International Journal of Agricultural and Environmental Sciences
2020; 5(1): 1-7
http://www.openscienceonline.com/journal/ijaes

Influence of Soil Bulk Density and Porosity on Soil Hydraulic Conductivities for Selected Land Management Practice in North-central Nigeria

John Jiya Musa[1, *], Otuaro Ebierin Akpoebidimiyen[2], Johnson Kayode Adewumi[3], Peter Chukwu Eze[4], Richard Adesiji[5], Yahaya Usman Gupa[1]

[1]Department of Agriculturale & Bioresources Engineering, School of Infrastructure, Process Engineering and Technology, Federal University of Technology, Minna, Nigeria

[2]Civil Engineering Department, Faculty of Engineering, Maritime University, Okerenkoko, Nigeria

[3]Department of Agricultural & Bioresources Engineering, College of Engineering, Federal University of Agriculture, Abeokuta, Nigeria

[4]Soil Science Department, School of Agriculture and Agricultural Technology, Federal University of Technology, Minna, Nigeria

[5]Department of Civil Engineering, School of Infrastructure, Process Engineering and Technology, Federal University of Technology, Minna, Nigeria

Email address

johnmusa@futminna.edu.ng (J. J. Musa), e.otuaro@yahoo.com (O. E. Akpoebidimiyen), jjkadewumi@gmail.com (J. K. Adewumi), pcemev66@futminna.edu.ng (P. C. Eze), arichard@futminna.edu.ng (R. Adesiji), yusmangupa@gmail.com (Y. U. Gupa)

[*]Corresponding author

To cite this article

John Jiya Musa, Otuaro Ebierin Akpoebidimiyen, Johnson Kayode Adewumi, Peter Chukwu Eze, Richard Adesiji, Yahaya Usman Gupa. Influence of Soil Bulk Density and Porosity on Soil Hydraulic Conductivities for Selected Land Management Practice in North-central Nigeria. *International Journal of Agricultural and Environmental Sciences.* Vol. 5, No. 1, 2020, pp. 1-7.

Received: January 29, 2020; **Accepted**: March 12, 2020; **Published**: April 7, 2020

Abstract

The purpose of this paper is to evaluate the variation of hydraulic conductivities of soil with bulk density and porosity on different areas, which include the forestland (teak and Melina plantation), grass, maize, beans, and yam cultivated areas using the constant head method. Results obtained from the different areas of the study locations serve as knowledge of the variability of soil that can assist in defining the best strategies for sustainable soil management through the provision of vital information for estimating soil susceptibility to erosion, hydrological modelling and efficient planning of irrigation projects. Hydraulic conductivity is one of the most important parameters for flow and transport-related phenomena in soil and a criterion for measuring soil ability to transfer water. The measurement is at different depths of 0-15 cm, 15-25 cm, 25-50 cm and 50-75cm. The results obtained had a statistical significance level of 0.05. The soil in forest zone (Teak and Gmalina plantations) had significantly high bulk density as 1.75 gcm^{-3} and 1.70 gcm^{-3} respectively at depth 50-75 cm compared to the low bulk density in grass, maize, beans, yam cultivated land as 1.50 gcm^{-3}, 1.48 gcm^{-3}, 1.52 gcm^{-3}, and 1.50 gcm^{-3} respectively at depth 50-75 cm. However, soil hydraulic conductivity was significantly high in the grass area at the surface with 2.88 cmh^{-1}. It is therefore concluded that the study area had different saturated hydraulic conductivity based on the difference in the textural difference of the area.

Keywords

Bulk Density, Hydraulic Conductivity, Land Management, Porosity, Soil

1. Introduction

Knowledge of variability of soil hydraulic conductivity can assist in defining the best strategies for sustainable soil management through the provision of vital information for estimating soil susceptibility to erosion, hydrological modelling and efficient planning of irrigation projects [1]. Hydraulic conductivity of soil is one of the most essential soil properties controlling water infiltration and surface runoff, leaching of pesticides from agricultural lands, and migration of pollutants from contaminated sites to the groundwater [2]. They also stated that hydraulic conductivity depends strongly on soil texture and structure and therefore can vary widely in space. They further stated that hydraulic conductivity also shows a temporal variability that depends on different interrelated factors, including soil physical and chemical characteristics affecting aggregate stability, climate, land use, dynamics of plant canopy and roots, tillage operations and activity of soil organisms.

