PREDICTABILITY OF PHYSICAL AND EMPIRICAL SOIL INFILTRATION MODELS ON A SANDY SOIL IN LAFIA, SOUTHERN GUINEA SAVANNA ZONE OF NIGERIA

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Abstract

Prediction of soil infiltration is a major problem due to its variability and proper selection of the technique used to determine the parameters of the models which depend on the local soil characteristics. Field experiments were conducted to assess the predictability of Kostiakov-Lewis and Philip's models on a sandy soil and to compare the measured and predicted cumulative infiltration using these models under local condition. A double ring infiltrometer was used to carry out three measurements each at 30 m interval in three different strips of 100m long and 30 m wide. A total of nine infiltration tests were conducted in the field. From the values of cumulative infiltration and time interval measured, the models parameters were determined. Using the two calibrated soil infiltration models, predictions of the cumulative infiltration were made for each strip. GENSTAT'package was use to analyze the results. The result of the study showed that the Kostiakov-Lewis model predicted the cumulative infiltration better than Philip's model with the average values of the slope between the measured and predicted far strips A, B and Cos (1.042,1.065,1.073) and (1.170,1.202,1.221), respectively and coefficient of determination, r^2 (0.999, 0.996, 0.995) and (0.993, 0.988, 0.986) respectively. The t~test result at 5% *level is not significant with values (-0.806, -0.851 and -0.717) and (-1.779,1.688 and-1.689) for Kostiakov-Lewis and Philip's models respectively and for strip A, B and C respectively which meant that both models were within the acceptable error limit.*

Keywords: Infiltration model, sandy soil, ring infiltrometer.

INTRODUCTION

Infiltration, a major component of the hydrologic cycle, is a key link in the process of water transformation of farmland ecosystem. Through . infiltration rainfall or irrigation water is turned into soil water and used to sustain the growth of crops or vegetation, replenish ground water supply to wells, springs and streams (Rawls *et al*, 1993). The process of water infiltration through soil surface is a complex interaction between rainfall or irrigation intensities, soil type and surface condition governing the rate at which water passes through the soil (Horton, 1940).

Infiltration characteristic of soil is one of the important parameters in the design, evaluation and management of an irrigation system as it is the mechanism that transforms and distributes water from the surface to the soil profile (Mustafa *et al.*, 2003). The characteristic determines advance and recession time, depth of infiltration and the uniformity and efficiency of water application during irrigation (Jobling & Turner, 1973). The ability to quantify infiltration is of great importance in ; watershed management. Quantification of infiltration is necessary to determine the availability of water for crop growth and to estimate the amount of additional water need for irrigation (Turner, 2006). Also by understanding the infiltration rate of a field, measures can be taken to increase infiltration rate and reduce the erosion and flooding caused by overland flow. The maximum rate at which a soil in any given condition is capable of absorbing water is called infiltration rate, which is a very important parameter to be determined during design of irrigation system, especially surface irrigation system. Infiltration rate is the soil characteristics determining the maximum rate at which water can enter the soil under specific conditions, including the presence of excess water. Evaluation of soil infiltration characteristics and determination of the soil's infiltration capacity (steady infiltration rate) are required for increased irrigation water use efficiency, planning land disposal of waste water, design irrigation systems, decide appropriate conservation (decreased water and soil losses) techniques in agricultural lands and hydrological modeling of runoff process (Haghighi *et al,* 2010).

The process of infiltration is a complex and physical one (Igbadun & Idris, 2007). Infiltration modeling approaches are often separated into two categories: physical and empirical models. Physical models such as those of Philip and Green and Ampt apply the physical principles governing infiltration for simplified boundary and initial conditions. They entail ponded surface condition from the time zero on (Hillel, 1998), and are based on assumption of uniform movement 'of water from the surface down through deep homogenous soil with a well defined wetting front; the assumptions are more valid for sandy soils than for clay soils (Haver-kamp *et at*, 1987). Equations that are physically based use parameters that can be obtained from soil water properties and do not require measured infiltration data. The empirical models such as Kostiakov-Lewis, Horton and Holtan tend to be less restricted by assumptions of soil surface and soil profile condition, but more restricted by the condition for which they were calibrated since their parameters are determined based on actual field measurement infiltration data (Hillel, 1998). Owing to their simplicity and minimal data requirement, the most commonly used infiltration equations in modeling are the empirical relationship (Zerihum & Sanchez, 2003) and particularly those of the Kostiakov-Lewis and modified Kostiakov-Lewis equation (Isrealsen & Hansen, 1962; McCornick *et al*, 1988; FAO, 1993).

