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Performance of Selected Water Infiltration Models in Sandy Clay Loam Soil in Samaru Zaria

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Abstract- The performance of selected water infiltration models were evaluated and reported herein. Ten (10) water infiltration models consisting of five (5) empirical (Philip (PH), Kostiakov (KT), Modified Kostiakov (MK), Kostiakov-Lewis (KL) and Natural resources conservation service(NRCS)), three (3) physically based (Green-Ampt (GA), Smith-Parlange (SP), Talsma-Parlange (TP)) and two (2) semi – empirical (Swartzendruber (SW) and Horton (HT)), were evaluated for sandy clay loam soil. The aim was to study the ability of the models in accurately predicted measured cumulative infiltration. The study was carried out at the Agricultural Engineering experimental plot at Samaru, Zaria. The soil was predominantly Sandy clay loam. The results showed that the coefficient of determination (r^2) between the models simulated and field measured cumulative infiltration ranged from 0.905 to 0.998.

Keywords: *water infiltration, empirical models, sandy clay loam, samaru zaria.*

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Abstract- The performance of selected water infiltration models were evaluated and reported herein. Ten (10) water infiltration models consisting of five (5) empirical (Philip (PH), Kostiakov (KT), Modified Kostiakov (MK), Kostiakov-Lewis (KL) and Natural resources conservation service(NRCS)), three (3) physically based (Green-Ampt (GA), Smith-Parlange (SP), Talsma - Parlange (TP)) and two (2) semi – empirical (Swartzendruber (SW) and Horton (HT)), were evaluated for sandy clay loam soil. The aim was to study the ability of the models in accurately predicted measured cumulative infiltration. The study was carried out at the Agricultural Engineering experimental plot at Samaru, Zaria. The soil was predominantly Sandy clay loam. The results showed that the coefficient of determination (r^2) between the models simulated and field measured cumulative infiltration ranged from 0.905 to 0.998. The value of the modeling efficiency (E) ranged from 0.623 to -7.145 while the. The Modified Kostiakov's model had the overall best performance, Green-Ampts model had the best performance amongst the physically based models and the modified Kostiakov's and Swartzendruber's model had the best performances in the empirical and semi-empirical group respectively.

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I. Introduction

Infiltration is the process of water movement from the ground surface into the soil and is an important component in the hydrological cycle (Haghaibi *et. al.,* 2011).

Adequate water resource management is essential for stable and efficient agriculture. Hence, efforts are being directed towards water management and conservation activities such as irrigation and control of flood and erosion. Realistic planning of these water management activities requires sufficient information on the rate at which different soils take up water under different conditions. Data on rates of infiltration of water into soils can be used to supplement other soil information which could assist soil scientists, engineers, hydrologists and others to deal more effectively with a wide spectrum of water resource management and conservation problems (Ajayi, 2015*;* Mishra *et al*., 2003).

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Infiltration characteristics of soils can be quantified by direct measurement on the field and/or when field infiltration data are fitted mathematically to infiltration models (Oku and Aiyelari, 2011). Lili*et al.,* (2008) reviewed the commonly used direct methods for measuring soil infiltration which include: single ring and double ring infiltrometers, mariotte-double ring infiltrometer, disc permeameter, rainfall simulator, runoff-on-ponding, runoff-on-out and linear source methods, the results obtained from field infiltration test and soil analysis are used for infiltration modeling.

Infiltration modeling approaches are often separated into three categories: physically based, approximate/semi-empirical (analytical), and empirical models. The physically based approaches use parameters that can be obtained from soil water properties and do not require measured infiltration data. The evaluation of semi-empirical/analytical models are purely mathematical or graphical, it is called semi-empirical because their evaluation process involves the use of the asymptomatic or steady state infiltration capacity unlike the physically based models that depends strictly on soil water characteristics. Empirical models tend to be less restricted by assumptions of soil surface and soil profile conditions, but more restricted by the conditions for which they were evaluated, since their parameters are determined based on actual field-measured infiltration data (Hillel, 1998; Skaggs and Khaleel, 1982).

Researchers have condensed soil infiltration characteristics into a number of simple mathematical models (Ajayi, 2015), confidence in the model predictions needs to be demonstrated through adequate field verification, with agreement between measured values and those predicted by the simulation model (Ogbe*et al.,* 2008).

