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Evaluation of Infiltration Characteristics of Soils Developed on Coastal Plain Sands in Calabar Municipality Local Government Area, Cross River State, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. Author OO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors EAA and JFA managed the analyses of the study. Author JFA managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Infiltration of water into the soil is an important physical process affecting the fate of water under field conditions, especially the amount of subsurface recharge and surface runoff and hence the hazard of soil erosion. The study was conducted to evaluate the infiltration models of soils developed on coastal plain sands and to select a suitable models as a basis to improve the management of the soil. A total of 16 infiltration runs were made with the double ring infiltrometer. For the purpose of getting best fitting model, the results obtained from various infiltration models were compared with observed field data. The parameters considered for best fitting of model were correlation coefficient and coefficient of variability (CV). Model-predicted cumulative infiltration consistently deviated from field-measured data, that is, the models under-predicted cumulative infiltration by several orders of magnitude for Kostiakov, Green Ampt and Philip model but the

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model over predicted cumulative infiltration for Horton model. The results of the soil samples analysed revealed that the mean values of 707.50, 208.13 and 84.38 gkg-1 for sand, silt and clay with the textural class of sandy loam. The bulk density, particle density and total porosity had mean values of 1.84 gcm^{-3}, 2.44 gcm^{-3} and 22.56%. However, there was a fairly good agreement between mean-measured cumulative infiltration (7.30 cm/hr, CV = 32.19%); Philips (1.93 cm/hr, CV = 42.49%); Kostiakov (0.13 cm/hr, CV = 30.77%); Horton (64.49 cm/hr, CV = 22.39%) and Green Ampt model (42.04 cm/hr, CV = 0.57%) respectively. The data however showed that the correlation coefficient for Kostiakov (1.00) was best fitting in predicting the field measured data and this was closely followed by Green Ampt (0.88); while Philip's model and Horton model showed a negative correlation (r = -0.88 and r = -0.82) with the field measured data. Conservation measures involving mulching, cover cropping and afforestation are recommended to improve the soil structure and infiltration capacity.

Keywords: Infiltration; infiltration rate; infiltration models; infiltration characteristics; water.

1. INTRODUCTION

Water is one of the principal factors limiting the growth of plants not only in arid and semi-arid environment where total crop needs usually exceed water supply, but also in the humid environment high rainfall distribution and low moisture availability to plants bring about water stress [11]. Infiltration is the movement of water into the soil from the surface. The water is driven into the porous soil by force of gravity and capillary action. First the water wets the soil grains and then the extra water moves down due to resulting gravitational force. The rate at which a given soil can absorb water at a given time is called infiltration rate and it depends on soil characteristics such as soil texture, hydraulic conductivity, soil structure, vegetation cover etc. [2].

Infiltration rate is a characteristic of the surface soil and varies greatly with the soil texture and being greatly influenced by depth and type of vegetation cover over the soil surface which dampen the kinetic energy impact of large raindrops from dislodging surface soil particles and producing surface sealing and crusting [3]. Water infiltration into the soil is a very important issue in soil water management and water resource conservative practices. Infiltration rate describes the capacity of a soil to absorb water. Its characteristics are key variables in hydrologic analysis and modelling [8]. Infiltration of water into the soil is of great practical importance to agriculture since it determines the amount of subsurface recharge and surface runoff, and hence the hazard of soil erosion. Knowledge of the infiltration process is a prerequisite for efficient soil and water conservation [10]. The two important parameters for characterizing the infiltration of water into the soil profile are the rate and the cumulative amount [14]. In order to design and manage different irrigation methods, the awareness of soil infiltration characteristics seems to be necessary.

Infiltration depends on soil characteristics and field surface conditions. The value of infiltration equation for a field necessitates executing field's tests under common conditions. The infiltration equations are presented as basic, empirical and physical models [12]. 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 water movement, affect coefficients of determination of infiltration models. 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. However, field measurements of soil infiltration are cumbersome, expensive, and time-consuming and give only local scale results. As such infiltration equations or models such as Kostiakov model, Green Ampt model, Philip's and Horton models offer a viable option to estimate field infiltration characteristics of soils [6]. The primary objective of this study was to evaluate the infiltration models and to select suitable models as a basis to improve the management of the soil.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The study was conducted in Calabar Municipality Local Government Area, Cross River State

(Latitude 04°58'N and Longitude 08°20'E). The climate is humid and tropical, with an average annual rainfall range of 1500 - 2,250 mm and mean annual temperature varying between 24°C and 33°C per annum in Calabar. The soils of the area are derived from coastal plain parent materials overlying the tertiary coastal plain sand geological formation.

