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Goodness of fit of three infiltration models of a soil under long-term trial in Samaru, Northern Guinea Savanna of Nigeria

A. H. Girei[1]*, A. Abdulkadir[2] and N. Abdu[2]

[1]Department of Soil Science, Faculty of Agriculture, Federal University Dutse, P.M.B. 7156, Jigawa, Nigeria.
[2]Department of Soil Science, Faculty of Agriculture, Institute for Agricultural Research, Ahmadu Bello University, P. M. B. 1044, Zaria, Nigeria.

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Good strategies for water conservation, runoff or flood control and erosion management can be achieved by proper understanding of soil water infiltration characteristics. Three infiltration models Kostiakov's (1932), Philip's (1957) and Horton's (1940) were used to evaluate the infiltration characteristics of soils in a long-term fertilizer experiment in the Northern Guinea Savanna Agro Ecological zone with regard to the effects of long term land use and soil management. A double ring infiltrometer was used to conduct infiltration measurement on ten plots having different combination of Dung (D), Nitrogen (N), Phosphorus (P), and Potassium (K) fertilizer treatments. Thus, the treatments combinations were DNPK, DN, DK, DP, D, NPK, N, P, K and CT (no fertilization). Soils were predominantly sandy loam and bulk density and organic carbon were significantly influenced by the fertilizer combinations. Linear least sum of squares was used to obtain the model fitting parameters. Measured infiltration rates for plots that received dung (singly or in combination with mineral fertilizer) were significantly higher ($p<0.05$) than for the CT plots. Kostiakov's and Philip models showed good agreement with measured infiltration due to large R^2 (0.9956 and 0.986) recorded, respectively except Horton's model, which gave low regression coefficient between measured and calculated data. Based on R^2 values obtained from comparing measured and calculated cumulative infiltration, Kostiakov's and then Philip's equations provided best predictions over Horton. Fitting parameters obtained are suggested for use of site-specific or management-specific solutions of infiltration-related application. Further work is required to obtain reliable fitting parameters for Horton's infiltration equation of the trial field.

Key words: Kostiakov, Philip, Horton, infiltration characteristics, DNPK plots.

INTRODUCTION

Infiltration characteristics of a soil are a useful property required in several hydrology-based studies that describe rate of water entry into the soil. Soil management and cultural practices, which have direct influence on soil

*Corresponding author. E-mail: gireihalilu@yahoo.com.

Table 1. Fertilizer combinations for the various treatments in the experimental plots (Abdulkadir and Habu, 2013).

Treatment	Abbreviation	Rates (kg ha^{-1})		
Dung	D	0	2500	5000
Urea	N	0	67.5	135.0
Single super				
Phosphate (SSP)	P	0	13.5	27.0
Muriate of potash	K	0	29.0	58.0

Each fertilizer applied at 3 levels of 0, 1, 2, (3 x 3 x 3 x 3 = 81). Each row of the application rates represents the level number 0, 1, 2 respectively.

water movement, affect coefficients of determination of infiltration models (Davidoff and Selim, 1986; Franzluebbers et al., 2002). Influence of several factors such as mulching, residue incorporation, soil compaction and bulk density on soil infiltration characteristics have been reported by Davidoff and Selim (1986) and Franzluebbers et al. (2002). They concluded that the predictive ability of these models varies among management and cultural practices, which influence water infiltration into soils. Water infiltration is also believed to increase with reduction in bulk density, establishment of cover crops, mulching, and incorporation of crop residues (Shukla et al., 2003a). Knowledge of soil infiltration characteristics is a required input in increasing irrigation water use efficiency, design of irrigation systems, and decrease water and soil losses, all of which are crucial factors in agriculture (Ogban and Utin, 2014). Infiltration data is also an important parameter in field drainage applications (Haghighi et al., 2011).