The aim of this paper is to assess the performance of ten(10) widely adaptable infiltration models for Sandy Clay loam soil. The selected models are: Philip (1957), Kostiakov (1937), Horton (1940), Modified Kostiakov (1978), Kostiakov-Lewis (1982), Green-Ampt (1911), Swartzendruber (1972), Smith-Parlange (1978), Talsma-Parlange (1972) and Natural resources conservation service (NRCS 1989) models. The specific objectives are to estimate the models parameters and to compare the cumulative infiltration depths estimated by the models with those measured in the field.

II. Materials and Methods

The study was carried out at the Department of Agricultural Engineering experimental field, Samaru, Zaria, Nigeria. Zaria is located on latitude 11° 11'N and longitude 07° 38'E, at an altitude of about 668 m above sea level. The portion of the field used was 200m long by 50m wide. Six points was chosen and soil samples were collected at 0-15 cm and 15-30 cm depths for soil analysis. Infiltration measurement was carried out using a double ring infiltrometer. The infiltrometer was driven into the soil to a depth of 15cm and a measuring tape was fixed inside the inner cylinder from where readings were taken. Readings were then taken at intervals to determine the amount of water infiltrated during the time interval with an average infiltration head of 5cm maintained. The infiltration rate and the cumulative infiltration were then calculated. The soil texture of the site was determined by mechanical analysis method. The United States Department of Agriculture (USDA) Textural Classification Triangle was used to classify the soil based on the results obtained from the analysis.

Table 1: Average soil physical characteristics of the strips

Strip	B.D(g/cm^3)	M.C(g/g)	K_s(cm/hr)	%Clay	%Silt	%Sand
CM	1.53	0.06	7.37	23.2	17.8	59.0
PM	1.21	0.12	5.92	24.0	20.0	56.0
CT	1.81	0.05	4.58	26.0	14.0	60.0

**BD = Bulk density; MC =Moisture content; K_s= Saturated Hydraulic Conductivity; C = % Clay ;Si = % Silt; Sa = % Sand;*

a) *Infiltration Models Studied*

The following infiltration models were assessed for finding best fitting model to observed field infiltration rate data, Table show the models and their respective parameters.

Table 2: Summary of Equations and fitting parameters of the Ten(10) models tested

S/N	Model Name	Cumulative Infiltration equation	Fitting parameters
1	Kostiakov(1932)	$I = kt^a$	*k and a*
2	Green-Ampt(1911)	$I = Kt + \psi\Delta\theta \ell n I\left[1+\frac{I}{\psi\Delta\theta}\right]$	*ψ, I and i*
3	Modified Kostiakov (1978)	$I = kt^a + b$	*k_1, a_1 and b*
4	Philip(1957)	$I = S\sqrt{t} + At$	*S and A*
5	Horton (1940)	$I = f_c t + \frac{f_0 - f_c}{k}[1 - e^{-kt}]$	*k, f_0 and f_c*
6	Kostiakov-Lewis (1982)	$I = kt^a + f_c t$	*A_2, k_2 and f_c*
7	NRCS Model (1989)	$I = at^b + 0.6985$	*a_3 and b*
8	Talsma & Parlange (1972)	$I = St^{1/2} + \frac{K_s t}{3} + \frac{K_s^2 t^{3/2}}{9S}$	*S and k_s*
9	Swartzendruber (1972)	$I = f_c t + \frac{c}{d}[1 - exp(-dt^{0.5})]$	*c and d*
10	Smith & Parlange (1978)	$I = k_s t\left[\frac{C_o}{k_s I} + 1\right]$	*C_o and k_s*

Where: I = cumulative infiltration (cm), i = infiltration rate, t= time from the start of infiltration (hr), and a, a_1, a_2, a_3, and k, k_1, k_2 are empirical parameters that need to be estimated. ψ = soil suction head at the sharp wetting front (cm);$\Delta\Theta$ = the change in water content (θ_s - θ_i) (g/g);θ_s = final moisture content or saturation moisture content(g/g);θ_i = initial moisture content before water infiltration (g/g);k_s = saturated Hydraulic conductivity (cm/hr); b = rectifying factor, S (cm/hr$^{1/2}$) = Sorptivity, A (cm/hr) =Transmitivity, f_0 = initial infiltration rate; f_c = steady state infiltration rate; k= Horton's decay constant specific to the soil, c = 0.6985 according to NRCS, *c* and *d* are Swartzendruber' sempirical constants, C_o = Soil's Transmitivity (cm^2/hr).

