Hydraulic Conductivity and Infiltration of Soils of Tropical Rain Forest Climate of Nigeria

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Abstract

Hydraulic conductivity (K_θ) is the single most important hydraulic parameter for flow and transport-related phenomena in soil. In this study, the effects of soil moisture contents, soil bulk density (BD), total porosity (PT), soil water holding capacity (WHC), organic matter content, and cation exchange capacity (CEC) on hydraulic conductivity of various sized aggregates of horizon A (0 – 20 cm soil layer) in five major cities (Ibadan, Ife, Akure, Owo and Ado-Ekiti) of the tropical rain forest zone of Nigeria was investigated. Hydraulic conductivity was determined by a steady-state flow using an infiltration device (mini-disk infiltrometer). Suction rates of 2 cm s^{-1}, 3 cm s^{-1}, and 4 cm s^{-1} were chosen at different locations on the fields for the infiltration measurement and subsequent estimation of soil hydraulic conductivity. At 2 cm s^{-1} suction rate, the mean value of K_θ ranged from 0.0022 ± 0.001 cm s^{-1} to 0.00071 ± 0.0004 cm s^{-1}. The highest and lowest mean bulk densities 1.5 g cm^{-3} and 1.33 g cm^{-3} were observed in soils of Ife and Akure, respectively. Similarly, mean total porosity values ranged between 0.44 cm^3 cm^{-3} and 0.5 cm^3 cm^{-3}. Statistical relationship between the total porosity and hydraulic conductivity gave a high correlation coefficient, r = 0.94 at $p < 0.05$. The correlation coefficient (r) between water holding capacity and hydraulic conductivity was 0.95. Results shows that Soil physical properties such as bulk density, total porosity and water holding capacity affect water infiltration characteristics of soils of the study area.

Keywords: Hydraulic conductivity, Infiltration, Total porosity, Bulk density, Nigeria

Introduction

Hydraulic conductivity (K_θ) is defined as "the metres per day of water seeping into the soil under the pull of gravity or under a unit hydraulic gradient" (Kirkham, 2005). It is governed by two forces, gravity, and capillary action (Kostiakov 1932). Cumulative Infiltration (I) is the total amount of water that enters into soil (Angelaki et al., 2004). Hydraulic conductivity and Cumulative infiltration of water are two interrelated parameters. Knowledge of hydraulic conductivity is very important in solving environmental problems because it is one of the most important soil physical properties for determining infiltration rate, irrigation and drainage practices, and other hydrological processes (Gulser and Candemir, 2008). It is an important soil property when evaluating the potential use of soil for many agricultural and non agricultural uses (Chakravorty et al., 1998-99). Hydraulic Conductivity is also useful in controlling water infiltration and surface runoff, leaching of Pesticides from agricultural lands and migration of Pollutants from contaminated sites to the groundwater (Bagarello and Sgroi, 2007).

Infiltration on the other hand is extremely important, because it determines not only the amount of water that will enter a soil, but also the entrainment of the "passenger" chemicals (nutrients, pollutants) dissolved in it (Kirkham, 2005). It also controls leaching, runoff, and crop water availability (Franzluebbers, 2002). Infiltration and evaporation are the most significant processes determining soil water storage (Lampurlanés and Cantero-Martínez, 2005). In saturated soils, the hydraulic conductivity is represented as K_{sat} and is the ease or ability in which water moves through a soil column when all pores are full of water, or conducting water (Reynolds, 1993; Lal and Shukla, 2004) while in unsaturated soils, the hydraulic conductivity is represented as K_{θ}. Under saturated conditions, continuous water phase and maximum conductivity is allowed because all of the pores are water-filled and conducting water (Hillel, 1998). Flow through an unsaturated soil is more complicated than flow through continuously saturated pore spaces. Macropores which are defined as soil pores greater than 1.0 mm (Luxmoore, 1981) are filled with air, leaving only finer pores to accommodate water movement. The movement of water in unsaturated soils is dictated by differences in matric potential, not gravity. The matric potential gradient is the difference in the matric potential of the moist soil areas (high matric potential) and nearby drier areas (low matric potential) into which the water is moving (Brady and Weil, 1999). Coarse-textured and well-aggregated soils are more conductive than clayey soils because of the large pore spaces (Halfmann, 2005). However, movement of the soil from a saturated state to an unsaturated state sharply decreases the hydraulic conductivity. As suction develops, the largest pores (the most conductive pores) are the first to empty, thus transferring flow to the smaller pores (Hillel, 1998). Water could be found along pore walls and may not have a continuous path; therefore, disrupting flow by causing "air" barriers. Water will flow as film creep along the walls of wide pores or as tube flow through narrow waterfilled pores (Hillel, 1998). The hydraulic conductivity of coarse-textured soils and/or well-aggregated soils will decrease more rapidly than fine-textured soils (Lal and Shukla, 2004).