However, field measurements of soil infiltration are cumbersome, expensive, time-consuming and give only local scale results (Shukla et al., 2003b; Lake et al., 2009). As such infiltration equations or models offer a viable option to estimate field infiltration characteristics of soils (Shukla et al., 2003a; Abdulkadir et al., 2011). Many infiltration models have been evaluated in different location of the world to test model fit with measured data models (Wudivira et al., 2001; Shukla et al., 2003a). For example, the superiority of Kostiakov (1932) and Green and Ampt (1911) equation over three other equations (Horton, 1940; Holtan, 1961; Philip, 1957) in the evaluation of their predictive abilities of under specific conditions was reported by Turner (2006). Better performance of Revised Modified Kostiakov (2007) was recorded by Mirzaee et al. (2014) in the evaluation of eight infiltration models with different numbers of fitting parameters in different soil texture classes. Shukla et al. (2003a) obtained a better result with the three parameter Horthon equation than nine other infiltration models for soil with different land use and soil management systems. Despites these findings, none of such work was conducted on a long-term fertilizer trial in Samaru, Northern Guinea Savanna of Nigeria. However, earlier work in the region focused on Talsma and Palange (1972), Kostiakov (1932) and Philip (1957) equation used to estimate the infiltration characteristics of soil (savanna Alfisol), such as those by Mudiare and Adewumi (2000), Wudivira et al. (2001) and Abdulkadir et al. (2011).

The objective of this study is therefore to test three infiltration models (Table 1) for their capability of describing water infiltration properties of a soil under a long-term management practices. A second objective was to develop fitting parameters for the three infiltration models.

MATERIALS AND METHODS

Experimental site

The study was carried out on selected plots in the long-term dung (D) and mineral fertilizer (NPK) trial field (that is, DNPK) of the Institute for Agricultural Research, Samaru (latitude11° 16’ North, longitude 07° 63’ East and 686 m altitude) in the Northern Guinea Savanna Ecology of Nigeria. The region is characterized by leached tropical ferruginous soils classified as Typic Halplustalf according to USDA soil taxonomy (Ogunwole et al., 2001). Each plot has a fertilization history with dung (D), nitrogen (N), phosphorus (P), and potassium (K) or their combinations under continuous cultivation from 1950 to 2008 (Ogunwole, 2008). A detailed description of these management practices vis a vis fertilizer combinations and application rates for each of the trial plot is presented in Table 1.

Plot descriptions and history of use

The long-term DNPK experiments was laid in 1949 and full experiments started in 1950 and is the oldest fertilizer experiment in West Africa that was modeled after the Rothamsted long-term trials in the United Kingdom (Amapu, 2007). It has 81 plots in 34 replicated factorial design randomly arranged with a plot size of 220 m^2. There are 27.4 m long ridges, which are 75 cm apart in each plot. Discarded areas of 0.91 m separate the plots from each other. The 81 treatments exist under combinations of DNPK fertilizers. The plots received different management practices that ranges from crop rotation, tillage practices, lime and micro nutrient application, and changes in mineral fertilizers as sources of the major nutrient and cultivated crops. Ogunwole and Ogunleye (2005) gave a detailed description of these management practices. Specifics of

Table 2. Infiltration models studied and parameters associated with each model.

Model no	Name	Equation	Parameter
1	Kostiakov (1932)	$I = Bt^n$	B and n
2	Philip (1957)	$I = St^{1/2} + At$	S and A
3	Horton (1940)	$f_p = f_c - f_0\ f_c\ e^{-\beta t}$	f_c, f_0 and β

the management practices adopted in the selected plot for this study can also be found in Ogunwole and Ogunleye (2005).

Soil sampling and analysis

The surface 20 cm soil depth of 10 selected plots were sampled for disturbed soils in three (3) replicates after sub-dividing each of the main plots (220 m^2) into three equal sized sub-plots. The replicate samples were bulked to obtain a composite sample per plot. The soil samples were appropriately labeled, air dried, ground to pass through 2 mm sieve and stored in polythene bags for routine analyses. Hydrometer method (Gee and Bauder, 1986) was used in determining particle size distribution in the soil. The textural classes of the soil were obtained from the textural triangle of SPAW hydrology model (Version 6.02.72) by computing percentage clay and sand fractions. Soil organic carbon was determined by dichromate oxidation method (Nelson and Sommers, 1982).