b) *Estimation of model parameters and model validation*

The averages of the cumulative infiltration depth 'I' and the cumulative infiltration time't' were used in the estimation of the models' parameters. Each model was first transformed into its linear equivalent in which 'I' and 't' are the dependent and independent variables, respectively, and the coefficients of the linear functions are the model parameters to be estimated, the physically based models and analytical models were also evaluated following standard procedures.

The values of the parameters estimated were then incorporated into the respective models and the capability of each model to simulate cumulative infiltration depth for each strip was evaluated by comparing the models simulated data with field-measured data. The field-measured data used for the comparison were those that were not previously used in determining the models parameters. The validation to check the closeness between the field-measured and model simulated cumulative infiltration depths were analyzed using the Root mean square error (RMSE) (Mahdian and Gallichand 1995), coefficient of determination (R^2) (Steel and Torrie 1960) and the Nash-Suctlife's (Nash and Sutcliffe 1970) statistical indices.

Table 3: The Average values cumulative infiltration for the entire strip

Time (min)	Strip A	Strip B	Strip C	Strip D	Strip E	Strip F
3	1.80	1.60	1.80	1.40	1.30	2.00
5	3.30	2.60	2.50	2.30	1.90	3.00
10	3.80	3.60	3.00	4.00	3.40	4.50
20	4.80	6.10	4.20	5.60	5.40	7.00
30	6.30	7.60	5.90	6.90	6.40	8.50
45	7.90	9.10	7.20	8.70	8.10	10.50
60	8.90	12.10	8.20	9.70	9.90	12.60
90	10.40	14.60	10.40	12.20	12.00	14.60
120	12.40	16.10	11.80	14.30	13.10	16.10
150	13.90	17.70	14.40	15.80	14.60	18.10
180	15.30	19.50	15.50	17.10	16.50	19.10
210	16.30	20.50	16.40	18.10	17.90	20.30
240	16.80	20.90	17.20	18.40	18.90	20.80

III. Results and Discussion

Tables4 and 5 below shows the models' simulated cumulative infiltration depth. The coefficients of determination (r^2) between the field-measured and model simulated data were very high (> 0.90) which implies that the ten models were able to simulate water infiltration in the study area adequately. The values of E (Nash-Sutcliffe's modeling efficiency) ranged from -7.145 to 0.978 for the entire study area, Kostiakov's model with the value of 0.978 gave the closest agreement between observed and predicted values while Horton and Swartzendruber's model showed the poorest agreement with values of -7.145and 0.623 respectively. The physically based models also showed good performance, and this shows their reliability in field application. To further check the discrepancies between the predicted and the measured values, Root Mean Square Error (RMSE) was used.

The result of the RMSE shows that Kostiakov and Modified Kostiakov's model had the least error in comparing the predicted values with field measured values followed by Philip's model The semi-empirical models which are Swartzendruber and Horton's model were poor in their prediction 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. Philips model performed better than Kostiakov, this is contrary to the work by Igbadun and Idris (2007), who observed that classical Kostiakov (1932) model, fitted experimental data better than Philip (1957) model for a hydromorphic soil at Samaru, Nigeria.

The result of this study agrees with the findings of Al-Azawi (1985), who evaluated six infiltration models on a relatively homogenous, coarse-textured soil. He found that Philip's model gave a very good representation of the infiltration while Kostiakov, modified Kostiakov, Green-Ampt, and Holtan-Overton performed in that order respectively. Berndtsson (1987) studied the application of Infiltration Equation to a Catchment with Large Spatial Variability in Infiltration" compared two commonly used infiltration equations on a heavy calcareous clay soil. The result showed that the Horton equation displayed a slightly better fit to observed infiltration as compared with Philip's equation. Hsu *et al.,* (2002) evaluated three models (Horton, Philip and Green-Ampt) for three soil types to assess the models based on Richard's equation. Result demonstrated that all three equations provided similar fits to the numerical results, but the Horton model differed most as compared to the other two models in terms of infiltration rate.

