Determination of hydraulic conductivity and infiltration ratesalong slopes on Coastal Plain Soils in Akwa Ibom State, Nigeria

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Abstract

Soil hydraulic conductivity and infiltration of water has become highly emotive issue in Agricultural development. Improper land use management has generated soil environmental problems posing danger in crop production. This study ascertained specifically to evaluate hydraulic conductivity and infiltration rate of soils along slope on coastal plain sands in Akwa Ibom State. Soil samples were collected in upper, middle and lower slope at 0-20 cm depth, analyzed for physical and chemical properties. Infiltration rate was determined using the double rings infiltrometer. Results showed soils were predominated by sand fractions, lower (856 g kg^{-1})>middle (845 g kg^{-1}) > upper (836 g kg^{-1}). Bulk density (Bd) showed that middle slope had (1.52 M gm^{-3}) > lower and upper (1.49 M gm^{-3}). Total porosity (Tp) revealed that upper slope valued (0.44 m^3 m^{-3}) > lower (0.43 m^3 m^{-3}) > middle (0.42 m^3 m^{-3}). Soils were slightly acidic with lower (5.5) > middle and upper (5.3). Low organic matter observed in all soils; upper (2.45 %), middle (2.31 %) and lower (2.19 %). Infiltration capacity result showed middle (13.84 $cmmin^{-1}$) > lower (11.39 cm min^{-1}) > upper (11.23 cm min^{-1}), while hydraulic conductivity results revealed upper (0.53 cm hr^{-1}) > lower (0.50 cm hr^{-1}) > middle (0.37 cm hr^{-1}). There was a positive correlation at $p < 0.01$. Upper slope had low Infiltration rate followed by lower slope with low organic matter content of the soils. Soil requires nutrient application to loosen and create larger pore spaces for water/solute transport for sustained crop productivity.

Key Words: Hydraulic conductivity, infiltration rate, upper slope, middle slope, lower slope

Introduction

Soil hydraulic conductivity and infiltration of water into the soil are important factors affecting soil erosion, irrigation planning and water storage in the root zone. Hydraulic properties of the soil such as sorptivity and saturated hydraulic conductivity generally affect solute movement in the soil and are critical components of mathematical models for studying and predicting water flow and solute transport processes in the vadose zone (Agah *et al.,* 2017). On the other hand, infiltration rate (IR) is defined as the actual rate at which water enters the soil through the surface, at a given time. It is synonymous to infiltration capacity which is influenced by factors like rainfall intensity and soil moisture. Infiltration rate (IR) is influenced by similar factors in addition to soil texture, structure, surface conditions (vegetation and slope) and soil temperature. Infiltration rates are typically measured in units of depths per unit time such as cm per hour (cm/h). Water that has infiltrated into the soil is one of the principal factors limiting the growth of plants not only in arid and semi-arid regions, but also in the humid environment, where poor moisture distribution and low moisture availability leads to water stress in plant.

Slope is one of the important components of topography that requires effective management and conservation. Slope relates to the configuration of the land surface and is described in terms of differences in elevation, and landscape position, in other words, it can be described as the gradient of a surface and is commonly express in percentage (Ogban and Essien, 2018).

Bormann and Klassen (2008) mentioned infiltration as one of the most commonly measured soil hydraulic properties. Hydraulic conductivity refers to the ability of soil to transmit water through it. Therefore, the measurement of soil water through infiltration is an important indicator for efficient irrigation and drainage management systems. Bouman*et al.* (2008) viewed infiltration as the entry of water into the soil under a downward hydraulic gradient influenced by capillary and gravitational forces, with capillary forces predominating at the initial stages of the infiltration process and gravitational forces at large times.