2.2 Experimental Layout

The area was marked out on a 6 m x 6 m grid and spaced at interval of 2 m giving a total of 16 observation points. Sampling is done at points (marked with dots) 1-16 for particle size distribution, bulk density, particle density and total porosity.

2.3 Measurement of Infiltration Rate

A cylinder infiltrometer of length 15 cm and diameter 5 cm was driven into the soil at each of the 16 points up to a depth of 7.5 cm. The base of the infiltrometer is mulched to reduce lateral flow of water. A 2 cm mark is made from the top of the cylinder, to serve as a constant hydraulic head. Water is poured into the infiltrometer up to the brim and the time of fall of the level of water to the 2 cm is noted. The procedure is repeated for an average infiltration rate before proceeding to the next point on the grid. Data collected were used to calculate infiltration rate and cumulative infiltration. Measured infiltration data were fitted into four different infiltration models (Green Ampt, Kostiakov's, Philip's and Horton's model) (Table 1) to determine the best-fit model for soils of the study area. Linear regression analysis with the use of SPSS software version 18 was used to obtain the model parameters. Undisturbed soil samples at depth of 0 to 15 cm and about 2 m apart from the infiltrometer were collected using a soil core sampler and spade. The samples were labelled and carefully transported to the laboratory for analysis.

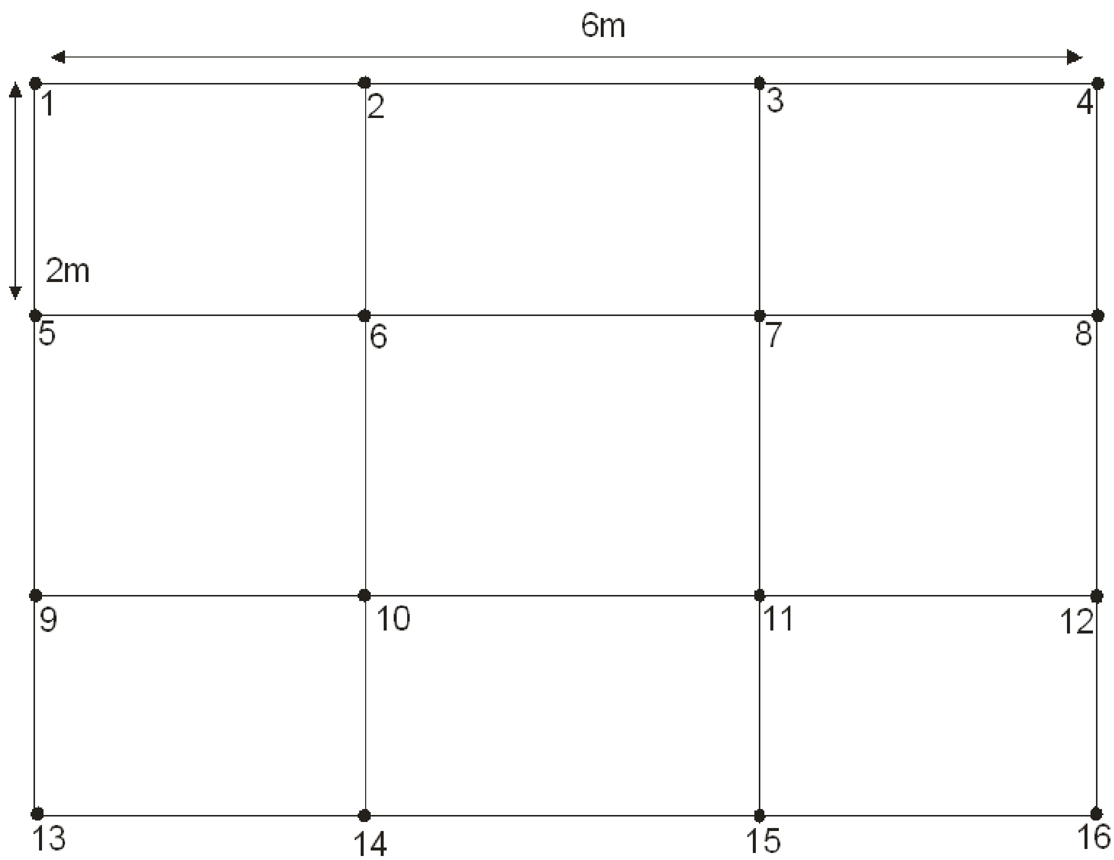

Fig. 1. A composite grid of 6m showing experimental test points (1-16)

Table 1. Infiltration models evaluated and methods of parameter estimation

Model name	Equation	Model parameter	Method of parameter estimation
Kostiakov	$I = Kt^{\alpha}$	K, α	Log I was plotted as ordinate against Log t as abscissa to give K and α as intercept and slope respectively
Philip	$I = St^{1/2} + At$	S, A	S was obtained by determining the slope of I/t versus t-1/2 while A was obtained from the intercept of the graph.
Horton	$I = fc + (f_0\text{-}f_c)\ e^{-kt}$	K	A plot of In against time gave the value of K as the slope of the graph
Green Ampt	$f = m + \frac{n}{F}$	m and n	M and n were obtained from the plot of infiltration rate against time as intercept and slope respectively.