The hydraulic conductivity of soil is a vital hydraulic property frequently used in hydrological modelling and water flow related studies in soils, such as irrigation and drainage system design and infiltration modelling; it is also a key parameter for the monitoring of soil and water management [3]. Knowledge of the rate of water permeability through various soil types is essential for determining the type of plants to be grown, spacing, yield, managing soil – water systems and erosion control. Many methods have been developed over time for field and laboratory measurement for hydraulic conductivity, unfortunately, these methods often yield substantially dissimilar results, as hydraulic conductivity is extremely sensitive to sample size, flow geometry and soil characteristics [4]. Research has shown that regardless of the land management practices, a small portion of the soil can be transported by a large portion of the water flow, indicating that the spatial hydraulic characteristics of soils are highly variable [5].

In addition, areas in Gidan Kwano are currently undergoing land-use change. The decrease of the forest, which is felled for land clearing, is countered by increasing areas of tree plantations and emerging on formerly agricultural areas, which were abandoned in the process of urbanization. These changes are known to affect the regional water cycle as a result of plant specific water demand and by influencing key soil properties which determine hydrological flow paths. One of these key properties sensitive to land-use change is the saturated hydraulic conductivity (Ks) as it governs vertical percolation of water within the soil profile

Based on the above statement, the major objective of this study is to evaluate the variation of hydraulic conductivities of soil with bulk density and porosity for the study area.

2. Materials and Methods

2.1. Study Area

The location for these crops is Gidan Kwano in Bosso local government area of Niger state. Gidan Kwano is located along Minna - Bida road and is approximately 12 km from the state capital, Minna. Gidan Kwano lies between Latitudes 9°31' N and Longitudes 6°26' E with an estimated landmass of about eighteen thousand nine hundred hectares (18,900 ha). The site is bounded Northwards by the Western rail line from Lagos to the northern part of the country and the eastern side by the Minna – Bida Road and to the North–West by the Dagga hill and river Dagga [6, 7]. The study was conducted in Teak, Gmelina plantation, Grassed, Maize, Beans and Yam cultivated areas at the following coordinates in Table 1. Six locations were selected to perform the experiment, which includes forest sites (Teak and Gmelina plantations), grass area (fallow) and maize cultivated beans cultivated yam cultivated area. Measurement of soil hydraulic conductivity was determined at four depths of 0-15 cm, 15-25 cm, 25-50 cm and 50-75 cm for each of the study locations.

Table 1. *Coordinate of the study sites.*

Locations	Latitude (North)	Longitude (East)
Teak plantation	9°31'1"	6°27'30"
Gmelina plantation	9°30'55"	6°27'28"
Grass area	9°31'55"	6°27'23"
Maize area	9°31'55"	6°27'39"
Beans area	9°31'57"	6°27'25"
Yam area	9°31'55"	6°27'40"

2.2. Laboratory Analysis

Particle size analyses were determined by the hydrometer method according to the procedure of [8] using sodium hexametaphosphate (Calgon) as a dispersant. Soil bulk densities were determined using a core method described by [9]. Soil samples were taken from soil core at depths 0-15 cm, 15-25 cm, 25-50 cm and 50-75 cm on each location of the study area using ring cylinders with height 5.1cm and diameter 5cm [10]. Porosity was determined for each sample collected from the study area [11]. The porosity of the soil was calculated from bulk density and particle density was assumed to be 2.65 mgm^{-3} [12]. The hydraulic conductivity of soil was carried out according to the guideline of Akanegbu [13].