Field infiltration test

A double ring infiltrometer consisting of an inner ring of 300 mm in diameter and an outer ring of 550 mm in diameter both of 300 mm in height were inserted 100 mm into the ground. The rings were ponded with water to the brim. The depth of water percolation/infiltration in the inner ring was measured with a ruler at 1 min interval for the first 5 min, 5 min interval for the next 15 min, 30, 60 and 120 min to give a total of 120 min for each of the measurements within a plot. The time was read from a stop watch and all infiltration measurements were carried out in February, 2013 during dry season. Data collected were used to calculate infiltration rate and cumulative infiltration. Measured infiltration data were fitted into 3 different infiltration models (Kostiakov's, Philip's and Horton's) to determine the best-fit model for soils of the study plots. Linear regression analysis of Microsoft excel was used to obtained the model parameters. The model performance was tested by R^2 value obtained when comparing the measured vs. predicted infiltration values using 1:1 regression analysis of the Microsoft excel also. Undisturbed soil samples at depths of 0 to 15 cm and about 50 cm apart from the infiltrometer, were collected using a soil core sampler. The samples were carefully transported to the laboratory for bulk density determinations.

In this study, three infiltration models were examined. The equations representing each model are summarized in Table 2. The first was the Kostiakov (1932) model express as:

$$I = Bt^n$$

where I is the accumulated infiltration (m) and t is time (s). The parameters B and n represent the intercept and slope of logarithmic relations between I and t and they were determined from the logarithmic form of equation earlier by plotting log I against log t, which results in a straight line as the data fits into the equation.

Model 2 in Table 2 was that developed by Philip (1957) express as:

$$I = St^{1/2} + At$$

where I is cumulative infiltration, *S* is the soil water sorptivity, *A* is the soil water transmissivity and t is time. A linear graph of cumulative infiltration divided by $t^{0.5}$ was plotted against the successive time to obtain the parameters A and S as the intercept and slope. After knowing A and S, the new infiltration rate was calculated by fitting these parameters into the Philip equation. Infiltration rate was calculated for each plot and later compared with the field measurement using linear regressions from Microsoft Excel.

Model 3 was an empirical exponential infiltration equation proposed by Horton (1940) and express as:

$$f_p = f_c + (f_o - f_c)\ e^{-\beta t}$$

where f_p, f_c and f_0 are infiltration rate at time, t, final infiltration rate at t=120 and infiltration rate at t=0, respectively, β is an empirical constant related to delay of time.

RESULTS AND DISCUSSION

Selected soil properties of the study site are given in Table 3. Soils were predominantly sandy loam, and silty loam in texture with very low organic carbon status, which may indicate poor soil aggregation and fertility (Jones et al., 1975; El-Swaify et al., 1987; Ogunwole and Ogunleye, 2005). DK, D and DN plots had higher sand fraction, respectively, while the P, N and DNPK plots were found to have higher clay content as well. The increase sand fractions of DK, D and DN treatment plots may be the result of a higher resistance of the soil to continuous cultivation (Ogunwole and Ogunleye, 2005). Soils in all plots have low bulk density, thus indicating the ease of root penetration and water uptake by plant (Lawal and Girei, 2013). Several studies have shown the positive effect of dung or organic fertilizer applications on bulk density and moisture retention (Ogunwole, 2008).

Considering the plot of cumulative infiltration versus time of all the treatments, an initial rapid increase in infiltration that stabilizes with time was observed (Figure 1). Soil inherent heterogeneity in all the plots may have influenced infiltration characteristics of soils in this study. Variability in cumulative infiltration for some treatments was higher than in other treatments. Such variability was more pronounce for DK, P and N plots as shown in Figure 1. Results also indicate that for the early stages of infiltration, cumulative infiltration between the treatments were not different even in the control plot. This finding indicate that for a given quantity of applied irrigation or rainfall water, larger proportion will infiltrate into the soil of K, DK and D treated plots than all other treatments plots,

Table 3. Selected soil properties of the study plots.

Plots	Soil organic carbon (%)	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	Textural class
D	1.04	1.43	59.19	34.49	6.32	Sandy Loam
DK	1.68	1.43	61.36	32.66	5.65	Silty Loam
NPK	0.63	1.43	57.19	32.32	6.99	Sandy Loam
N	1.02	1.43	50.32	42.33	7.32	Silty Loam
DNPK	1.41	1.53	46.02	46.66	7.32	Silty Loam
DP	1.51	1.44	55.94	38.24	5.82	Sandy Loam
CT	1.08	1.44	50.02	43.32	6.65	Sandy Loam
P	1.86	1.43	52.68	39.67	7.49	Sandy loam
DN	0.74	1.44	59.02	32.32	5.32	Sandy Loam
K	0.80	1.43	57.19	35.83	6.99	Sandy Loam

N: Nitrogen; P: Phosphorus; K: Potassium; D: Dung; CT: control; FC: Field Capacity; PWP: Permanent Wilting Point.

