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Performance of Horton Infiltration model in Predicting the Infiltration Capacity of some Soils of the Sudan Savanna of Nigeria.

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ABSTRACT

Infiltration study is very crucial in modelling water requirement of crops during their growth season. Infiltration rate measurements were carried out on dryland areas of Sokoto, Sudan savanna ecological zone of Nigeria; using the double ring infiltrometer. Disturbed and undisturbed soil samples were used to determine some physical characteristics (Texture, Saturated hydraulic Conductivity, particle density, bulk density, porosity and organic matter) of the soil. The results showed that the cumulative infiltration predicted by Horton infiltration model was very close to the field measurements for all the spots from the average values (3.35, 2.83 and 1.71 cm/min) and predicted rates (2.37,2.34 and 1.54 cm/min) with co-efficient of determination (R^2) close to unity (0.98, 0.97, 0.97) for the three spots. The study showed that the Horton infiltration model can be applied to estimate infiltration characteristics of some soils in Sudan Savanna of Nigeria.

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1. Introduction

Water management is one of the major challenges affecting the growth of plants in an arid and semi-arid environment. The purpose of such management is to obtain, conserve and to use the water efficiently, and to avoid negative impact to the soil structure. An understanding of plant water requirements with the initial soil moisture content is very important in the assessment of the infiltration rate of any type of soil and our ability to relate surface and subsurface processes in describing the hydrologic cycle (Ferre and Warrick 2005; Ayu *et al*., 2013). Different soils exhibit different infiltration rate depending on its characteristics (Osuji *et al*., 2010). Arid soils are characterised with rapid infiltration rate resulting from high porosity, low organic matter, poor vegetation covers and light viscosity of water. Rainfall as the only source of recharge in the hydrological cycles of this region is characterised as often erratic and inadequate in amount and distribution for production of some crops (Utsev *et al*., 2014). The constant (Steady state infiltration) rate of such soil is only met after a long period of time. Infiltration is the vertical movement of water from the soil surface to just below the surface via its horizons by gravitational flow (Osuji, 1984; Diamond and Thomas, 2013). When soil received the minimum water at constant water ponding, it is referred to as steady infiltration rate of a soil (Mbagwu, 1993) which mainly depends on the characteristics of the soil (Mawardi, 2012).

However, field measurements of soil infiltration are difficult, time-consuming, expensive and give only local scale results (Shukla *et al*., 2003; Lake *et al*., 2009). Since obtaining the steady state infiltration rate is time consuming, several models have been proposed to determine this parameter (Haghighi *et al.,* 2010). 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*., 2003). Haghighi *et al*. (2010) reported that empirical models such as those of Kostiakov (1932) and Horton (1940), and physical models such as that of Philip (1957) as the most commonly models used to estimate final infiltration rate. The superiority of Horton model among Kostiakov and Philip's when considering the infiltration data of mostly semi-arid range lands in Australia under specific conditions was reported by Gifford (1976). Ramesh *et al*. (2008) proved that the Horton Model gives the best representation on the level of infiltration and the time of infiltration on a different land use of Vertisols. Shukla *et al*. (2003) obtained a better result with the three parameter Horton equation than nine other infiltration models for soil with different land use and soil management systems. Hajabbasi (2006) evaluated the Kostiakov, Horton, and Philip's infiltration models under different tillage and rotations in a clay-loam in North-west Iran and reported that the Horton's model gave the best prediction of infiltration rate in that region as reported by Haghighi *et al*. (2010). The initial moisture content, condition of the surface, hydraulic conductivity of the soil profile, texture, porosity, degree of swelling of soil colloids, organic matter, vegetative cover, duration of irrigation or rainfall and viscosity of water are reported to be among the major soil and water characteristics affecting infiltration rates (Osuji *et al*., 2010; Saxton *et al*.,1986).

Information about soil infiltration characteristics is very important in the estimation of crop water requirement of a drylands need. This information is useful in water management of dryland which can suggest an idea about the water requirements of crop during their growing periods. Earlier work in the region focused on Talsma and Palange (1972), Kostiakov (1932) and Philip (1957) equations used to estimate the infiltration characteristics of soil (savanna Alfisols), such as those by Mudiare and Adewumi (2000), Wudivira *et al*. (2001) and Abdulkadir *et al*. (2011). Only few studies reported the applicability of Horton in the prediction of infiltration rate.