Hydraulic conductivity depends on physical characteristics of soil such as the intrinsic permeability (soil or fractures), the degree of saturation, the type of soil, bulk density, total porosity and the configuration of the soil pores. It is influenced by the properties of the fluid being transmitted (such as viscosity) as well as the porous medium. The interpretation of these physical characteristics of soil and the management of agricultural practices requires assessment of the hydraulic properties of soil, such as infiltration and sorptivity (Green et al., 2003). Pore size and continuity are also important to the hydraulic conductivity of soils. Pore continuity or better-connected pores help increase infiltration (Ankeny et al., 1990). If soil moisture increases, soil pores may expand in soils with high organic matter content (Tsuboyama et al., 1994). It is well known that infiltration of water and chemicals in many field soils is enhanced by macropores (Logsdon and Jaynes, 1996; Mohanty et al., 1997, 1998; Shouse and Mohanty, 1998). Thus, the spatial variation, size, and interconnectedness of biological and structural macropores would play a key role in determining the rate of influx through soils (Das Gupta et al., 2006). Furthermore, Macropores and earthworm and decaying root channels vastly increase the amount of water that will infiltrate the soil (Fuentes et al., 2004). Hydraulic conductivity generally decreases according to soil textural class as follows; sandy soil > loamy soil > clay soil (Ozdemir, 1998). Increases sand and silt content in soil texture generally increase soil bulk density (Hillel, 1982) and decreases total porosity, but increases ratio of macro porosity in total porosity (Gulser and Candemir, 2008).

Hydraulic conductivity may change as water permeates and flows in a soil due to various chemical, physical and biological processes (Gulser and Candemir, 2008). Some soil physical characteristics which affect hydraulic conductivity are the total porosity, the distribution of pore sizes, and the pore geometry of the soil (Hillel, 1982). Several studies have been conducted in the past to study the spatial and temporal variations of saturated hydraulic conductivities, with contrasting results. Cassel and Nelson (1985) demonstrated a large temporal variation in saturated hydraulic conductivities at different depths in a laboratory soil column. Few independent spatial (Mohanty et al., 1994) or temporal (Lin et al., 1998) variability studies have been conducted for unsaturated hydraulic conductivity parameters. Messing and Jarvis (1993) and Logsdon and Jaynes (1996) investigated the temporal variations in unsaturated hydraulic properties due to agricultural operations (Das Gupta et al., 2006). According to Messing and Jarvis (1993) studies to monitor the spatiotemporal variations of both saturated and unsaturated hydraulic parameters in a plowed and unplowed plots in a clay soil, strong temporal trends in unsaturated hydraulic conductivity values that resulted from changes in the climatic conditions as well as tillage practices were observed (Das Gupta et al., 2006). Logsdon and Jaynes (1996), states that unsaturated hydraulic conductivity variability reflected the evolution in micropores with tillage. The saturated hydraulic conductivity values did not show consistent temporal variations, but were more spatially correlated. They attributed this phenomenon to the influence of macropores, which were unstable due to tillage, shrink– swell phenomena, and root activities (Das Gupta et al., 2006). Lin et al. (1998) observed that the spatial variability of unsaturated hydraulic conductivity at low soil water tension could be related to soil macropore distribution in Vertisols and vertic intergrades (Das Gupta et al., 2006). They also noticed marked temporal variations of unsaturated hydraulic conductivity and saturated hydraulic conductivity values during a 3-month period between August and October 1997. They attributed this behavior to the shrink–swell characteristics of the clay due to the variations in precipitation during the measurement period (Das Gupta et al., 2006). Hydraulic conductivity can be influenced by seasonal changes. As the growing season progresses, hydraulic conductivity can decrease because of increased root growth clogging pores, soil slaking, and a breakdown of structure in tilled soils (Lampurlanés and Cantero-Martínez, 2005).

Because of its high natural spatial and temporal variability, hydraulic conductivity is often a poor indicator of soil hydraulic response to management practices because natural variability often obfuscates treatment variability therefore robust estimates of soil hydraulic parameters are needed to differentiate management effects and spatial variability with statistical significance (Strudley et al, 2008) and also to properly characterize the spatial variability of soil parameters. Considering these importance of hydraulic conductivity, the research was aimed at to determining infiltration, water retention characteristic and hydraulic conductivity of soils in the tropical rainforest of Nigeria.

