

Figure 1 Map of Cross River State, Nigeria showing experimental location.

was 50 cm high with a diameter of 60 cm. The cylinders were driven into the soil to a depth of 25 cm with a sledgehammer, being careful not to disturb the soil surface during this process. Ponded water was kept in both rings while measurements of water intake were made only in the inner cylinder. As described by Mbagwu (1997), one side of the inner cylinder was marked at two points (5 cm and 15 cm) from the ring with a meter rule permanently glued to the inside of the inner ring. These two points served as the reference levels. Water was quickly poured into the inner and outer rings. When the water level dropped to the 5 cm reference point, enough water was quickly added to bring the water level to its initial level. The level and time before filling and the level after filling were recorded with a stopwatch. The process continued until the steady-state rate was attained. The equilibrium rate or steady flow rate was attained after approximately 6 h at each location. As advised by Mbagwu (1997), the interval between the refilling of the ring was kept short to avoid errors caused by water intake during the refilling period, since the analysis of data from this type of measurement assumes that the refilling is instantaneous.

Fitting infiltration models

The infiltration data were analyzed according to the model of Kostiakov (1932) using Equation 1 and Philip (1957) using Equation 2 as these two models are frequently used in the humid forest zone to characterize infiltration:

$$I = C t^{\alpha} \tag{1}$$
$$I = St^{1/2} + At \tag{2}$$

where

I = Cumulative infiltration (cm)

C = Initial infiltration (cm min^{-1} or cm h^{-1})

α = Index of sorptivity of the soil reflecting the decline of the infiltration rate

S = Sorptivity and embodies the influence of the soil water relation (matric suction and conductivity) in the wetting process

A = Transmissivity (hydraulic conductivity) and represents the effect of gravity

t = time elapsed (min)

The nonlinear, least–square fitting procedure was employed to determine the parameter of the infiltration models. The coefficient of variability (CV) of infiltration was determined using Fisher classical statistics. The CV values were grouped into three classes: least (low) variable, where CV < 15%; moderately (medium) variable, where $15 \leq CV \leq 35\%$; and highly (high) variable, where CV > 35% (Upchurch et al., 1988; Wilding et al., 1994). A Chi square test was used to test for disparity between the measured and the predicted infiltration.

RESULTS AND DISCUSSION

The physico-chemical properties of the soil on the experimental site and sample sites location are presented in Table 1. Table 2 shows the spatial behavior of the soil water and the infiltration rate along the 5% Inceptisol slope. Initial one-minute infiltration and cumulative infiltration (cm) after 6 h elapsed time showed high variation with topographic position having CV values of 43 and 45%, respectively, (Mulla and McBratney, 2001). Curve fitting using the least-square method was used to obtain the transmissivity and sorptivity of Philip's model and the index of soil sorptivity and the initial infiltration (sorptivity) of Kostiakov's model. The coefficient of determination (R^2) was 0.99 (Table 2) implying the models accounted for almost all of the variability in the data and indicating that Philip's and Kostiakov's models both provided a very good fit to the data. Comparable results have

been reported by Ahmed and Duru (1985); Kureve *et al*. (1995) and Wuddivira and Abdulkadir (2000) for the Typic Haplustalf soil type of the northern Guinea savannah of Nigeria. At 60 m down the slope, Philip's model accounted for only 76% of the variability ($R^2 = 0.76$), which was the lowest value.

The sorptive forces of the soil largely govern the initial water infiltration rate. The sorptivity values obtained in the present study were high (1.12 to 8.03). Transmissivity of Philip's model ranged from 0.14 to 1.29. These values invariably put the soil conductivity class between "very slow" and "slow" (FAO, 1963). In a uniform

Table 1 Physico-chemical properties at soil depth of 0–15 cm at the experimental site.

Soil property	Mean values
Sand (g kg^{-1})	886
Silt (g kg^{-1})	74
Clay (g kg^{-1})	40
Texture	Loamy sand
pH	4.22
Organic carbon (g kg^{-1})	12.91
Total nitrogen (g kg^{-1})	1.53
Available P (mg kg^{-1})	14.08
Calcium (c mol kg^{-1})	0.12
Magnesium (c mol kg^{-1})	0.18
Sodium (c mol kg^{-1})	2.63
Potassium (c mol kg^{-1}))	1.53
ECEC (c mol kg^{-1})	8.11
Base saturation (g kg^{-1})	549.9

Table 2 Infiltration characteristics along 5% Inceptisol slope in humid forest zone in Nigeria.