Several studies have been conducted to establish model parameters, validate models or compare model efficiencies and applicability for different soil conditions (Ahmed & Dura, 1985; ssMudiare &Adewumi, 2000; Oku & Alyelari, 2011). However, the need for continuous in-depth and field specific study of the applicability of infiltration equations cannot be over emphasized since model parameters and performance vary for different soils and with time. Through analyzing the infiltration models and combining research results (Furman *et al.*, 2006; Igbadun & Idris, 2007; Haghighi *et al*, 2010; Oku &Alyelari, 2011), the explicit credible infiltration models Kostiakov-Lewis and Philip's equations were chosen based on simplicity, minimal data requirement and assumptions. In order for such models to be adopted by practitioners, confidence in the model predictions needs to be demonstrated, with agreement between measured values and those predicted by the model. Prediction of soil infiltration is a major problem due to its variability and proper selection of the technique used to determine the parameters of the models which depend on the local soil characteristics. There has been no calibration or validation of any infiltration model for the College of Agriculture Lafia Experimental Farm, thereby creating a dearth of information that can be easily applied to irrigation system design, evaluation and management in order to optimize for specific field condition. This research work was conducted to determine infiltration parameters of the Kostiakov-Lewis and Philips' infiltration models and determine their suitability to the specific field condition in the College of Agriculture Experimental Farm.

The objective of the study therefore, is to assess the predictability of the Kostiakov-Lewis and Philips' infiltration models under local condition and to compare the observed and predicated cumulative infiltration using calibrated models.

MATERIALS AND METHODS

Study Area

The experiment was carried out at the Research and Teaching Farm of the College of Agriculture, Lafia (08° 35' N, 08° 33' E), located in the Guinea Savanna i Zone of North Central Nigeria at an attitude of 177 m above sea level. The mean monthly maximum and minimum temperature range between 35.1 °C 36.4 °C and 20.2 °C 20.5 °C, respectively while the mean monthly relative humidity and rainfall are 74.67 % and 168.90 mm respectively.

Field Measurements

Field experiment was carried out at the College of Agriculture Experimental Farm, Lafia. The portion of the field used was 100 m long by 90 m wide. The field was divided into three strips of 100 m by 30 m Three points at 30m interval the length was marked out and infiltration test carried out at those points; for each strip. Soil samples were also collected from] the adjacent area of the marked points at 0-15 cm and 15-30 cm depths for soil analysis.

Infiltration measurement was carried out using **al** double ring infiltrometer. The infiltrometer **wasl** driven into the soil to a depth of 10 cm and **al** measuring tape was fixed inside the inner cylinderj from where readings were taken. Readings then taken at intervals to determine the amount (water infiltrated during the time interval with anj average infiltration head of 5 cm maintained. The! infiltration rate and the cumulative infiltrat were then calculated.

Moisture content was determined by gravime method. The soil texture of the site was deter by mechanical analysis method. The United Statt Department of Agriculture (USDA) Textural Classification Triangle was used to classify the i based on the results obtained from the analysis.

Infiltration Models
Kostiakov-Lewis equation

Kostiakov (1932) and Lewis (1938) independently tproposed a simple empirical infiltration equation based on curve fitting data. It relates infiltration to time as a power function as presented by Equation (i).

$$Z = kt^{a} \quad (i)$$

where,
Z= cumulative infiltration (cm/hr)
t=time from start of infiltration (min)
k, a= constants that depend on the soil and initial conditions.

Philip's equation

Philip (1957) proposed that by truncating his series solution for infiltration from a pounded surface after the first two terms, a concise infiltration equation could be obtained which would be useful for small times.
The resulting equation is

$$Z = St^{M} + At \quad (2)$$

where:
S"Sorptivity
A « Parameter related to saturated hydraulic conductivity
Z and t are as previously defined in Equation (1).

Estimation of Infiltration Characteristics

The cumulative infiltration at any time, t can be estimated from the Kosliakuv-Lewis infiltration equation as Z = kt", which shows a non-linear relationship. Taking logs of both sides, this expression can be written as;
logZ = logk+alogt.
Plotting the log of cumulative infiltration against log of time, which gives a linear relationship, the values of (k) and (a) were obtained as the intercept and slope respectively.
Philip's equation expresses cumulative infiltration as Z •» St^{M} + At. To determine the parameters, the equation was divided through by t, therefore, becomes
$Z/t = St^{o5} + A$
Thus, the linear relationship between the terms (Z/t) was plotted against ($t^{"OJi}$). Parameters (S) and (A) were obtained as the slope and intercept of the best line of fit respectively.