Materials and Methods

Description of Study Areas

The study was conducted in the Humid Sub-tropical Climate of Nigeria. This climate is influenced by the monsoons originating from the South Atlantic Ocean, which is brought into the country by the (maritime tropical) MT airmass. The Tropical rainforest has a very small temperature range; the temperature ranges are almost constant throughout the year. The southern part of Nigeria experiences heavy and abundant rainfall. The storms are usually conventional in making, due to the region proximity, to the equatorial belt. The annual rainfall received in this region, is very high, usually above the 2000 millimeters rainfall giving for tropical rainforest climates worldwide. More than half of humid zone of Nigeria is covered by pre-cambrian basement complex. Five locations were chosen within the southwestern part of Nigeria for the experiment and they include Akure (Ondo state), Ibadan (Oyo state), Ife (Osun state), Owo (Ondo state), and Ado (Ekiti state).

Akure, (latitude $7^0$14'N and longitude $5^0$08'E) is located within the humid region of Nigeria. Akure lies in the rain forest zone with a mean annual rainfall of between 1300 – 1600 mm and with an average temperature of 27^0C. The relative humidity ranges between 85 and 100% during the rainy season and less than 60% during the dry season period. Akure is about 351 m above the sea level. Akure is an area of about 2,303 km^2, situated within the western upland area (Fasinmirin and Oguntuase, 2008). Ibadan, (latitude $7^0$23'47'N and longitude $3^0$55'0'E) is 1,189.2 sq mi (3, 080 km^2) in area with a density of 2, 144.5/sq mi (250/km^2). Ibadan has a tropical wet and dry climate, with a lengthy wet season and relatively constant temperature throughout the course of the year. The wet season runs from April through October, though August sees somewhat of a lull in precipitation. The remaining months forms the dry season. Ibadan experiences the Harmattan between the months of November and February. It has an average temperature of 26.5^0C and relative humidity of 81%. The average rainfall is about 1,316 mm. the city ranges in elevation from 150 m in the valley area to 275 m above sea level on the major north-south ridge which crosses the central part of the city. Ile-Ife is also located within the humid region of Nigeria. Total annual rainfall of Ile-Ife is about 1350 mm. The average daily minimum temperature ranged between 20 ^{0}C and 22 ^{0}C, and the average maximum temperature between 27 ^{0}C and 35 ^{0}C (Osunbitan et al., 2005). Ife lies at the intersection of roads from Ibadan (40 miles [64 kilometer] west), Ilesha, and Ondo. Owo lies within latitude 7˚11'N and longitude 5˚35 'E. Mean annual rainfall is between 1000 mm and 1400 mm, most of this being recorded in the months of April to September. The heaviest rains in Owo come in May/June and September/October. Owo is in southwestern Nigeria, at the southern edge of the Yoruba Hills, and at the intersection of the roads from Akure, Kabba, Benin city and Siluko. Ado Ekiti, (latitude $7^0$37'N and longitude $5^0$15'E) is the capital of Ekiti state in the southwest Nigeria. The mean annual rainfall is about 1600 mm with a temperature range of 23^0C to 34^0C and the relative humidity ranges between 48 and 100%.

Field Experimentation and Soil Sampling

Field experiments were conducted from February to May, 2011. It includes the determination of the soil's infiltration rates, moisture content, soil temperature, air temperature and relative humidity of the sites. Soil samples were collected from soil profiles at three different points, approximately 200 m apart within the 0 - 20 cm soil layer (horizon A). The soil sampling was conducted at the five different locations in the tropical rainforest zone of Nigeria. The samples were packed in plastic bags, and transferred to the laboratory and allowed to dry in the open air until reaching friability.

Physical-chemical Characterization of Soils

The chemical characterization of the various soil sample collected from all the locations includes the analysis of organic matter content, Cation Exchange Capacity (CEC) at pH 7.0, soil pH and base saturation whereas the physical characterization consisted of particle size analysis, water holding capacity, particle density, bulk density and total porosity determination. The percentage Nitrogen, extractable Phosphorus and exchangeable Potassium (K^+) was extracted with HCl solution and their levels determined by flame photometry. The cation exchange capacity (CEC) at pH 7.0 with Ammonium Acetate was determined following the procedure described by Chapman (1965). Soil particle sizes were determined by the pipette method using the ASTM D 422 - Standard Test Method for Particle-Size Analysis of Soils. Textural classification was carried out using the USDA classification system. The bulk density (BD) was obtained by the gravimetric soil core method described by (Blake and Hartage, 1986) using a 5.0 cm long by 7.1 cm diameter cylindrical metal core and the particle density (PD) was assumed to be 2.65 g cm^{-3}. The total porosity (PT) was calculated from BD and PD using the equation and relationship developed by Danielson and Sutherland (1986).

$$\text{Total Porosity} = \frac{1 - \text{Bulk density (g cm}-3)}{2.65 \text{ g cm}-3} \qquad (1)$$

The organic matter content (OMC) was determined using the ASTM D 2974 – Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Organic Soils.