2.4 Laboratory Analysis

The soil samples collected were air-dried, then gently crushed to pass through a 2 mm mesh sieve. Particle size distribution was determined by a modified Bouyoucos hydrometer method as described by [5]. Bulk density was determined by core method according to [7]. Particle density was determined by the pycnometer method [1]. Total Porosity was calculated from the result of Bulk density using the formula:

$$\text{Total porosity} = 1 - \frac{\text{Bulk density}}{\text{Particle density}} \times 100$$

2.5 Statistical Analysis

The results on the infiltration rate and soil physical properties were statistically analysed using range, mean, standard deviation, coefficient of variability and linear regression analysis was used to obtain the model parameters with the use of SPSS software version 18.

3. RESULTS AND DISCUSSION

3.1 Physical Properties

Table 2 show the physical properties of the studied area.

3.2 Particle Size Distribution

The particle size distribution of soils developed on coastal plain sands in Calabar Municipality shows that Sand was the dominant soil fraction and it ranged from 660 to 760 gkg^{-1} with mean value 707.50 gkg^{-1} and coefficient of variation 4.11 per cent while the silt fraction ranged from 160 to 230 gkg^{-1} with mean value 208.13 gkg^{-1} and coefficient of variation 9.32 per cent and the clay fraction ranged from 50 to 120 gkg^{-1} with mean value 84.38 gkg^{-1} and coefficient of variation 22.47 per cent with a textural class of sandy loam for the 16 point. The soil is unsuitable for surface irrigation as rated by [9], but could support cultivation of cassava and some other arable crops.

3.3 Bulk Density

The bulk density ranged from 1.60 to 2.20 gcm^{-3} with mean value 1.84 gcm^{-3} and coefficient of variation of 9.78 per cent. The high Bulk density suggests that mechanical impedance might have occurred probably due to Fulani Cattle trampling.

3.4 Particle Density and Total Porosity

The particle density ranged from 1.89 to 2.94 gcm^{-3} with mean value 2.44 gcm^{-3} and coefficient of variation of 10.66 per cent while the total porosity ranged from 10.00 to 38.80 per cent with mean value 22.56 per cent and coefficient of variation 43.62 per cent for the 16 observation point.

3.5 Infiltration Rate of the Soil

The infiltration rate of the soils as shown in Table 3 ranged from 2.55 to 10.91 cm/hr with mean value of 7.30 cm/hr and coefficient of variation of 32.19 per cent as shown in Table.3. This was similar to the finding of [4] who reported that the infiltration rate in the soils of Akpabuyo Area was 7.6 cm/hr. Surface irrigation was therefore not recommended probably because of the high sand and low clay contents as well as high bulk density which influence water movement into the soil.

Table 2. Physical properties of soils developed on coastal plain sands in Calabar Municipality Local Government Area

Sampling point	Sand gkg^{-1}	Silt gkg^{-1}	Clay gkg^{-1}	Textural class	B.D (gcm^{-3})	P.D (gcm^{-3})	Total Porosity (%)
1	710	230	60	SL	1.9	2.22	14.40
2	690	220	90	SL	1.8	2.94	38.80
3	680	210	110	SL	1.8	2.50	28.00
4	710	210	80	SL	1.7	2.46	30.90
5	700	210	90	SL	1.7	2.52	32.50
6	680	210	110	SL	2.2	2.56	14.06
7	660	220	120	SL	2.1	2.42	13.20
8	760	160	80	SL	1.7	2.56	15.60
9	730	180	90	SL	1.9	2.24	15.18
10	730	190	80	SL	2.1	2.50	16.00
11	680	230	90	SL	1.7	2.40	29.2
12	710	210	80	SL	2.0	2.71	26.2
13	730	210	60	SL	1.6	2.50	36.00
14	760	190	50	SL	1.7	1.89	10.05
15	710	220	70	SL	1.8	2.00	10.00
16	680	230	90	SL	1.8	2.60	30.80
MIN	660	160	50		1.60	1.89	10.00
MAX	760	230	120		2.20	2.94	38.80
MEAN	707.50	208.13	84.38		1.84	2.44	22.56
StDev	29.09	19.40	18.96		0.18	0.26	9.84
CV	4.11	9.32	22.47		9.78	10.66	43.62