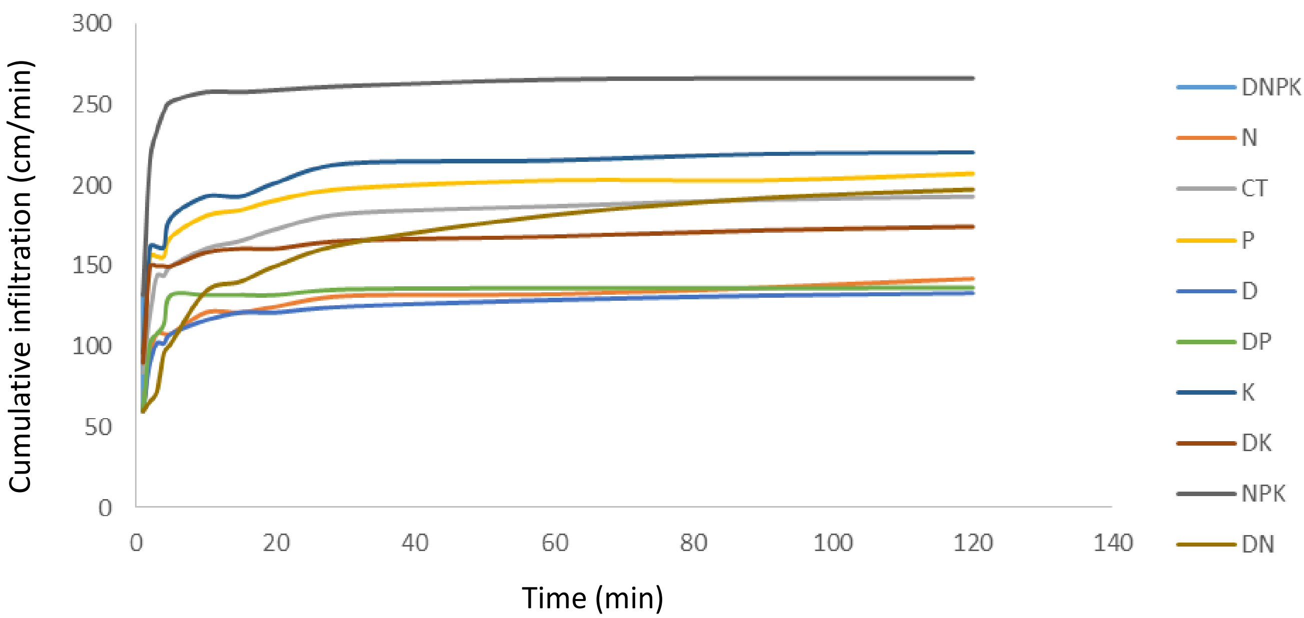

Figure 1. Cumulative infiltration versus time for all the treatments. The different colours refer to the different treatments. D: Dung; N: nitrogen; P: phosphorus; K: potassium; CT: control.

with probable less runoff occurrence in these plots. The same trend as observed in the plot of cumulative infiltration versus time above applies to plot of infiltration rate against time, but here, infiltration rate progressively decreases with time for all the plots (Figure 2).

High infiltration rate observed in the K, DK and D treated plots might be due to low bulk density and organic carbon presence in such plots (Table 3). A positively correlation between soil hydraulic properties and dry large macroaggregates, dry mean weight diameter and bulk density in such plots is also reported by Girei (2015) to be another factor resulting in such scenario. The role played by organic matter in improving soil structure and binding of soil particle into stable aggregates that enhance pore space and infiltration was shown by Poudel et al. (2001) and Turner (2006). Shehu (2013) and Schnug and Haneklaus (2002), reported relationships between the improved soil mechanical stability and increased infiltration rates. High infiltration rate, good tilth and adequate aeration for plant growth are generally known to be improved by well aggregated soils with large pores whose continued presence depends on the stability of soil aggregates (Kemper and Rosenau, 1986). Low infiltration values recorded despite the addition of organic manures in some plots might be connected with the presence of few large macroaggregates. Spatial variability of soil properties within the field (Cambardella et al., 1994) could be another reason for the low