Soil moisture content (MC) was recorded during infiltration using a hand-held digital soil moisture meter - Lutron PMS-714; IP- 65 water resistance, heavy duty ranging from 0-50% moisture content with a 7.9" SS probe supplied by Lutron Electronic Enterprise Co., Ltd. Measurement were taken at 5cm, 10cm, 15cm, and 20cm depth respectively at the experimental sites. Soil temperature (ST) was measured using the Soil digital thermometer DTM-307 supplied by Tecpel Co., Ltd., Taiwan. Tecpel soil digital thermometer has temperature sensors that make measurement precise. Soil temperature is measured by inserting the two sensors into the soil and recording the corresponding temperature values. The relative humidity (RH) and air temperature (AT) of the experimental sites during this research was measured using the Lutron LM-8000 pocket environment anemometer.

The Hydraulic conductivity test was carried out using the mini–disk infiltrometer made by Decagon Devices (Pullman, Washington). It consists of a plastic tube, 22.5 cm long and 3.1 cm in outside diameter, marked with milliliter gradation (0 to 100 mL), a rubber stopper placed in the top, and a styrofoam-looking base that holds the tension. One-half centimeter above the base

is an air-inlet tube. The infiltrometer is constructed of a polycarbonate tube with a semi-permeable stainless steel sintered disk (4.5 cm diameter, 3 mm thick) at set suctions of 0.5 cm and 7.0 cm with a radius of 1.55 cm. Suction rates of 2cm, 3cm, and 4cm per seconds were chosen at different points on the field for the infiltration measurement, which was recorded every 30 seconds for the duration of the experiment. The different suction rates were chosen for better accommodation of infiltration measurement for the different soil types. Data collected were used to calculate the water infiltration rates of the soil.
The hydraulic conductivity of soil was calculated using the method of Zhang (1997), which works well for measurements of infiltration into dry soil. The method requires measuring cumulative infiltration against time and fitting the results with the function:

$$I = C_1 t + C_2 \sqrt{t} \qquad (2)$$

where C_1 (m s^{-1}) and C_2 (m $s^{-1/2}$) are parameters. C_1 is related to hydraulic conductivity, and C_2 is the soil sorptivity.

The hydraulic conductivity of the soil (K_θ) was computed using the relationship

$$K_\theta = \frac{C_1}{A} \qquad (3)$$

where C_1 is the slope of the curve of the cumulative infiltration vs. the square root of time, and A is a value relating the van Genuchten parameters for a given soil type to the suction rate and radius of the infiltrometer disk. A is computed from:

$$A = \frac{11.68\left(n^{0.1}-1\right)\exp\left[2.92(n-1.9)\alpha h_0\right]}{(\alpha r_0)^{0.91}} \qquad n \geq 1.9 \qquad (4a)$$

$$A = \frac{11.66\left(n^{0.1}-1\right)\exp\left[7.5(n-1.9)\alpha h_0\right]}{(\alpha r_0)^{0.91}} \qquad n \quad 1.9 \qquad (4b)$$

where n and α are the van Genuchten parameters for the soil, r_0 is the disk radius, and h_0 is the suction at the disk surface.

Statistical Analysis

The slope of the curve of the cumulative infiltration vs. the square root of time was determined using a Basic Microsoft Excel spreadsheet macro created by Decagon (Decagon Devices, 2007). Soil properties for the different locations were compared using a one way analysis of variance ANOVA and the existence of inter-relationships between data set was tested by linear correlation and the correlation coefficients using statistical package for social sciences (SPSS). Hydraulic conductivity was subjected to statistical analysis to determine the mean, standard deviation, coefficient of variation among soil samples from different locations.

Results and Discussion

Weather Conditions of the Project Locations

The mean maximum soil temperature during the period of the experiment was recorded in Ado (41.9°C), while Ibadan site has the mean minimum soil temperature (29.1°C). The mean soil temperature of Ife is equally high. This might have contributed to the cycle of wetting and drying of the soil and indirect increases in soil bulk density with time. The mean air temperature ranged from 39.2°C to 28.5°C with Ife and Akure having the highest and the lowest values respectively. Ibadan has the maximum relative humidity (66.8%) while Ado has the minimum relative humidity (41.8%). The relative humidity influences the rate of evapotranspiration which in turn affect the soil moisture content. Ambient relative humidity (RH) or the water potential is one of the most important factors that affect the water content and the wettability in surface soil (Doerr et al. 2002; Goebel et al. 2004).

Table 1: Mean maximum and minimum soil temperature (Ts), air temperature (Ta), and relative humidity (RH) of horizon A of the experimental sites.