2.3. Statistical Analysis

To compare various results obtained from different plantations for the study areas, a statistical test was carried out. All tests were carried out using SPSS 20.0 version 2010 at a significance level of 0.05. For each of the locations or different plantations, the mean and standard deviation were calculated. In addition, the effect of the plantations on soil hydraulic conductivity, porosity and soil bulk density were investigated.

3. Results and Discussion

The results of soil aggregates and their USDA textural classifications obtained from different sites of the study areas are presented in Table 2. Sandy soil is the most predominant soil in the study areas that are easily detached but hard to transport while clayey soil is hard to detach but easily taken far distance if finally detached. This thus reveals that the actual percentage of sand in any soil sample determines to a great extent the saturated hydraulic conductivity of that particular soil [14].

Table 2: Shows the result of particle size composition of the collected soil samples. The teak plantation shows that there is 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 0-15 cm and 25-50 cm depth are predominantly Sandy clay loam while those of 15-25 cm and 50-75 cm depth are sandy clay and sandy loam respectively. The highest value of sand observed 68% at depth 50-75 cm. It also has the lowest percentage of clay at the same depth. This is in line with research work on manure teak plantation by Fernández-Moya *et al*., [15]. Results from the gmelina plantation showed that at depth 0-15 cm and 25 cm-50 cm had the same percentage of sand content with the teak plantation which was also observed in the studying of Fernández-Moya *et al*., [15]. Same values of clay contents found at depth 15-25 and 25-50 cm as 20%. From the results obtained in the grassed area, it showed that sand contents had the highest value of 65% at depth 0-15 cm and the lowest value of silt content of 15%. At depths between 25-50 cm and 50-75 cm, the clay content was observed to be same. The results from the maize cultivated area showed that at depth of 0-15 cm, 15-25 cm, and 25-50 cm the soil samples collected are predominantly sandy loam while that of depth 50-75 cm was sandy clay loam. The area cultivated with beans indicated that at 0-15 cm and 25-50 cm, the silt content is at 15-25 cm and 25-50 cm the silt content was 15%.

Table 2. *Soil textural classification of the experimental site.*

Study location	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	USDA Textural class
Teak plantation					
	0-15	60	12	28	sandy clay loam
	15-25	50	8	42	sandy clay
	25-50	65	10	25	sandy clay loam
	50-75	68	12	20	Sandy loam
Gmelina plantation					
	0-15	72	10	18	sandy loam
	15-25	62	18	20	sandy clay loam
	25-50	72	8	20	sandy clay loam
	50-75	65	17	18	sandy clay
Grassed land					
	0-15	65	15	20	sandy clay loam
	15-25	60	22	18	sandy loam
	25-50	58	20	22	sandy loam
	50-75	55	23	22	sandy clay loam
Maize cultivated land					
	0-15	72	17	11	sandy loam
	15-25	70	17	13	sandy loam
	25-50	65	22	13	sandy loam
	50-75	60	18	22	sandy clay loam
Beans land					
	0-15	75	13	12	Sandy loam
	15-25	72	15	13	Sandy loam
	25-50	68	15	17	Sandy loam
	50-75	58	20	22	sandy clay loam
Yam land					
	0-15	78	12	10	Sandy loam
	15-25	70	16	14	Sandy loam
	25-50	68	20	12	Sandy loam
	50-75	59	20	21	sandy clay loam

Results of the yam-cultivated area showed that sand content has the highest value of 78% among the plantations and at 0-15 cm depth been the highest. The results obtained from soil textural classification throughout the land use were predominantly having a high percentage of sand particles. This result justifies the works carried by Musa *et al*., [6] for the same study area and similar to the works of Olorunfemi and Fasinmirin, [16], which recorded a high percentage of, sand particles throughout their study. However, the values obtained from their study were observed to be lower when compared with values from this study location. This could be linked to the fact that their study location is in the forest zone where they experience a high amount of rainfall compared to this study location.