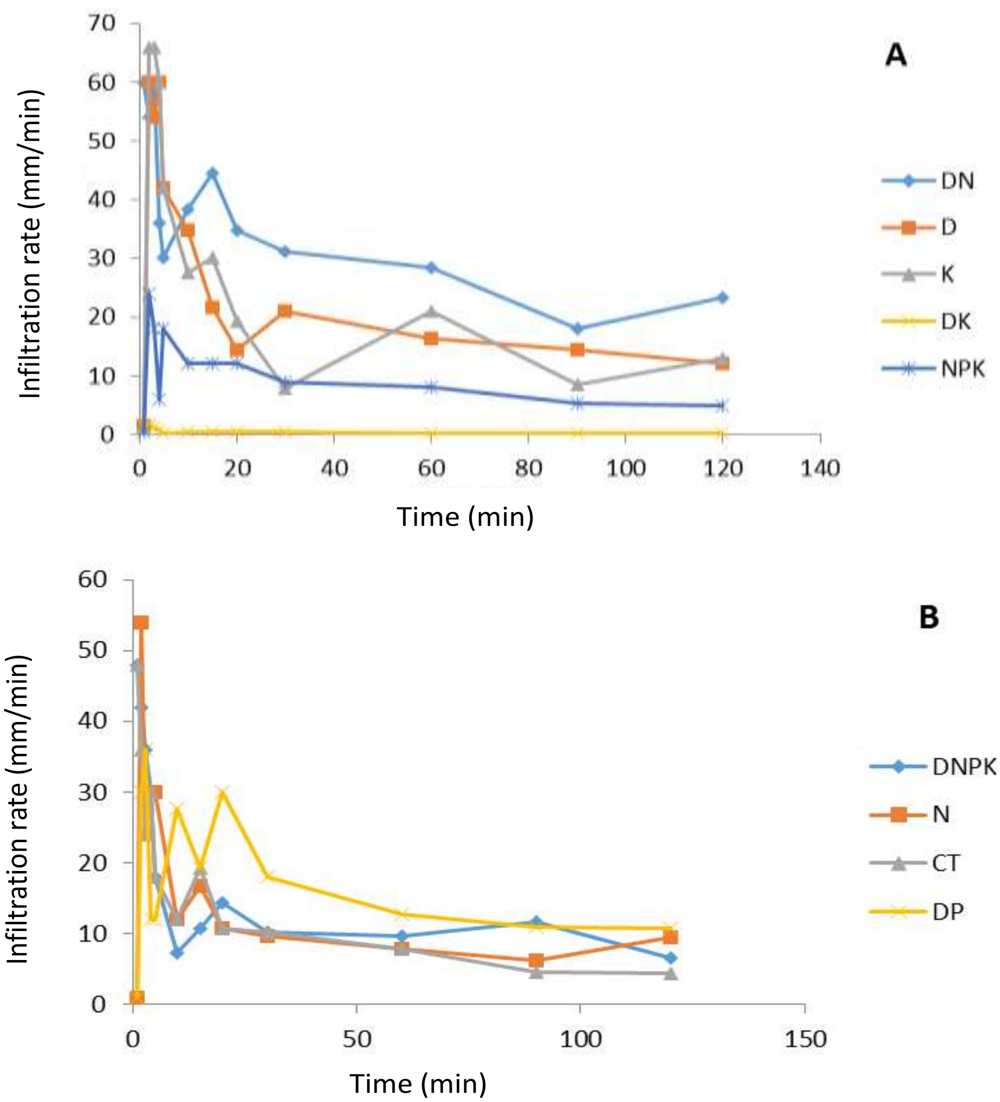

Figure 2. Infiltration rate versus time for all the treatments. The different colours and symbol refer to the different treatments. D: Dung; N: nitrogen; P: phosphorus; K: potassium; CT: control.

infiltration rate observed in the study.

Infiltration models

Kostiakov's model

B and n are the two parameters evaluated from measured infiltration data, for this equation. Both values were very high in virtually across all the treatments. The higher the value of n, the steeper the slope and the greater the rate of decline of infiltration. The greater the value of B the greater the initial infiltration value (Naeth et al., 1991; Turner, 2006). The value of n was consistently less than one as observed in Table 4. Mbagwu (1990) reported similar findings. Plot treated with DNPK recorded the least value of B (Table 4). Mbagwu (1994) found that the two soil properties with greatest influence over the B term are the effective porosity and bulk density.