Location	Ts (°C)		Ta (°C)	RH (%)	
	Max	Min		Max	Min
Ado	41.9 ± 4.24	39.6 ± 3.59	37.5 ± 6.84	41.9 ± 13.52	41.8 ± 13.54
Akure	30.5 ± 6.09	29.8 ± 5.69	28.5 ± 2.89	72.6 ± 8.63	72.3 ± 8.71
Ibadan	29.9 ± 2.49	29.1 ± 2.41	29.9 ± 2.38	66.8 ± 10.15	66.6 ± 10.18
Ife	38.6 ± 3.62	37.8 ± 4.04	39.2 ± 10.47	50.3 ± 22.54	50.2 ± 22.53
Owo	33.4 ± 5.89	33.1 ± 5.89	33.4 ± 3.82	55.2 ± 15.06	55.0 ± 15.06

Physical and Chemical Properties of Sampled Soils

Table 2 shows the result of particle size composition of the collected soil samples. There was little variation in the percentages of sand, silt, and clay among the collected soil samples. According to the USDA classification system, the soil samples collected at the Akure, Ibadan, and Owo sites are predominantly Sandy clay loam while those of Ado and Ife are loam and Sandy loam respectively. Akure has a slightly higher sand content (68.16%) than the others, as well as the lowest silt (10.35%) content. Ado has the lowest sand content (53.68%) and the highest silt (28.32%) content respectively. Ado and Ibadan have the highest clay content (24.33% and 24.32%) while Ife has the lowest clay (14%) content.

Table 2.Textural classifications of soil of the experimental sites.

Location	Sand %	Silt %	Clay %	USDA Textural Class
Ado	53.68	28.32	18	Loam
Akure	68.16	10.35	21.49	Sandy clay loam
Ibadan	59.68	16	24.32	Sandy clay loam
Ife	59.68	26.32	14	Sandy loam
Owo	55.67	20	24.33	Sandy clay loam

The mean percentage organic matter content (OMC) of sites of experiment are 1.45 (±0.08), 1.12(±0.17), 0.58(±0.33), 1.51(±0.48) and 3.29 (±0.38) for Ado, Akure, Ibadan, Ife and Owo, respectively (Table 3). The organic matter content (OMC) was above 3% in Owo with a value of 3.22%, which is the highest value recorded. Ibadan has the least OMC value of 0.58%. Least significant difference (LSD) test conducted on the mean OMC between Ado and Akure soils, Ado and Ife soils, Akure and Ibadan soils, and Akure and Ife soils showed no significant difference at p = 0.05 (Table 4). However, the difference in OMC between Ado and Ibadan soils, Ado and Owo soils, Akure and Owo soils, Ibadan and Ife soils, and Ife and Owo soils is significant at p = 0.05. The differences in mean OMC observed between the different locations may have been caused by both the slightly different textural classes of soils and the levels of residue cover on sampled soils. The highest soil pH value of 6 was observed in Owo and the lowest pH of 5.2 was obtained in Ado. Generally, the CEC at pH 7.0 for all the sites ranged from 3.22 to 0.63 $cmol_c\ kg^{-1}$. Owo which has the highest organic matter content was found to have the highest soil pH and CEC (Table 3). This agrees with the works of Bayer and Bertol (1999) and Vogelmann et al., (2010) who reported that soil samples with higher values of CEC were found to have high levels of organic matter and pH. The high organic matter content of Owo soil might also be due to the high clay content of the sampled soils at Owo and this conforms to the findings that as clay contents increases soil organic matter increases (FAO, 2005). The exception observed in soil samples at Ibadan might have occurred due to the low value of CEC.

Sampled soils collected at Ife equally agree with Bayer and Bertol (1999) and Vogelmann et al., (2010) with CEC and organic matter content of 1.96 $cmol_c\ kg^{-1}$ and 1.51%, respectively. Soil samples from Ibadan exhibited the least CEC and organic matter content, the least percentage nitrogen (0.63%) and exchangeable potassium (0.1 $cmol_c\ kg^{-1}$) but the highest extractable phosphorus (85.61mg kg^{-1}). Ado which has the lowest soil pH also has the lowest extractable phosphorus of 6.71 mg kg^{-1}; this is because Phosphorus availability is strongly influenced by soil pH as reported by Mullen (2009). Availability of Phosphorus is maximized when soil pH is between 5.5 and 7.5 (Mullen, 2009).

Table 3: Means of organic matter content, soil pH, CEC at pH, percentage nitrogen, extractable phosphorus and exchangeable potassium.