For the purpose of this study empirical, semi-empirical and physically based models where used, Modified Kostiakov, Swartzendruber and Green-Ampt's model had best performance in their respective groups using the RMSE indices. Mbagwu (1993) recommended the modified Kostiakov equation for routine modeling of the infiltration process on soils with rapid water intake rates. The Kostiakov and modified Kostiakov equations tend to be the preferred models used for irrigation infiltration, probably because it is less restrictive as to the mode of water application than some other models.

Table 4: Estimated values for the model parameters

Model	Estimated Parameter
Kostiakov (1932)	k=9.303 a=0.530
Modified Kostiakov (1978)	k=9.992 a=0.627b= -0.54
Kostiakov-Lewis (1982)	k=3.435 a=0.119 fc= 4.58
Philip (1957)	S=8.731 A= 0.492
Natural resources conservation service (1989)	k=8.336a=0.6168 c=0.6985
Horton (1940)	k= -1.184 f_o = 35.0f_c= 4.5
Green-Ampt (1911)	k_s= 4.58 $\Delta\theta$ = 0.314 ψ= 101.57
Talsma-Parlange (1972)	K_s= 4.58 S= *10.68*
Swartzendruber (1972)	*c= 0.758 d= 0.018* f_c *= 4.5*
Smith-Parlange (1978)	C_o*= 57.73*k_s*= 4.58*

Table 5: Observed and Model predicted cumulative infiltration

Time(hr)	Obs	KT	MK	KL	HT	PH	NRCS	GA	TP	SW	SP
0.05	1.57	1.90	2.02	1.91	1.92	1.98	2.01	2.18	2.42	0.39	1.75
0.08	2.40	2.49	2.50	1.87	3.15	2.56	2.50	2.86	3.13	0.59	2.27
0.17	3.97	3.60	3.44	2.02	6.04	3.65	3.46	4.14	4.46	1.06	3.26
0.33	6.00	5.20	4.90	2.58	11.14	5.21	4.93	6.00	6.37	1.94	4.70
0.50	7.27	6.44	6.10	3.25	15.46	6.42	6.14	7.50	7.87	2.78	5.85
0.75	9.10	7.99	7.64	4.30	20.77	7.93	7.68	9.36	9.72	4.03	7.29
1.00	10.73	9.30	9.00	5.39	25.02	9.22	9.04	10.96	11.32	5.25	8.56
1.50	12.93	11.53	11.39	7.60	31.31	11.43	11.40	13.80	14.05	7.67	10.76
2.00	14.50	13.43	13.49	9.84	35.80	13.33	13.48	16.27	16.41	10.06	12.71
2.50	16.17	15.12	15.40	12.09	39.28	15.03	15.37	18.54	18.53	12.43	14.49
3.00	17.57	16.65	17.17	14.36	42.22	16.60	17.11	20.64	20.49	14.79	16.15
3.50	18.77	18.07	18.84	16.62	44.85	18.05	18.75	22.64	22.32	17.14	17.73
4.00	19.37	19.39	20.42	18.89	47.31	19.43	20.29	24.55	24.05	19.49	19.24
	R^2	0.993	0.983	0.905	0.917	0.991	0.984	0.986	0.990	0.931	0.985
	RMSE	0.894	1.017	3.568	17.172	0.946	0.995	2.177	2.079	3.693	1.416
	E	0.978	0.971	0.648	-7.145	0.975	0.973	0.869	0.881	0.623	0.945

IV. Conclusions

The parameters and prediction accuracy of ten infiltration models was carefully studied, among the ten infiltration models studied, Modified Kostiakov model and Philip's model performed better in their ability to predict cumulative infiltration, although the other models provided good overall agreement with the field measured cumulative infiltration depths and are therefore capable of simulating infiltration under the field conditions in this study, Horton's model performed well initially at 20 minutes after the test began, however it over-predicted cumulative infiltration after this time. Consequently, the application of these equations 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.

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