All the linear curve fittings used to estimate the parameters of the Kostiakov infiltration equation yielded coefficients of determination (r^2) close to unity (Tables 4). This was further established when fitting parameters were computed directly into the Kostiakov model which yielded calculated model values with average means r^2 values of 0.9956 for all points (Table 4). This confirms the close relationship between observed and predicted infiltration rates. It also confirms the applicability of Kostiakov equation in estimating infiltration parameters therefore predicting cumulative infiltration of Guinea Savanna soils of Nigeria.

Linear regression plots of observed versus predicted

Table 4. Fitting parameters and fitting equations of selected DNPK experimental plots in Samaru from Kostiakov's infiltration model.

Trt	n	B	r^2	Equation
CT	0.685	1.5241	0.961	I=1.5241*t^0.685
DNPK	0.709	1.0093	0.977	I=1.0093*t^0.709
DP	0.748	1.1885	0.996	I=1.1885*t^0.748
P	0.579	1.2883	0.995	I=1.2883*t^0.579
NPK	0.715	1.9272	0.998	I=1.9272*t^0.715
K	0.658	1.5346	0.987	I=1.5346*t^0.658
DK	0.634	1.7458	0.997	I=2.7458*t^0.634
N	0.759	1.2794	0.989	I=1.2794*t^0.759
D	0.634	1.7378	0.997	I=1.7378*t^0.634
DN	0.828	1.0864	0.998	I=1.0864*t^0.828
Mean	-	-	0.9895	-

†Trt treatment, B and n are Kostiakov fitting parameters, r^2 coefficient of determination.

Table 5. Linear regression coefficients and relationships between measured and predicted.

Trt	Regression equation	r^2
CT	Y=1.0688X-0.621	0.9840
DN	Y=1.0545X-0.630	0.9970
DNPK	Y=1.1085X-0.578	0.9928
DP	Y=1.4468X-0.303	0.9968
P	Y=0.951X=0.278	0.9971
NPK	Y=3.7932X-0.329	0.9977
D	Y=1.0124X-0.122	0.9992
K	Y=1.0615X-0.546	0.9947
DK	Y=0.9977X+0.191	0.9984
N	Y=1.0635X-0.587	0.9979
Mean	-	0.9956

†Y is the measured and X is the predicted cumulative infiltration.

cumulative infiltration of all plots gave regression lines with slopes closed to unity (Table 5). This is evidence that Kostiakov's model is sensitive and capable of illustrating the differences among treatments.

Earlier studies of two infiltration models by Shehu (2013) in Samaru showed superiority of Kostiakov over Philip's equation. However, Abdulkadir et al. (2011) reported that earlier comparative studies on two infiltration models in Samaru, using non-linear least square initially and later linear least-square regression, reveals the superiority of Philip's equation over the Kostiakov's equation. Also Dashtaki et al. (2009) reported a better performance for Horton model than Kostiakov and Philip models.

Philip's equation

The S parameter recorded here depends on the initial soil infiltration. It was largest in D (1.833) and DK (1.784) treatments. Similar findings were reported by Shukla et al. (2003b) who concluded that application of manure improved soil structure, thus improving the water transmission properties of the soil. Other factors such as antecedent soil moisture of the soil, or macro or biopores is also suspected to have influence the S parameter recorded as reported by Shaver et al. (2002) and Shukla et al. (2003a). Variation of the S parameter among treatments may be caused by the differences in continuity and arrangements of soil pores. The A parameter (Soil water transmissivity) is a gravity factor, which is due to the impact of pores on the flow of water through soil under the influence of gravity (Ogban and Utin, 2014). It governs the final steady state infiltration rate. It was more predominant in plots treated with NPK (1.257) followed by DP (0.185). However, for all plots studied, non recorded negative A value.

Table 6. Fitting parameters and fitting equations of selected DNPK experimental plots in Samaru from Philip's infiltration model.