The objective of this study is to evaluate the use of Horton infiltration model in predicting the infiltration of a soil of the Sudan savanna.

2. Material and Methods

2.1 Experimental site

The experimental site was the dryland farm which is located at the Usmanu Danfodiyo University, Sokoto. Dryland farm is located within the University premises near Dundaye town in Wammako local Government of Sokoto state on latitude 13^{o} 02^{1}N and longitude 5^{o} 02^{1}E at an altitude of 300 meters above sea level. The ecological zone is Sudan savannah which is characterised by sparse vegetation and scattered trees. Mean annual rainfall and temperature is 600 mm and 30^{o}C respectively (SERC, 2011).

2.2 Soil sampling and analysis

Soil samples were collected randomly from three different points diagonally on each spot using soil auger and cores. These consist of nine (9) soil samples each from 0-15 cm and 15-30 cm, making a total of eighteen (18) samples. Soil samples collected with auger were bulked to form a composite sample/spot, passed through 2mm sieve and stored in a labelled polythene bag for subsequent routine analyses.

Particle density was determined using pycnometer bottle and bulk density by core method (Blake and Hartge, 1986). Porosity was determined indirectly from the measured bulk density and particle density (2.65 Mg m^{-3}) value of a mineral soils following an equation given by Baver *et al.* (1972).

$$\text{Total porosity} \quad 1 - \left(\frac{\text{Bulk density}}{\text{Particle density}}\right) \times 100 \qquad (1)$$

Particle size analysis was conducted using Bouyoucos hydrometer method (Gee and Bauder, 1986). The USDA textural triangle was used to determine the textural class of the soil samples.

Walkley-Black wet combustion method (1934) was used for Organic carbon (OC) determination, after which the OC values were multiplied by 1.724 to obtain the organic matter content of the soil (Jones, 2001). Soil pH in a soil–water suspension with a soil-to-water ratio of 1:2.5 (McLean, 1982) using a pH meter. The saturated hydraulic conductivity of the soil samples was determined by constant head method (Klute and Dirksen, 1986).

2.2.1 Infiltration studies

The infiltration data were obtained by the Double Ring method from 3 different spots of the experiment. Each infiltration measurement was carried out using a double ring apparatus with outer and inner diameters of 550 and 300 mm respectively. The steady state infiltration rate was estimated using $\frac{\Delta y}{\Delta x}$ values of the cumulative infiltration curve. The model parameters were determined via the common method employed by Mudiare *et al*. (2011).

Data generated were used to calculate predicted infiltration rate and cumulative infiltration. Measured infiltration data were fitted into Horton's infiltration model to determine the fitness of the model for soils of the study plots. Linear regression analysis using microsoft excel was used to obtain 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.

Infiltration equation

Data analysis for estimating the capacity of soil infiltration uses the Horton Infiltration Model:

$f = fc + (fo - fc)\ e^{-kt}$

f = infiltration capacity (mm h-1); fc = infiltration capacity at the time of constant infiltration; fo = initial infiltration capacity (at t = 0); k = constant for a certain soil; t = time.

Process of the model fitting refers to the equation ft = fc (f0-fc) e^{-kt}. The fc value is estimated from plotting of the relationship between the infiltration rate and time. Determination of the K value is performed using the equation: $K = \frac{1}{(t2-t1)} \ln \frac{(f1-fc)}{(f2-fc)}$. The K values for subsequent points can be done in the same manner.

Statistical Analysis and Assessing the Goodness of fit of The Model

Data obtained were subjected to Statistical Analyses System (SAS Institute Inc., 2011). Analysis of Variance was used to determine the significant effect of the sampling spots on various measured properties ($p<0.05$). Least significant difference (LSD) was used to detect significant different between means.

In this study, the goodness of fit of the selected model and its ability to estimate the final soil infiltration rate was evaluated using root mean squared error (RMSE) and the coefficient of regression (R^2).

3. Results and Discussion

Table 1 shows the result of the soil analysis of the study area. The soil analysis result shows that the soil texture of the area ranges from Sand to Sandy-loam (Table 1b). The soil pH ranged from 5.8 to 6.0. This reveals that the soil of the study area was slightly acidic. Other soil properties assess were not significantly different from each other as observed from Table 1a.