Water infiltration into the soil is highly sensitive to soil management, which can alter the nature and properties of the soil surface, resulting in the alteration of the hydrological balance and the infiltration characteristics of the soil. Infiltration capacity is the maximum rate at which a soil can absorb and transmit water through its pores and is important in soil science. However, Antigha and Amalu (1999) pointed out that the rate of infiltration is influenced by soil characteristics including entry, storage capacity and transmission rate through the soil. The soil texture and structure, vegetation types and covers, water content of the soil, soil temperature and rainfall intensity also impact infiltration. Hydraulic conductivity refers to the capacity of soil to transmit water, and is crucial across various soil-related applications. It is a key parameter in understanding groundwater flow, infiltration, and drainage. High hydraulic conductivity soils tend to have high infiltration capacities. Infiltration is gravity driven in coarse-textured soil and capillary in fine-textured soil and higher in the former than in the later (Godwin and Dresser, 2003). Hillel (1998) reported that low infiltration indicates high runoff, and the soil may be susceptible to erosion as well as flooding. Ogban*et al.* (2013) and Ogban (2017) observed that if rainfall intensity exceeds the infiltration rate, runoff usually occurs. High infiltration rate on the other hand indicates that the soil can absorb and transmit water quickly; reducing runoff and increasing ground water recharge (Hillel, 1998).

Cumulative infiltration is the total quantity of water that enters the soil in a given time, thus infiltration rate and cumulative infiltration are two parameters commonly used in evaluating the infiltration characteristics of the soils. Lal and Shukla (2005) stated that infiltration characteristics of soils are quantified when field infiltration data are fitted mathematical to infiltration models. Since there is limited information regarding hydraulic conductivity and infiltration capacity of soils along slopes in the coastal plain sands, there is need to determine infiltration capacity and use the knowledge to improve water storage, estimating soil hydraulic conductivity in order to model soil water movement for crop consumption.

Materials and methods

Study Area: The study was carried out on the coastal plain sands in Akwa Ibom State south-eastern Nigeria. Akwa Ibom State is located between latitudes 4° 30' and 5° 30' N and longitudes 7° 30' and 8° 30' E. The state covers a total landmass of 8412 km^2 (Petters *et al.*, 1989). The coastal plain sands is situated between latitudes 4° 40' and 5° 15' N and longitudes 7° 30' and 8° 15' E (Ibok and Daniel, 2014). The state is characterized by dual seasons, the wet season which spans from the month of March through November and dry season which spans from December through February. Rainfall is bimodal and ranges from 2,500 mm on the Northern fringe to 3,000 mm along the coast (Petters*et al.*,1989). The soil is well drained, deeply weathered, formed from the Coastal Plain Sand parent material and is classified as Ultisols. Temperature ranges from 26° C to 30^0 C. The area is a tropical rainforest characterized by high humidity of about 75-95 % and evapotranspiration of 4.11 to 4.95 mm (Enwezor*et al.*, 1990). The coastal plain sands are derived from unconsolidated tertiary sand stones of the Benin formation with associated shale and limestone (Petters*et al.*, 1989). Sandy soil is known to have high rate of infiltration or leaching, which explains the poor soil fertility. The vegetation of the study area has been almost completely replaced by secondary forest, predominated by wild oil palm trees and woody shrubs with various types of undergrowth.

Field Methods: Six locations or slopes were selected for the study, namely, Abak, EtimEkpo, ObotAkara, OrukAnam, Ukanafun and IkotEkpene. On each slope, of an average 100 m, soil samples were taken from 0-20 cm depth in the upper, middle and lower slope, giving a total of eighteen soil samples for particle size and chemical analyses. Eighteen undisturbed soil samples were also collected using core samplers for the determination of bulk density, saturated hydraulic conductivity while total porosity was calculated. Eighteen infiltration runs were done in each of the sampling points.

Laboratory Analysis: The soil samples were air-dried and sieved through a 2 mm sieve for particle size and organic matter analyses. Particle size analysis was done according to Bouyoucos hydrometer method (Udo*et al.*, 2009). Bulk density was determined using the core samples (Dane and Topp, 2002). Soil samples were oven-dried at 105 ° C to a constant weight and bulk density calculated.

Total organic carbon was measured by the dichromate wet oxidation method of Walkley and Black as reported by Nelson and Sommers (1996). Organic matter was calculated by multiplying percentage organic carbon value by Van Bemmelen factor of 1.724.

Infiltration: Infiltration rate determination was done with the use of double rings infiltrometer (Nimmo and Shillito, 2023). The equation used is:

$$I.R = \frac{C.I}{T}$$

where I.R = Infiltration rate, C.I = Cumulative infiltration, T = Time lapse.