Trt	S	A	r^2	Equation
CT	1.194	0.166	0.557	I=1.194*t^0.5+0.166*t
DN	1.00	0.387	0.958	I=1.00*t^0.5+0.387*t
DNPK	1.138	0.137	0.726	I=1.138*t^0.5+0.137*t
DP	0.835	0.185	0.928	I=0.835*t^0.5+0.185*t
P	1.30	0.063	0.885	I=1.30*t^0.5+0.063*t
NPK	1.54	1.257	0.654	I=1.54*t^0.5-1.257*t
K	1.69	0.144	0.737	I=1.69*t^0.5+0.144*t
DK	1.784	0.157	0.939	I=1.784*t^0.5+0.157*t
N	1.373	0.276	0.901	I=1.373*t^0.5+0.27*t
D	1.833	0.143	0.876	I=1.833*t^0.5+0.143*t

[†]S and A; Philip's fitting parameters; Trt: Treatment, r^2=coefficient of determination.

Table 7. Linear regression coefficients and relationships between measured and predicted cumulative infiltration from Philip's infiltration Model.

Trt	Regression equation	r^2
CT	Y = 1.043X - 0.288	0.989
DN	Y = 0.975X + 0.187	0.984
DNPK	Y = 0.977X + 0.153	0.995
DP	Y = 1.038X - 0.265	0.987
P	Y = 1.063X - 0.559	0.987
NPK	Y = 0.992X+0.627	0.981
D	Y=1.0298X -0.347	0.996
K	Y=1.0827X-1.485	0.954
DK	Y=1.0084-0.1315	0.999
N	Y=1.0115X-0.081	0.996
Mean	-	0.986

[†]Y is the measured and X is the predicted cumulative infiltration.

A very good r^2 value was recorded for the fitting parameters of Philip's infiltration equation; A and S (Table 6). The coefficient of determination r^2 value (0.986) obtained where closed to unity when comparing predicted with measured cumulative infiltration, although lower than those obtained with Kostiakov's equation (0.996) (Table 7). This indicates the fitness of the infiltration data into Philip's model.

However, the superiority of Philips model over Green and Ampt's and linearized Philip's model was reported by Swartzendruber and Youngs (1974) in their studies of three physical-based infiltration models. This is not the case here. The ability of the Philip's equation together with other equations to simulate the long term infiltration rates of surface reclaimed mine soil relatively well was reported by Cook et al. (1982). Shukla et al. (2003b) also reported the superiority of Philips (1957) together with Green and Ampt (1911) in the prediction of infiltration coefficients of soils over nine other models.

Horton's equation

A wide variation was observed when calculated infiltration rate was compared with field measured result using Horton equation for this study. The same observation was made when infiltration measurement was repeated in the second year on the same plots in order to validate the former observation of fitting Horton's model. Wudivira et al. (2001) reported failure of Horton equation in the measurement of infiltration rates of soils using non-linear least square regression when comparing three infiltration models in Samaru and attributed the apparent failure of the Horton equation to difficulty of the iteration procedure to handle three parameters at the same time. Same reason was suspected to cause the observed result. However, a good performance of Horton model was observed by Abdulkadir et al. (2011) using linear and non-linear least-squares regression procedures simultaneously. Also, an overall best performance of three-parameter Horton model in Ohio was observed by Shukla et al. (2003b). Berndtsson (1987) reported a better fit of Horton model over Philips infiltration models for semi-arid soils in Northern Tunisia. Dashtaki et al. (2009) reported a better performance for Horton model than Kostiakov and Philip models. However, such was not the case in this study.

Conclusion

For model verification and goodness of fit, the three models were used to describe the experimental data for each treatment plot. Among the three models, Kostiakov (1932) gave the best representation of the infiltration rate – time relationship with higher mean r^2 value of 0.9956. The fitting parameters B, n, A, and S were time dependent and were higher in plots treated with organic manure singly or in combination than other treatment. Treatments had significant influence on both initial and final steady infiltration parameters of the two infiltration models.

This gives a clear indication of the good performance and the superiority of the two models (Kostiakov, 1932; Philip, 1957) in estimating or predicting infiltration characteristics of an Alfisols soils under a long term fertilizer trial in Northern Guinea Savanna of Nigeria. Further study of infiltration characteristics of the trial exploring other Models is recommended to improve its hydraulic data.

Conflict of Interests

The authors have not declared any conflict of interest.

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