Location	OMC (%)	pH	CEC ($cmol_c kg^{-1}$)	N (%)	P (mg kg^{-1})	K ($cmol_c\ kg^{-1}$)
Ado	1.45(±0.08)	5.20(±0.56)	1.47(±0.11)	0.13(±0.03)	6.71(±0.18)	0.15(±0.11)
Akure	1.12(±0.17)	5.34(±0.88	1.71(±0.19)	1.40(±0.14)	16.93(±0.25)	0.58(±0.06)
Ibadan	0.58(±0.33)	5.60(±0.58)	0.63(±0.18)	0.11(±0.03)	85.61(±0.15)	0.10(±0.18)
Ife	1.51(±0.48)	5.80(±0.30)	1.96(±0.24)	0.14(±0.02)	32.31(±0.07)	1.36(±0.47)
Owo	3.29(±0.38)	6.00(±0.21)	3.22(±0.24)	0.18(±0.03)	31.47(±0.13)	0.26(±0.65)

Table 4: Multiple comparisons of mean OMC of the study areas (LSD test at p = 0.05)

Locations		OMC mean difference	Std. Error	Sig.
I	j	i – j		
Ado	Akure	0.33	0.263	0.24^{ns}
	Ibadan	0.87	0.263	0.01*
	Ife	0.06	0.263	0.82^{ns}
	Owo	1.84	0.263	0*
Akure	Ibadan	0.54	0.263	0.07^{ns}
	Ife	0.39	0.263	0.17^{ns}
	Owo	2.17	0.263	0*
Ibadan	Ife	0.93	0.263	0.01*
	Owo	2.71	0.263	0*
Ife	Owo	1.78	0.263	0*

* The mean difference is significant at the 0.05 level
ns – Not significant.

The mean values of soil moisture content at different soil depths and the trend showing their variations from one location to another is presented in Table 5 and Fig. 1 , respectively. The 0 - 5 cm depth had the lowest soil moisture, while the 15 - 20 cm depth has the highest soil moisture. It shows that the soil moisture content increase with depths. This is in agreement with work of Halfmann, (2005) who also noted that soil moisture increases with depth and that there was a significant increase in soil moisture at the 5-10 cm depth. Soil moisture of all the sites varied according to the seasonal distribution of both rainfall and air temperature and this influenced the hydraulic conductivity as high values were obtained in drier soils than in the wetter soils (Bagarello and Sgroi, 2007). The effects of initial water content on infiltration are also well known qualitatively (Philip 1957a, 1969).

Table 5: Means of soil moisture contents at different depths.

	Mean moisture contents (%)			
	Depths (cm)			
Location	0 - 5	5 - 10.	10 - 15.	15 - 20.
Ado	5 ± 2.24	8.7 ± 1.02	10 ± 1.52	10.3 ± 2.37
Akure	2.6 ± 3.61	6.3 ± 4.36	8.1 ± 5.43	10 ± 6.17
Ibadan	4.2 ± 2.71	6.2 ± 2.91	8.1 ± 1.56	10 ± 2.4
Ife	4.7 ± 3.08	6.2 ± 3.37	7.6 ± 1.8	8.5 ± 1.43
Owo	3.3 ± 1.87	5.6 ± 2.84	7.3 ± 2.42	9.2 ± 2.58

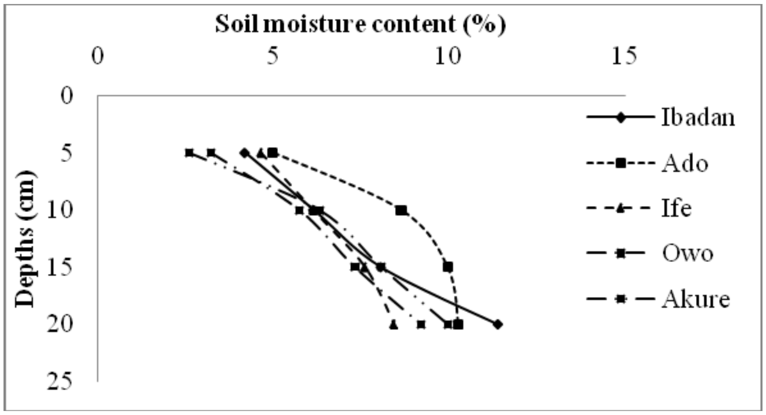

Fig. 1: Soil moisture variation with depths at the sites of experiment

The results of bulk density, total porosity, water holding capacity and soil moisture content are shown in Table 6. The bulk density ranges between 1.5 g cm^{-3} to 1.33 g cm^{-3}. Ife with a sandy loam texture has the highest mean bulk density; this must have been due to the successive rainfall observed towards the final stage of the experiment. This is in conformation with the findings of Fohrer et al. (1999) who reported that soils with low antecedent moisture content were more susceptible to compaction under rainfall. Osunbitan et al. (2005) suggested that high rainfall in combination with cycles of wetting and drying of soil may be responsible for the general increase in soil bulk density with time. The high bulk density values at Ife and Ado could also be due to increase in sand and silt contents of their soil, which according to Hillel, (1982) generally increase soil bulk density.