3.1. Statistical Results of Bulk Density, Porosity and Soil Hydraulic Conductivity

Table 3 shows the results of mean soil hydraulic conductivity, bulk density and porosity with their respective standard deviation at the different study location. This measurement of soil hydraulic conductivity was determined at four depths of 0-15 cm, 15-25 cm, 25-50 cm and 50-75 cm for each of the locations.

Teak plantation showed that the soil bulk density value was observed to be highest at depth 50-75 cm with little pore space of 33.96%. This pore space is too compacted which recorded 1.00 cmh^{-1} of soil hydraulic conductivity at that depth. The lowest bulk density was observed at the surface i.e depth 0-15 cm which is in line with the study of Ajibola *et al.,* [17]. They carried out the study at Akure, the capital city of Ondo state where they recorded similar hydraulic conductivity at forest area. It was also observed that soil hydraulic conductivity decreases from the surface to the bottom that is from 0-15 cm to 50-75 cm. These values observed from the teak plantation area were much lower than those found by Rubio *et al*., [18] and the study was carried out Vallcebre research catchments, in headwaters of the Llobregat River (NE Spain).

Table 3. *Selected physical properties of the various study locations and their standard deviation.*

Location	Depth (cm)	ρ_b (gcm^{-3})	*P* (%)	K_{sat} (cmh^{-1})
Teak plantation				
	0-15	1.41±0.02	46.92±0.58	1.11±0.02
	15-25	1.50±0.02	43.40±0.76	1.02±0.03
	25-50	1.62±0.03	38.87±0.99	1.01±0.03
	50-75	1.75±0.03	33.84±0.95	1.00±0.02
Gmelina plantation				
	0-15	1.57±0.07	42.39±0.78	1.00±0.03
	15-25	1.59±0.11	42.01±0.43	1.00±0.02
	25-50	1.61±0.07	39.24±1.00	1.01±0.03
	50-75	1.70±0.07	36.48±0.95	1.01±0.03
Grassland				
	0-15	1.30±0.02	51.94±0.65	2.88±0.02
	15-25	1.35±0.02	48.93±0.79	1.48±0.03
	25-50	1.35±0.03	48.93±1.16	1.50±0.02
	50-75	1.50±0.02	43.40±0.76	1.38±0.02
Maize cultivated land				
	0-15	1.30±0.04	50.07±1.43	1.22±0.02
	15-25	1.35±0.01	48.93±0.43	1.15±0.03
	25-50	1.35±0.04	48.93±1.16	1.11±0.03
	50-75	1.48±0.02	44.03±0.79	0.98±0.08
Beans land				
	0-15	1.40±0.02	47.29±0.58	1.50±0.02
	15-25	1.47±0.02	44.40±0.79	1.48±0.02
	25-50	1.37±0.03	48.43±0.95	1.53±0.03
	50-75	1.52±0.03	42.64±0.99	1.37±0.03
Yam land				
	0-15	1.46±0.03	45.03±1.43	1.35±0.03
	15-25	1.40±0.02	47.05±0.87	1.39±0.02
	25-50	1.40±0.01	47.17±0.38	1.39±0.01
	50-75	1.50±0.03	43.39±1.00	1.35±0.03

Where ρ_b=soil bulk density, *P* = porosity and K_{sat} = hydraulic conductivity

The result shows some variation down the profile and these changes down the profile are also in line with the work of Rubio *et al*., [18] due to these variations of soil bulk density, it can be stated that soil bulk density is one of the major soil properties that affect soil hydraulic conductivity. Soil hydraulic conductivities for the selected areas at 0-15 cm depth were recorded the highest value due to low soil bulk densities at the depth. In addition, results for maize cultivated area indicated that the soil bulk densities at 15-25 cm and 25-50 cm are the same and the soil hydraulic conductivity at that depth varies by a small value. At depth 50-75 cm the soil hydraulic conductivity was lowest this could be because of high bulk density and soil textural class at the region and. The highest value of soil hydraulic conductivities from different plantations was recorded in the grassland at 0-15 cm depth and these are as a result of low soil bulk density.