Statistical Analysis: The data of the physical properties were summarized using descriptive statistics (mean value, standard deviation and coefficient of variability). Multiple correlation coefficients and their levels of significance were computed using IBM SPSS version 20. Coefficient of variability (CV) is a statistical measure that describes the relative variability of a dataset or distribution. It is expressed in percentage and used in comparing variability and assessing precision, with lower values indicating higher precision.

Results and Discussion

Results of soil physical properties affected by slope are shown in Table 1. The results obtained in lower slope has the highest mean value of sand fraction of 856 $\pm$ 28.85 g kg^{-1} (CV = 0.03 %), > middle slope with mean value of 845 $\pm$ 45.69 g kg^{-1} (0.05 %), > upper slope with mean value of 836 $\pm$ 14.85 g kg^{-1} (CV = 0.02 %). Middle slope recorded the highest mean value of silt fraction of 48 $\pm$ 15.96 g kg^{-1} (CV = 0.33 %) > lower and uppers with mean values of 46 $\pm$ 11.22 g kg^{-1} (CV = 0.25 %) and 46 $\pm$ 12.23 g kg^{-1} (CV = 0.26 %), respectively. The lower slope had the highest mean value of clay fraction of 111 $\pm$ 17.09 g kg^{-1} (cv = 0.15 %), > the middle slope with mean value of 99 $\pm$ 35.57 gkg^{-1} (CV = 0.36 %), > the upper slope of 98 $\pm$18.97 g kg^{-1} (CV = 0.19 %). Particle size fraction is a surrogate of parent material and the textural characteristics at the three points of the slopes derived from coastal plain sands consist of primary minerals (Ogban and

Essien, 2016; Essien*et al.*, 2019). The middle slope recorded mean bulk density of 1.52 ± 0.09 Mg m^{-3} (CV = 0.06 %), slightly higher than lower and upper slopes with mean values of 1.49±0.12 Mg m^{-3} (0.08 %) and 1.49± 0.11Mg m^{-3} (0.07 %), respectively. Furthermore, Ogban and Essien (2016) reported that the magnitude of bulk densities was attributed to the influence of particle size fractions. The total porosity results revealed that upper slope had the highest mean value of 0.44± 0.04 m^3 m^{-3} (CV = 0.09 %), > the lower slope with mean value of 0.43±0.04 m^3m^{-3} (CV = 0.09 %), > the middle slope with mean value of 0.42 ± 0.04 m^3 m^{-3} (CV = 0.10 %).

The upper slope had the highest mean value of organic matter content of 2.45 ± 1.00 % (CV = 0.41 %), > the middle slope with mean value of 2.31 ± 0.66 % (CV = 0.29 %) and > the lower slope with mean value of 2.19 ± 1.12 % (CV = 0.51 %). The highest organic matter content in the upper slope may have been due to accumulation of organic litter and vegetative cover over the years on the soil surface, in line with the work done by Umoh *et al.* (2021), who researched on soil properties as influenced by land uses system.

Effect of slope on infiltration rate: The results of effect of slope on infiltration rate are presented in Figure 1. The results revealed that infiltration rate was higher in the middle slope, with highest average value of 13.83 ± 6.20 cm hr^{-1} (CV = 0.45 %), > lower slope with mean value of 11.39 ± 5.13 cm hr^{-1} (0.45 %), > upper slope with mean value of 11.23 ± 7.60 (CV = 0.68 %). The high infiltration capacity obtained from the middle slope could be attributed to the high porosity and coarse soil particles of the area, which is characterized by large pore spaces. This implies that the soils were not highly saturated rather, more water infiltrated into the soil more rapidly across the slope (Tayfun, 2005).

Effect of Slope on Saturated Hydraulic Conductivity: The result of effect of slope on saturated hydraulic conductivity is presented in Figure 2. The results revealed that in upper slope the highest value obtained of hydraulic conductivity were 0.53±0.27cm hr^{-1}(CV = 0.50 %) > lower slope with mean value 0.50±0.32cm hr^{-1} = 0.63 %) > the middle slope 0.37±0.16 cm hr^{-1}(CV = 0.44 %).