The total porosity varies from 0.44 cm cm^{-3} to 0.5 cm cm^{-3} with Ife having the lowest while Ibadan and Owo have the highest values. This shows an inverse relationship between the bulk density and the total porosity of soils of the various experimental sites as shown in Fig. 2 (a) and (b). This observation agrees with the works of Vogelmann et al., (2010), Kay and Angers (2002), Gantzer and Anderson (2002) and Ringrose-Voase (1996). The water holding capacity ranged from 25.15% to 36.69% for all soil samples but the highest was recorded in Owo while the lowest occurred in Ife. Owo soils had the highest water holding capacity values (Table 6) probably because it had the highest clay content while Ife with the lowest clay content had the lowest water holding capacity values. This agrees with the findings of Leelamanie (2010), who states that water content of soil samples increased with increasing clay content. According to Hillel (1998), “a sandy soil will absorb water more rapidly during infiltration, but clay can sustain the evaporation process longer”. The result shows that if clay contents increase, water holding capacity of the soil which has a high correlation with the hydraulic conductivity (k) also increase as shown in Fig. 2(c). Also, the high soil temperature observed in Ife (Table 1) site and the consequent drying of the soils might have been responsible for the low water holding capacity. This finding agrees with the observation of Doerr et al., (2006), who stated that the “greater drying of soils is making them less able to retain water”.

Table 6: Means of bulk density (BD), total porosity (PT), and water holding capacity (WHC) horizon A of the experimental sites.

Location	BD (kg cm^{-3})	PT(cm³ cm^{-3})	WHC (%)
Ado	1.44 ± 0.03	0.46 ± 0.01	31.98
Akure	1.33 ± 0.03	0.5 ± 0.01	34.86
Ibadan	1.41 ± 0.19	0.47 ± 0.08	33.57
Ife	1.5 ± 0.06	0.44 ± 0.02	25.15
Owo	1.41 ± 0.03	0.47 ± 0.02	36.69

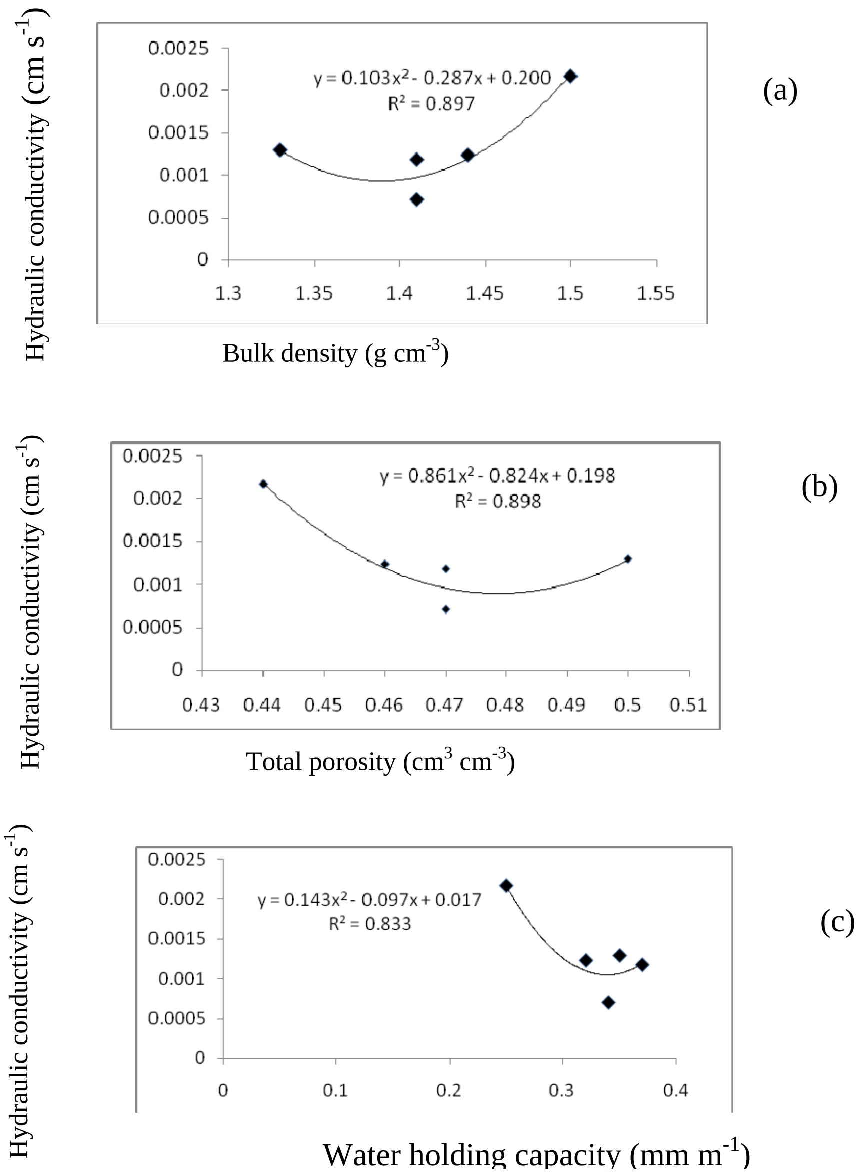

Fig. 2: Relationship between the hydraulic conductivity and bulk density (a), total porosity (b), and water holding capacity (c).