Key: Textural Class: SL = Sandy loam; B.D = Bulk density; P.D = Particle density; MIN = Minimum; MAX = Maximum; StDev = Standard deviation; CV = Coefficient of variability

Table 3. Calculated Infiltration rates from different Infiltration models of soils developed on Coastal Plain Sands in Calabar Municipality

Sampling point	Time (min)	Observed Infiltration rate(cm/hr)	Infiltration rate by Horton's model (cm/hr)	Infiltration rate by Green Ampt model (cm/hr)	Infiltration rate by Kostiakov model (cm/hr)	Infiltration rate by Philip's model (cm/hr)
1	47	2.55	114.023	41.276	0.044	4.550
2	19	6.32	63.733	42.038	0.109	1.968
3	16	7.50	59.832	42.119	0.130	1.684
4	13	9.23	56.158	42.201	0.160	1.397
5	13	9.23	56.158	42.201	0.160	1.397
6	21	5.71	66.467	41.983	0.099	2.156
7	19	6.32	63.733	42.038	0.109	1.968
8	27	4.44	75.357	41.820	0.077	2.716
9	17	7.06	61.106	42.092	0.122	1.694
10	21	5.71	66.467	41.983	0.099	2.156
11	18	6.67	62.407	42.065	0.116	1.874
12	21	5.71	66.467	41.983	0.099	2.156
13	11	10.91	53.829	42.255	0.189	1.204
14	12	10.00	54.981	42.228	0.173	1.301
15	14	8.57	57.358	42.174	0.149	1.493
16	11	10.91	53.829	42.255	0.189	1.204
	Min	2.55	53.83	41.28	0.04	1.20
	Max	10.91	114.02	42.26	0.19	4.55
	Mean	7.30	64.49	42.04	0.13	1.93
	Std. Dev	2.35	14.44	0.24	0.04	0.82
	C.V	32.19	22.39	0.57	30.77	42.49
	Correlation Coefficient	-	-0.82	0.88	1.00	-0.88

Key: Min = Minimum; Max = Maximum; Std Dev = Standard deviation; CV = Coefficient of variability

Table 4. The values of different parameters of infiltration models of soils developed on coastal plain sands in Calabar Municipality

Horton's model $f = fc + (f_0 - f_c)e^{-kt}$	Green Ampt model $f = m + \frac{n}{F}$		Kostiakov model $I = Kt^{\alpha}$		Philips model $I = St^{1/2} + At$	
K	**M**	**N**	**K**	**A**	**S**	**A**
-0.020	42.554	-3.260	2.079	-1.000	0.081	0.085

Key: K = rate constant; M = saturated hydraulic conductivity; N = storage suction factor; K = measure of initial rate of infiltration;α =index of structural stability; S = sorptivity; A = transmissivity

3.6 Infiltration Models of the Soil

A comparison between measured and model-predicted cumulative infiltration (Table 3) showed that consistently the values predicted by Kostiakov, Green Ampt, and Philip's model deviated mostly from field measured data, that is, the models under-predicted cumulative infiltration but however on the other hand the model over-predicted cumulative infiltration for Horton model in this study. The data further showed high spatial variability of measured and predicted cumulative infiltration. The Kostiakov model was best fitting in predicting the cumulative infiltration in the study area with a high correlation coefficient (r = 1.00 with CV = 30.77%) and this was in agreement with the finding of [10]; this was closely followed by Green Ampt model (r = 0.88 with CV = 0.57%) but Philip's model and Horton model showed a negative correlation coefficient (r = -0.88 with CV = 42.49%; r = -0.82 and CV = 22.39%).

4. CONCLUSION

The study evaluated the infiltration characteristics of soils developed on coastal plain sands in Calabar Municipality Local Government Area, Cross River State-Nigeria. The results showed that the soils of the study area have an infiltration rate which had a mean value of 7.30 cm/hr with high sand content and low clay contents as well as high bulk density which influence water movement into the soil. Among the four models used for the studied area, Kostiakov model (r = 1.00) was best fitting in predicting the cumulative infiltration and followed by Green Ampt model (r = 0.88) while Philip's and Horton model showed a negative correlation. This result could be used to plan good irrigation scheduling for optimum crop growth and to advice farmers on the type of irrigation method to be adopted during farming season.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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