Correlation matrix between infiltration rate and other soil properties on the upper slope: The results of correlation between infiltration rate and soil properties are presented in Table 3. The results indicated that there was no relationship between infiltration rate and soil properties in the upper slope. Total porosity significantly correlated negatively with silt and clay (-0.881* and -0.953**), at $p<0.05$ and $p<0.01$, respectively. Bulk density significantly correlated negatively with TP (-0.998**) at $p<0.01$.

Correlation matrix between infiltration rate and soil properties on middle slope: Correlation matrix between infiltration rate and soil properties on the middle slope is shown in Table 2. The result obtained showed that infiltration capacity had no significant correlation with Ts, Si, Cl, Bd at $p<0.05$, respectively. Total sand (Ts) significantly correlated negatively with clay (-0.963**) atp<0.01. Bulk density (Bd) significantly correlated negatively with TP (-0.978**) at $p<0.01$.

Correlation matrix between infiltration rate and soil properties on lower slope: Correlation matrix between infiltration rate and soil properties on lower slope is shown in Table 4. The results showed that TS significantly correlated negatively with Si and Clay (-0.0937** and -0.814*) at $p<0.01$ and $p< 0.05$, respectively and positively with Na (0.839*) at $p< 0.05$. Cl correlated significantly with OM (-0.877*) at $p < 0.05$.

Conclusion

The study investigated the hydraulic conductivity and infiltration rates of soils along slopes on Coastal Plain Sandsin AkwaIbom State. The findings revealed variability in soil properties along the slopes. The soils were slightly acidic and generally low in organic matter content and exchangeable bases. Hydraulic conductivity and infiltration rates were hampered in some of these slope positions. Conservative management practices to control erosion and proper manipulation of soil with application of organic manures to loosen and create larger pore spaces for proper infiltration are recommended for sustainable agricultural production.

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Table 1: Effect of Slope on Soil Physical Properties

Soil physical parameters	Slope Position		
	Lower Slope	Middle Slope	Upper Slope
Ts(g kg^{-1})	856±28.85=0.03	845±45.69 = 0.05	836±14.85 = 0.02
Si (g kg^{-1})	46±11.22=0.25	48±15.96 = 0.03	46±12.23 = 0.26
Cl(g kg^{-1})	111±17.09=0.15	99±35.57 = 0.36	98±18.97 = 0.19
Bd (Mgm^{-3})	1.49±0.12 = 0.08	1.52±0.09 = 0.06	1.49±0.11 = 0.07
Tp (m^3m^{-3})	0.43±0.04 = 0.09	0.42±0.04 = 0.10	0.44±0.04 = 0.09
OM (%)	2.19 ± 1.12 = 0.51	2.31 ±0.66 = 0.29	2.45 ± 1.00 = 0.41

Ts – Total Sand, Si – Silt, Cl – Clay, Bulk density, K_{sat} – Hydraulic Conductivity, Tp – Total Porosity, OM = organic matter