Table 1(a): Average values of soil analyses of the study area at the two different depths

Physical properties	0-15 cm	15-30 cm
Sand (%)	95±0.70a	87±1.67b
Silt (%)	2±0.04b	4±0.50a
Clay (%)	3±0.33b	9±1.00a
pH in water	5.8a	6.0a
Textural class	Sand	Loamy sand
Sat. Hydraulic Conductivity (cm hr^{-1})	14.1±0.9a	7.54±0.53b
Particle Density (Mg m^{-3})	2.64±0.08a	2.65±0.01a
Bulk density (Mg m^{-3})	1.40±0.007 b	1.45±0.01a
Porosity (%)	47±0.33a	45±0.03b
Organic matter (%)	1.78±0.08a	1.59±0.06b

Table1(b): Particle size distribution across the spots at different depths

Particle size distribution	Sand (%)	Silt (%)	Clay (%)	Textural class
Sampling spots				
		0-15 cm depth		
A	96a	2a	2b	Sand
B	96a	2a	2b	Sand
C	93a	2a	5a	Sand
SE (±)	1.33	0.30	0.44	
		15-30 cm depths		
A	89a	5a	6bc	Sand
B	91a	2b	7b	Sand
C	81b	6a	13a	Sandy Loam
SE (±)	0.67	0.3	0.33	

Means followed by the same letters within the same column at the same depth are not significantly different from one another at 5% level of significant. SE-standard error

Figure 1 Shows the infiltration studies of upland soil (Dryland farm) of the three (3) sampling spots at different time intervals against water intake. The infiltration rate kept increasing with increases in time, although the rate of the water intake was higher in the beginning and decreases as the study progressed. The field measurement of infiltration rate (Figure 1) and estimation of infiltration rate (Horton Model) (Figure 2) show a similar asymptotic pattern; the rate of infiltration decreases up to a maximum limit of the soil to absorb water; the soil infiltrability is high early in the process and then gradually decreased with time. The soils can be said to have a rapid infiltration capacity.

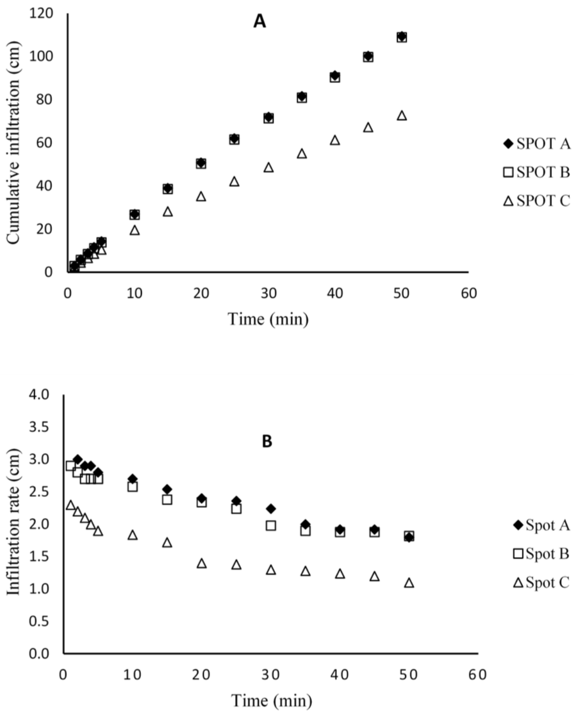

Figure 1: Measured (A) cumulative infiltration and (B) infiltration rate of the dryland soil

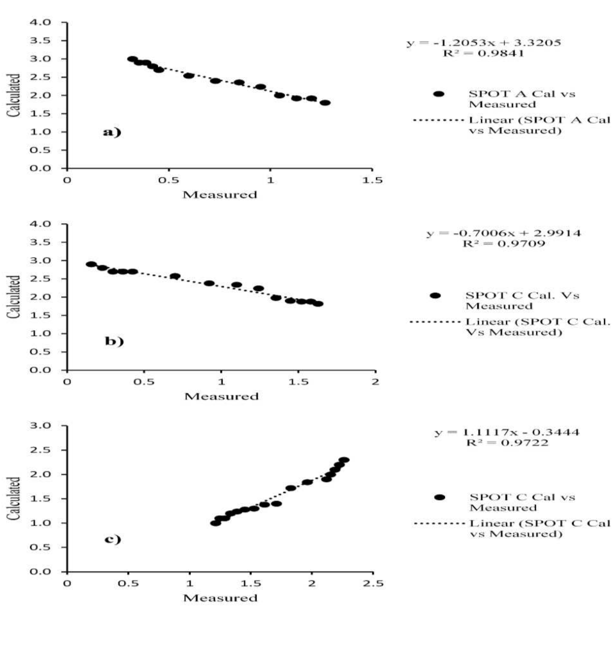

Figure 2: Calculated against measured Infiltration rates of (a) spot A, (b) spot B and (c) spot C of the dryland soil.