Statistical Analysis

The accuracy of the different equations for predicting the cumulative infiltration were evaluated by comparing the observed values of measurement on the field and the predicted values based on the fitted equation. The data were then subjected to a linear regression analysis and the t-paired test using GENSTAT package.

RESULTS AND DISCUSSION

Soil Properties

The result of analysis of soil physical properties of the study area is presented in Table 1. The results show that the texture of the field surface (0 -15) cm and the sub-surface (15 - 30) cm depths for the three sampled strips were predominantly sandy, having sand fraction that ranged from 88-92 %. The average bulk densities werel.54 g/cm^3 arid 1.55 g/cm^3 with average porosities of 42.01 % and 41.63 % at 0 15 cm and 15 30 cm depths, respectively. The average initial antecedent moisture contents were 4.43% and 4.97% at the various depths, respectively.

Infiltration Parameters

The average infiltration parameters of the Kostiakov-Lewis equation and Philip's equation for the three strips in the field are shown in Table 2. The average values of the time exponent of Kostiakov-Lewis equation were observed to range between 0.781 and 0.785 which is in accordance to the theory of infiltration that puts the value to lie between 0 and 1. However, most observed values lies between 0.2 and 0.9 (Blair & Reddell, 1983; Serralheiro, 1988). The values of these parameters do not possess any specific physical meaning; however they reflected the effect of soil physical properties of influence on infiltration as well as antecedent soil moisture content and surface conditions (Zerihun & Sanchez, 2003). The equation describes the measured infiltration curve and given the soil and initial water condition, allows prediction of an infiltration curve using the same constants developed for those conditions.

Performance Indices

Evaluating the performance of the soil infiltration models involves determining their overall accuracy to predict infiltration for a given field condition. The performances of the two models at the college of agriculture, farm were quantified by calculating the slope, e", absolute mean difference (AMD), standard error of mean (SEM), coefficient of determination, R^2, t-paired test value, t and absolute error E. Table 4 shows the average values of the performance indices of the two equations for the three strips.

In establishing the Kostiakov-Lewis and Philip's infiltration model parameters, the predicted cumulative infiltration by the models were compared with the measured values. Considering the limited number of infiltration event (9) monitored in the evaluation of the models, the average values of the slope between the measured and predicted by Kostiakov-Lewis and Philip's

Table 1: Average soil properties at different depths. . ;:j

Strip	Depth (cm)	Clay(%) ,	Silt(%)	Sand (%)	Texture	Bulk density (g/cm^3)	Porosity	MC(%!
A	0-15	8.6	3.4	88	Sandy	1.46	44.90 .	
	15-30 ,	6.6	3.4	90	Sandy	1.43	46.03	5.30 1
B	0-15	8.6"	1.4	90	Sandy	1.74	34,33	4.20 ;
	15-30	"6,6	1.4	92	Sandy	1.75	33.96	5.20 ;
C	0-15	10.6	1.4	88	Sandy	1,41	46.79	4.40
	.: 15-30	6.6	1.4	92	Sandy	1.46	44.90	4.40

MC - Moisture content

Table 2: Average values of Kostiakov-Lewis equation and Philip's equation parameters for the three strips

Strip,	k	a	S	A
A	1.3868	0.781	1.211	0.400
B	1.55%	0.784	1.302	0.466
C	1.5171	0.785	1.241	0.462

Table 3: Values of the various performance indices for the two infiltration models in each strip

Strip	Equation	Slope	AMD	S.D	SEM	«*	t	E(%)
A	.KL	1.042	0.2919	1.4482	0.3620	0.999	-0,806	4.13
	P	1.170	2.3688	5.3266	1.3317,	0.993	-1.779	9.16
B	KL	1.065	0.5750	2.7020	0.6755	0.996	-0.851	5.35
	P	1.202	3.1187	7.3913	1.8478	0.988	-1.688	10.35
C	KL	1.073	0.5438	3.0316	0.7579	0,995	-0.717	6,09
	P	1.221	3.3125	7.8442	1.9611	0.986	-1.689	11.09