Hydraulic Conductivity and Infiltration of Sampled Soils

The hydraulic conductivity (K_θ) increases with increasing organic matter content. At 2 cm and 4 cm suction, sample soils collected at Ife, which has the highest K_θ value (2.17 x 10^{-3} cm s^{-1} and 1.08 x 10^{-3}cm s^{-1}) has OMC value of 1.51% while at 3 cm suction, Owo soil samples, which has the highest K_θ value (1.47 x 10^{-3} cm s^{-1}) also has the highest OMC value of 3.29%. The organic matter content as reported by Bayer and Bertol (1999) and Vogelmann et al., (2010) is influenced by the CEC as soil samples with high CEC have high OMC and pH. The soil moisture of all the sites varies with times as influenced by the weather conditions such as rainfall, air temperature and relative humidity and in turn affects the infiltration rates and hydraulic conductivity. If the soil profile is initially wetter, then the initial rate of infiltration is generally lower, corresponding to reduced absorption (Furman et al., 2006) and vice versa. The soils bulk density, total porosity and water holding capacity relationship with hydraulic conductivity was shown in Figure 2. Statistical relationship between the total porosity and hydraulic conductivity gave a high correlation coefficient, r = 0.94 at $p < 0.05$. Increasing macro porosity or decreasing micro porosity in soil structure causes increases in soil hydraulic conductivity (Ahuja et al., 1984). Similarly, bulk density and hydraulic conductivity gave a high correlation coefficient, r = 0.94 at $p < 0.05$. The correlation coefficient (r) between water holding capacity and hydraulic conductivity was 0.95. K_θ of Ife at 2 cm suction was 51.1%, 200.8%, and 80.3% higher over the K_θ of Akure, Ibadan, and Owo soils respectively. The difference of mean of K_θ among all soils at the experimental sites are not significantly different at p = 0.05.

Table 7: Means of soil hydraulic conductivity of sampled soils at different suction rates.

	Mean hydraulic conductivity x 10^{-3} (cm s^{-1})		
	Suction rates (cm s^{-1})		
Location	2	3	4
Ado	1.24 ± 0.91	0.69 ± 0.38	0.53 ± 0.29
Akure	1.3 ± 1.05	0.42 ± 0.39	0.48 ± 0.23
Ibadan	0.71 ± 0.39	0.54 ± 0.19	0.37 ± 0.2
Ife	2.17 ± 0.53	1.27 ± 0.21	1.08 ± 0.56
Owo	1.18 ± 1.02	1.47 ± 0.47	0.69 ± 0.41

Table 8: Pearson correlation coefficient (r) among various soil properties

	OMC	PT	BD	MC
OMC	-	0.50 *	-0.50 *	-0.09 ns
PT	0.50 *	-	-0.99**	-0.56*
BD	-0.50 *	-0.99**	-	0.54*
MC	-0.09 ns	-0.56*	0.54*	-

** Correlation is significant at the 0.01 level, * Correlation is significant at the 0.05 level.

Correlation coefficients among some soil physical properties are presented in Table 8. Organic matter content significantly correlated with total porosity and bulk density at p = 0.01. Total porosity correlated significantly with organic matter content, bulk density and moisture content, while the correlation between bulk density and organic matter, total porosity and moisture content were significant at p = 0.05. In this study, increased soil OMC increases the PT and decreases the BD. The inverse relationship between PT and BD was shown (Table 8) as PT significantly increases with decrease in BD and vice versa.

Conclusion

In this research, variations in soil bulk density, total porosity, water holding capacity, and moisture content in five different locations within the south western part of Nigeria were investigated. Also the variability of hydraulic conductivity of soils specifically from horizon A was determined. Total porosity and bulk density shows inverse relationship. Soils hydraulic conductivity increased with increase in organic matter content depending on CEC and soil pH. Soil hydraulic conductivity is highly dependent on soil bulk density, total porosity, and water holding capacity. Results shows that soil physical and chemical properties such as bulk density, total porosity, water holding capacity, organic matter content, and aggregation affect water retention characteristic, infiltration and hydraulic conductivity of soils of the study areas.

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