The result obtained from maize cultivated area showed that the lowest soil hydraulic conductivity was recorded at depth 50-75 cm with the corresponding soil bulk density been the highest at the same depth with the smallest value of porosity at the same depth. The result from yam land shows that at depth 15-25 and 25-50 cm the soil bulk density was the same as 1.40 gcm^{-3} at the same depth and they are classified in the same soil textural class. The soil hydraulic conductivity at the surface (0-15 cm) is much lower than at the 15-25 cm and 25-50 cm and these are in line with work carried out by [19]. In general, the maize and yam site at depth of 15-25 cm the bulk density is same which is 1.35 gcm^{-3} also maize and beans site at 25-50 cm depth the bulk density is same as in-depth 15-25 cm of maize and yam site as 1.35 gcm^{-3}. The highest bulk densities are found in teak and gmelina plantation while the lowest bulk density is found in the grassland. These show clearly that the forest plantation, which consists of Teak and Gmelina plantation, showed that there is much compaction in the area, which lead to low soil hydraulic conductivity, and the low saturated hydraulic conductivity varied at different locations. This confirms the spatial variation of hydraulic conductivity as reported by other researchers [18, 20]. This variation was also confirmed by the statistical difference shown by other properties of soil determined which include porosity and bulk density. It was also noted that locations with the same soil textural class had different values of soil hydraulic conductivity. This is in line with the report of Ritzema, [20] that soils of identical texture may have different soil hydraulic conductivity values due to differences in structure.

3.2. Variation of Soil Hydraulic Conductivity Across the Depth

Saturated hydraulic conductivity (Ksat) of soils as affected by texture, structure, bulk density and the compaction problem [21]. Results of this study have shown significantly higher values of Ksat in soils of grass area (2.88 $cmhr^{-1}$) compared to other cultivated areas as shown in Figure 1. this is in line with a work carried out by Osuji *et al*. [22] which stated that vegetation decreases soil bulk density and increases soil organic matter content, which may lead to increases in the flow network of fluids; this increasing the infiltration rates. The Ksat value obtained from the grass area was much lower than the study carried out by Göl, and Yilmaz, [23]. From Figure 1, there is no significant difference between teak and gmelina cultivated area as well as beans, and yam cultivated area. The values of the soil hydraulic conductivity were significantly lower in the forest Soils (Teak and Gmelina cultivated area) than in other cultivated areas of the study areas. This is in accordance with the works of [24, 25, 26]. This could be linked to the traffic of animals by herdsmen around the study area and this contradicts the work carried out by Plaster [27] which stated that the hydraulic conductivity was measured to be lowest in grassland soils and the highest in agricultural soils. This indicates a specific significance of forest in regards to water transport processes in the landscape. Results of the analysis indicate that conversion from forest to grassland or other land use will increase soil hydraulic conductivity. Figure 1 indicates that the deeper the depth the lower the soil hydraulic conductivity which means the soil is compacted down the soil pits of the study areas. Ajibola, *et al.*, [17] stated that low soil hydraulic conductivity in the forest zone is as a result of low exposure of soil to sunlight and low rate of infiltration of water in the soil which was due to the effects of the weight of the overlying soil.

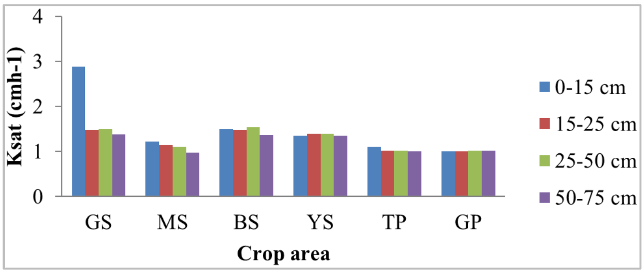

Figure 1. *Variation of plantations on soil hydraulic conductivity at the different plantation.*