KL-Kostiakov-Lewis equation P-
Philip's equation

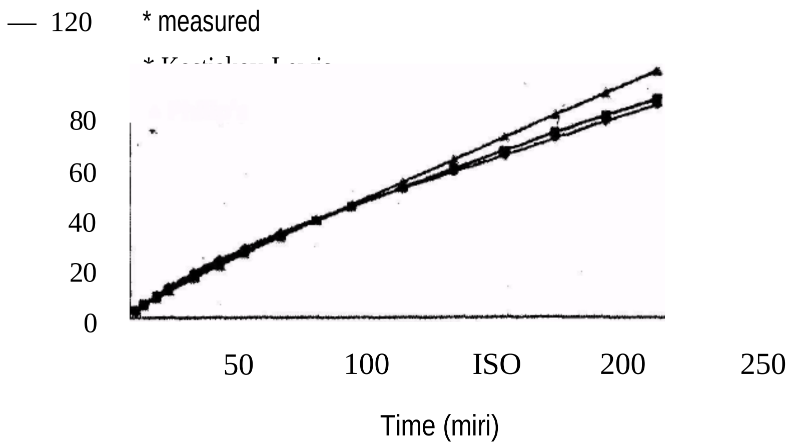
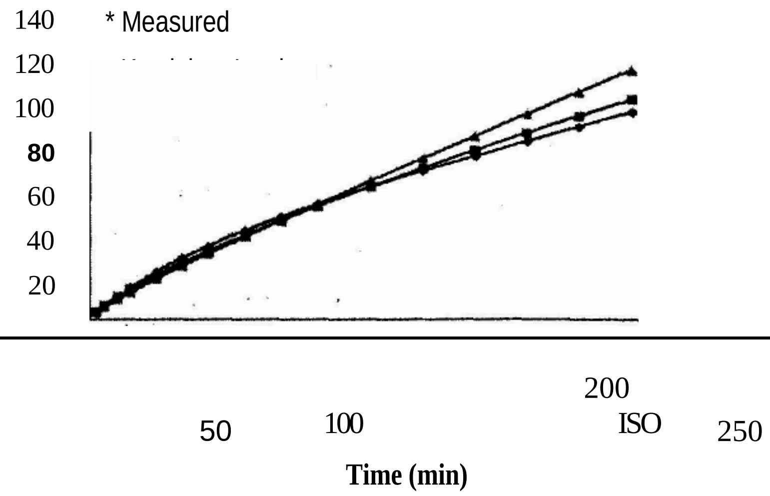


Fig la: Cumulative infiltration predicted by Kostiakov-Lewis and Philip's model with that measured for strip A ,



Figlb: Cumulative infiltration predicted by Kostiakov-Lewis and Philip's model with that measured for strip B models for strip A, B and C were (1.042,1.065,1.073) and (1.170,1.202,1.221), respectively which show that the model predicted data closely agree with the measured data for all strips. Their coefficients of determination, r^2 (0.999, 0.996, 0.995) and (0.993, 0.988, 0.986) respectively, were very high. This implied that the two models were able to pi edict water infiltration in the soil under study very well. The standard error of mean (SEM) between "the measured and predicted cumulative infiltration by Kostiakov-Lewis model for strip A, B and C were 0.3620,0.6755 and 0.7579, respectively while 1.3317, 1.8478 and 1,9611 were the standard error of mean between measured and predicted cumulative infiltration by Philip's model, respectively.

The t-test result show that the table value for 15 degrees[1] of freedom and 5% level of significance (2.131) was higher than the calculated average values (-0.806, -0.851 and -0.717) and (-1.779,1:688 and -1.689) for Kostiakov-Lewis and Philip's equations respectively and for strip A, B and C respectively. It implied that the difference between the means of the predicted values by the models and the measured values were not statistically significant at 5% level of significance. Therefore, the measured values and those predicted are at par. Figures la to Ic for strips A, B and C, respectively show that the models had reasonable predictions of the measured data except for Philip's model with little over prediction as from the 148 minutes for all the strips but still within the acceptable range of absolute error (9.16%, 10.35% and 11.09%) which are less than 12% suggested by Mudiare (1982). This means the Kostiakov-Lewis equation is superior to the Philip's equation for predicting infiltration at this site to plan for good irrigation scheduling and evaluations of surface irrigation system. This agrees with the findings of some research (Igbadun & Idris, 2007; Musa & Adeoye, 2010). The reason could be that the kostiakov-lewis equation describes both the actual and theoretical inf iltration accurately on small to medium time scale (Philip, 1957; Fok & Bishop, 1965). This may also be associated to the assumption on which Philip's equation was established. He assumed infiltration into a uniform homogenous soil (Philip and Farrell, 1964, Serralheiro, 1995) which is often not satisfied in the field.

CONCLUSION

In conclusion, for the prediction of cumulative infiltration, the performance of the Kostiakov-Lewis infiltration model and Philip's infiltration model were satisfactory though Kostiakov-Lewis model was found to be the best infiltration model to simulate infiltration under the field condition* encountered in the present study. Therefore, the application of these equations under verified field conditions leads to the determination of the appropriate infiltration characteristics for the two equations that would optimize infiltration simulation, irrigation performance and minimize water wastage.

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