Infiltration points down the slope (m)	Initial infiltration (L min cm^{-1})	Cumulative infiltration (6 h)	Philip's model			Kostiakov's model		
			A	S	R^2	α	C	R^2
10	4.00	312.00	0.64	4.48	0.99	0.78	0.50	0.99
20	2.00	131.20	0.30	1.12	0.99	0.80	0.03	0.99
30	4.50	405.00	0.95	3.78	0.99	0.84	0.47	0.99
40	3.50	460.00	1.16	2.14	0.99	0.88	0.39	0.99
50	5.00	394.00	0.92	3.35	0.99	0.82	0.48	0.99
60	7.50	489.50	0.52	2.00	0.76	0.65	1.09	0.98
70	6.50	550.00	1.29	7.00	0.98	0.81	0.68	0.99
80	3.00	252.00	0.58	2.77	0.99	0.80	0.35	0.99
90	6.50	555.20	1.22	8.03	0.98	0.80	0.73	0.99
100	2.00	84.90	0.14	1.67	0.99	0.69	0.13	0.99
SD	1.92	165.34	0.36	2.29		0.068	0.30	
CV%	43	46	43	63		9	62	

A = transmissivity; S = sorptivity; α = index of sorptivity of soil related to decline of infiltration rate; C = initial infiltration (sorptivity); R^2 = coefficient of determination.

soil without sealing and after prolonged ponding, the flux of water tends to approach the hydraulic conductivity (Pla, 2007). Water transmissivity showed high variation along the slope (CV 43%) Mulla and McBratney (2001) (Table 2). The index of sorptivity was highly related to the infiltration capacity (α); a higher value of α indicates a higher sorptivity rate of the soil. The α values showed low variability (CV < 15%) with topographic

position. The initial infiltration sorptivity of Kostiakov's model ranged from 0.03 to 1.09 with the values showing high variation with topographic position (CV > 35%).

The observed (field) values of initial infiltration showed no disparity with the initial infiltration parameter value and the predicted initial infiltration of Philip's model (Figures 2 and 3). There was disparity when the field values
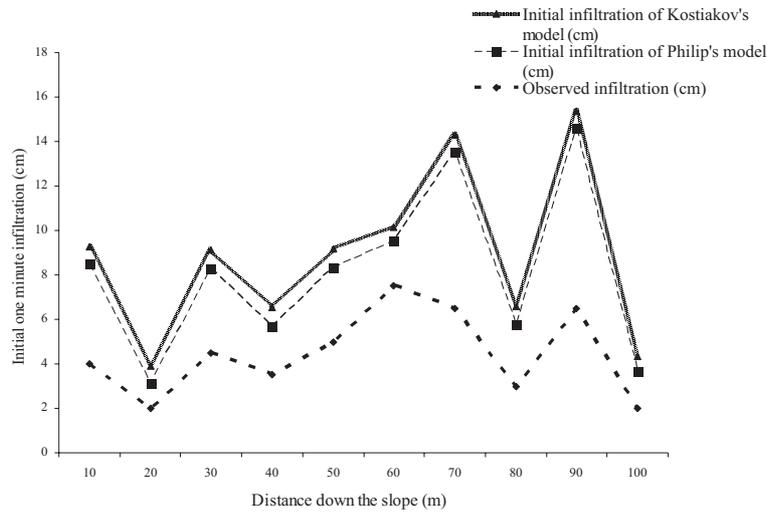

Figure 2 Comparison of observed initial infiltration with initial infiltration predicted by Philip's and Kostiakov's models.
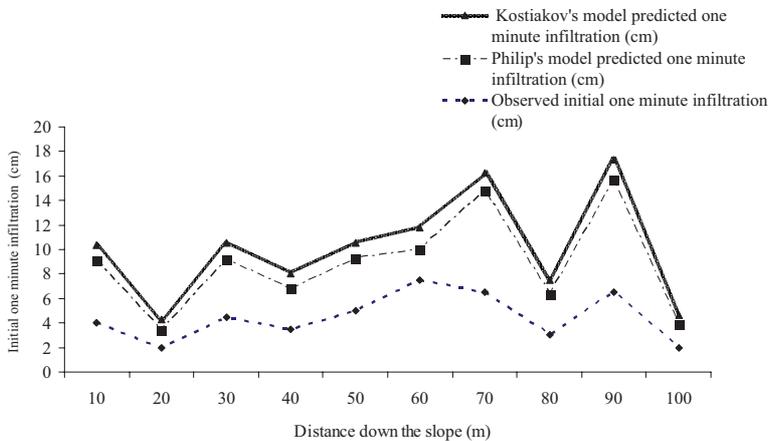