3.3. Variation of Soil Bulk Density Across the Depth

Figure 2 presents the bulk density values under different plantations. The lowest values were observed in the maize cultivated and grass area as 1.30 gcm^{-3} at 0-15 cm depth respectively and the highest value was measured in teak plantation (1.75 gcm^{-3}). These results contradicted the works of Göl, and Yilmaz [23]. The differences in bulk density values were found to be statistically significant with respect to the cultivated areas at the 0.05 level. Most of the highest values obtained in Figure 2 were at the surface layer (0-15 cm) depth and the highest bulk density was recorded at the 50-75 cm depth. This clearly indicates that the soil bulk density increases with compaction and tends to increase with depth for the study areas and these increases in bulk density are associated with soil compaction which can cause substantial decreases in soil hydraulic conductivity.

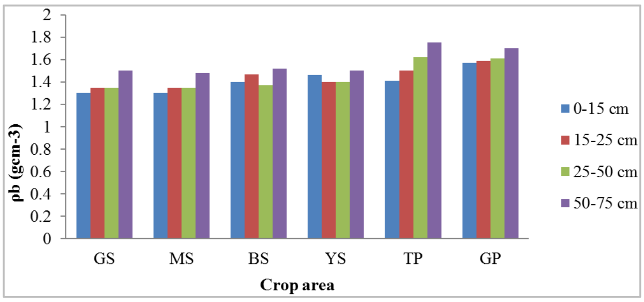

Figure 2. *Variation of bulk density across the depth at the different plantation.*

3.4. Variation of Porosity with Across the Depth

These show the level of pores of each of the areas. Figure 3 shows some level of uniformity of pores, especially for the grass and maize cultivated areas. There is fair uniformity between bean and yam cultivated area while the forest zone (Teak and Gmelina plantation) has the lowest value of pores in the study area. This lowest value of pore space is an indication of low values of soil hydraulic conductivity in the forest zone, which is due to soil compaction, or high values of soil bulk density in the forest zone. This high bulk density is due to the animals' traffic (cow and sheep) in the area by herdsmen. The grass and maize cultivated area have the highest porosity as shown in Figure 3, which allows root growth and development in the soil. Thus, enhancing grain yield compared to the compacted areas of teak and gmelina plantation. The effect of compaction was much more noticed within the 50-75 cm depth in the plantations, which poses different restrictions to rooting depths of the study areas.

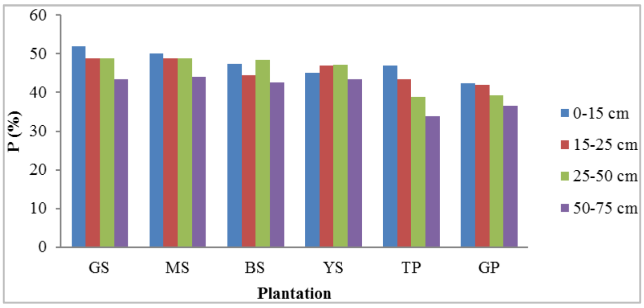

Figure 3. *Variation of porosity across the depths at the different plantation.*

4. Conclusion

The results obtained have shown that saturated hydraulic conductivity varied at different locations. This variation was also confirmed by the statistical difference shown by other properties of soil determined which include porosity and bulk density. It was also noted that locations with the same soil textural class had different values of soil hydraulic conductivity.

The study further reveals the significant differences in the soil of six areas in Gidan Kwano, Nigeria. The soil in forest zone (Teak and Gmelina plantations) had significantly high bulk density as compared to the low bulk density in the grass, maize, beans and yam sites. Soil hydraulic conductivity is highly dependent on soil bulk density, porosity and soil texture. Results show that soil bulk density and porosity, affect soil hydraulic conductivity of soils of the study areas. These results also serve as Knowledge of variability of soil properties that can assist in defining the best strategies for sustainable soil management through the provision of vital information for estimating soil susceptibility to erosion, hydrological modelling and efficient planning of irrigation projects.

Finally, the results of the experiment revealed that soil hydraulic conductivity varies considerably among the study areas and saturated hydraulic conductivity was higher in the grasslands than in other areas.

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