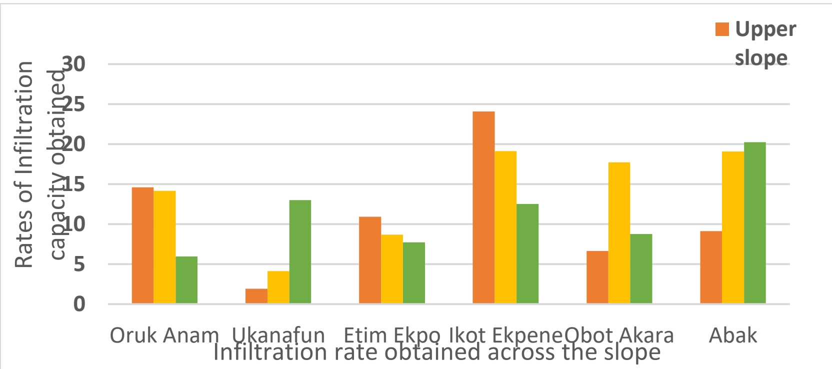

Figure 1: Effect of slope on Infiltration rate

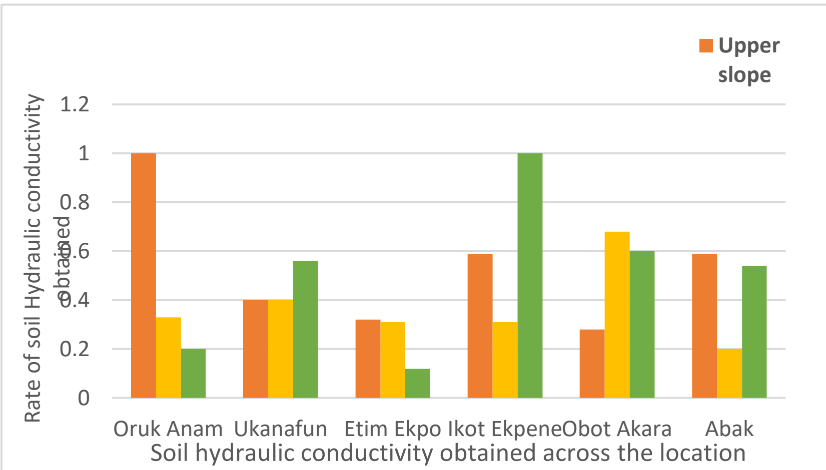

Figure 2: Effect of slope on soil hydraulic conductivity

Table 2: Correlation matrix between infiltration rate and soil properties on upper slope

	Infiltration rate	Ts	Si	Cl	Bd	Tp	Ksat	pH	OM
Infiltration rate	1								
Ts	-0.320	1							
Si	0.409	-0.881*	1						
Cl	0.223	-0.953**	0.696	1					
Bd	-0.714	0.215	-0.313	-0.125	1				
Tp	0.708	-0.166	0.289	0.067	-0.998**	1			
Ksat	0.463	-0.298	0.086	0.398	-0.303	0.283	1		
pH	0.408	0.339	-0.331	-0.302	0.209	-0.192	0.353	1	
OM	-0.660	0.507	-0.714	-0.310	0.710	-0.701	0.166	0.284	1

Ts- total Sand, Si- silt, Cl- Clay, Tp – Total porosity, Bd – Bulk density, Ksat – saturated hydraulic conductivity, OM- organic matter
** Correlation is significant at 0.01 level, * Correlation is significant at 0.05 level

Table 3: Correlation matrix between infiltration rate and soil physical properties on middle slope

	Infiltration rate	Ts	Si	Cl	Bd	Tp	Ksat	pH	OM
Infiltration rate	1								
Ts	0.500	1							
Si	-0.556	-0.759	1						
Cl	-0.551	-0.963**	0.730	1					
Bd	0.115	-0.340	0.004	0.498	1				
Tp	-0.125	0.465	-0.162	-0.593	-0.978**	1			
Ksat	0.001	-0.652	0.721	0.696	0.528	-0.678	1		
pH	0.600	0.586	-0.547	-0.450	0.167	-0.092	-0.037	1	
OM	-0.419	0.159	-0.112	-0.003	0.348	-0.220	-0.227	-0.211	1

Ts- total Sand, Si- silt, Cl- Clay, Tp – Total porosity, Bd – Bulk density, Ksat – saturated hydraulic conductivity, OM- organic matter
** Correlation is significant at 0.01 level,* Correlation is significant at 0.05 level

Table 4: Correlation matrix between infiltration capacity and soil physical properties on lower slope

	Infiltration rate	Ts	Si	Cl	Bd	Tp	Ksat	pH	OM
Infiltration rate	1								
Ts	0.336	1							
Si	-0.026	-0.937**	1						
Cl	0.082	-0.814*	0.912	1					
Bd	-0.289	-0.545	0.381	0.170	1				
Tp	0.209	0.596	-0.518	-0.230	-0.909*	1			
Ksat	0.465	0.279	-0.046	0.264	-0.507	0.412	1		
pH	0.778	0.155	0.182	0.282	-0.317	0.058	0.762	1	
OM	-0.486	0.482	-0.723	-0.877*	0.195	-0.067	-0.530	-0.625	1

Ts- total Sand, Si- silt, Cl- Clay, Tp – Total porosity, Bd – Bulk density, OM- organic matter
Ksat – saturated hydraulic conductivity,
** Correlation is significant at 0.01 level,* Correlation is significant at 0.05 level