Figure 3 Comparison of observed initial one-minute infiltration with initial one-minute infiltration predicted by Philip's and Kostiakov's models.

were fitted to Kostiakov's model. The Chi square goodness of fit expresses the amount of disparity between the measured and predicted values of the two models. It was observed that the calculated Chi square values for 9 out of 10 topographic infiltration positions for Philip's model were lower than the table values of Chi square at the 0.05 and 0.01 levels of significance. This shows that the disparity between the measured and the predicted values was not significant so Philip's model can be used to predict the initial infiltration into this soil. The predicted initial infiltration for Kostiakov's model was not significantly different from the observed value for 5 out of 10 of the infiltration topographic positions. This shows that Philip's model is more suitable for predicting the initial water infiltration into the Inceptisols in a humid forest zone.

The differences between the observed values of cumulative infiltration and those predicted by Kostiakov's model were greater than those between the observed values compared with those predicted by Philip's model (Figure 4). The Chi square goodness of fit showed there was no disparity between measured and predicted cumulative infiltration under Philip's model for 7 out of 10 of the topographic positions studied. With Kostiakov's model, only 3 out of the 10 infiltration topographic positions showed no disparity between measured and predicted cumulative infiltration. This shows that Philip's model was more suitable than Kostiakov's model for predicting the cumulative infiltration under the Inceptisols in a humid forest zone.

Contrary to the present study, Mustafa *et al.* (2003) reported that observed cumulative infiltration from the field compared well with the predictions by Kostiakov's model. However the soil type used for that study was not reported and the results observed from the present study (and from studies by other researchers mentioned earlier) indicate that not all models are applicable in all soils.
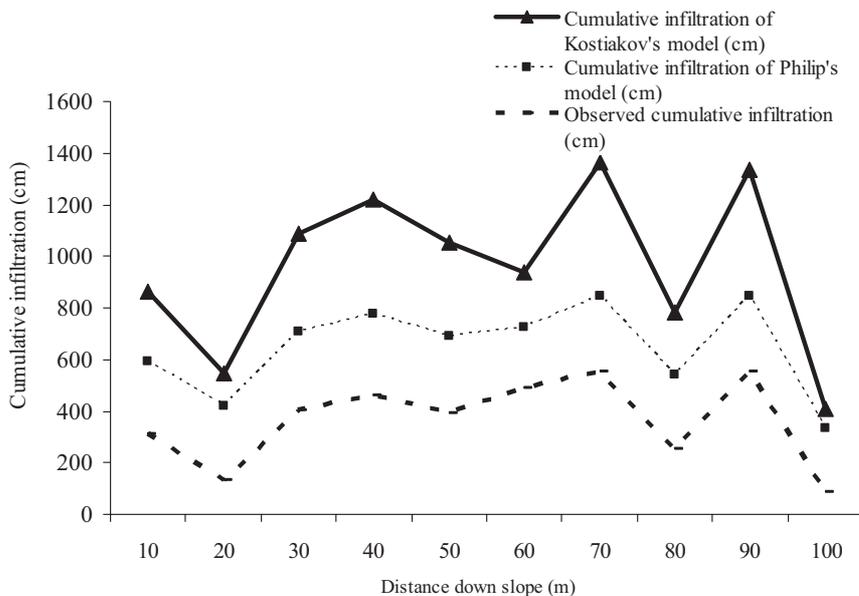

Figure 4 Comparison over elapsed time period of 6 h of observed cumulative infiltration and cumulative infiltration predicted by Philip's and Kostiakov's models.

CONCLUSION

The Philip's infiltration model was more suitable than Kostiakov's infiltration model for predicting water infiltration into Inceptisols in the forest humid zone in Nigeria. Consequently Philip's model is recommended for use for Inceptisols in humid forest zones. This could be of immense importance in the design and planning of irrigation projects. For instance once the values of the infiltration rate are constant, the basic infiltration rate has been reached and the established curve can be used to determine how long it will take to infiltrate a certain amount of water. This information is important when determining irrigation duration and water management.

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