Values of RMSE and R^2 (0.9841, 0.9722 and 0.9709) showed that estimated infiltration rates by the Horton's model, were closer to the measured ones (Table 2). Different values of RMSE and R^2 were observed among the spots which could be attributed to differences in soil particle size distribution (Haghighi *et al*., 2010). Infiltrability of spots with high sand contents was observed to be increasing compared to spots with low clay content that displayed decreasing soil infiltrability. High dependency of infiltration rate on soil texture was reported by several authors (Mohammadi and Refahi, 2006 Mirzaee *et al*., 2014; Girei *et al*., 2016) as soils with greater proportion of sand exhibits higher infiltration rates. Comparing measured values with estimated final infiltration rates among the three spots, showed that the Horton three-parameter model estimated the final infiltration rate of all the three spots having yielded coefficients of determination (R^2) close to unity. A calculated model values with mean R^2 value of 0.97 obtained for all the 3 spots when fitting parameters were later computed directly in the Horton's infiltration model further established this finding. This further verify a close agreement of the measured and calculated infiltration rates and further confirms that the approach adapted in this study can be applied to estimate parameters and predict infiltration rates for some soils in the Sudan savannah regions of Nigeria using the Horton's infiltration equation (Abdulkadir *et al*., 2011; Horton, 1940).

The RMSE statistic is an index of the correspondence between measured and predicted data and has frequently been used as a means for evaluating the accuracy of models (Mirzaee *et al*., 2014). A considered model was better when its RMSE was smaller. In addition, the mean R^2 values of all soil studied were calculated. The spot having the smallest RMSE value and highest mean R^2 was selected as the best soil the model perform very good in predicting its infiltration rate according to these goodness-of-fit statistics as indicated in Table 2 and 3 respectively.

Table 2: The criteria for assessing the performance of Horton infiltration model

Statistical Criterion	Value	Classification
Coefficient of determination (R2)	$0.00 \leq R2 \leq 0.50$	Unsatisfactory
	$0.050 < R2 \leq 1.00$	Satisfactory
RMSE	Values below half standard deviation of the observed data	Satisfactory

Source: Suryoputro *et al*. (2018)

Table 3: Performance score parameters of the three different spots of study

	Performance Score	
Location	[1]RMSE	[2]R^2
SPOT A	1.83	0.98
SPOT B	1.68	0.97
SPOT C	0.17	0.97

[1] Root Means Square Error
[2] Coefficient of determination

The result of this study agrees with the findings of Hsu *et al.* (2002) who evaluated three models (Horton, Philip and Green -Ampt) for three soil types to assess the models based on Richard's equation. His results showed that all the 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. A better fit of the Horton Model over kostiakov, modified-Kostiakov and Philip infiltration models was observed for a sandy soil of southern guinea savannah by Ogbe *et al*. (2011). Failure of the Horton Model in predicting the infiltration of guinea savanna using linear regression was reported by Wudivira *et al*. (2001). They attributed the failure to the difficulties of the iteration procedure to handle three unknown parameters at the same time. However, Abdulkadir *et al*. (2011) reported superiority of Horton in its ability to predict the infiltration rate of same soil using the stepwise regression to derive the estimates/constants.

4. Conclusions

This paper revealed that the Horton infiltration model can be employed in simulating infiltration rate of some savanna soils because of its comprehensiveness and it formed its basis on three physical pa-rameters (initial (io), final steady-state infiltration (ic) and k). The fitted parameters were time dependent. Fitting these estimated parameters in to Horton's model yield calculated/simulated infiltration rates that are in overall agreement with the field measured cumulative infiltration rates, and are therefore, capable of simulating infiltration under the field conditions encountered in the present study. A clear indication of the good performance of the Horton model in predicting the infiltration characteristics of some Sudan savanna soil is therefore established from this study having arrived at a mean R^2 value of 0.97 from good relationship between the measured and predicted infiltration rates.

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