Effects of Soil Compaction and Seasonal Influence on Soil Infiltration Rate in Semi-Arid Region of Nigeria

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Abstract
This paper investigates the effect of soil compaction and seasonal changes on infiltration rates of soils. Study area was divided into three stations having both compacted and non-compacted soils for infiltration capacity tests covered both dry and wet seasons. For dry season measurements, the infiltration rate of a fine/silty sand non-compacted soil range from 2.8 cm/hr to 10.3 cm/hr and 1.7 cm/hr to 5.5 cm/hr for a compacted fine/silty sand soil. For wet season measurements, average infiltration rate of a non-compacted fine/silty sand soil in all the stations range from 1.3 cm/hr to 5.7 cm/hr and 0.8 cm/hr to 3.9 cm/hr for a compacted fine/silty sand soil in all the stations. This shows the influence of both the seasonal changes and soil compaction on soil infiltration rate as compacted soil gave significant lower infiltration rates. Infiltration rates during the dry season was observed to be higher compared to the wet season as a result of more voids being filled with moisture during the wet season. Soil permeability was also observed to be higher in the non-compacted soils than compacted ones. The study is helpful in enhancing the passage of sufficient moisture into the root zones for crop use and preventing excessive runoff. Further studies on effects of different levels of soil compaction on soil infiltration are recommended.

Keywords: Infiltration capacity, seasonal changes, soil compaction, soil permeability.

Introduction

When rain falls upon the ground surface, it wets the vegetation and parts of it runoff the soil surface. When the ground surface is dry, and most of the crops are at the verge of the wilting point, rainfall continues to infiltrate into the soil until a certain soil condition is reached when the subsequent rainfall would begin to runoff the ground surface without further infiltration into the soil mass. This process of water movement into the soil mass, especially through the root zone has been described as infiltration (Haverkamp *et al.*, 2016; Jin *et al.*, 2018). The soil, at this point, is said to be saturated and further addition of water in form of rainfall will further result to surface runoff which move over the soil surface. Infiltration of rainwater into the soil mass is one of the major components of hydrologic cycle. It is a very important component of hydrology as the soil moisture needed by the crops is a function of infiltrated soil which depends on soil texture, vegetation cover, and rainfall intensity and frequency (Archer *et al.*, 2016).

Gao *et al.* (2010) defined infiltration as the movement of water into the soil from the surface by downward or gravitational flow. The study further defined infiltration capacity as the maximum rate at which water can be absorbed by a given soil per unit area under given duration. The infiltration rate decreases as the soil becomes saturated. If the precipitation rates exceed the infiltration rate, runoff will usually occur unless there is some physical barrier (Mangala *et al.*, 2016). Infiltration rate mainly depends on the characteristics of the soil as reported by Leung *et al.* (2015). Libohova *et al.* (2018) also noted that the major soil and water characteristics affecting infiltration rates range from the initial moisture content, hydraulic conductivity of the soil profile, soil texture, porosity, degree of swelling of soil colloids, organic matter, vegetative cover, duration of irrigation or rainfall and viscosity of water'. Of all these characteristics, soil texture and structure are predominant as reported by Bedbabis *et al.* (2014). Osuji*et al.* (2010) also concluded that well-structured soils, in terms of particle size distribution, have optimum infiltration rates at varying moisture levels.

Due to the governments readiness to tackle the menace of under-development in their respective societies and the need to combat the issue of infrastructural decay in most of the major cities of the world, major developmental works are on-going which are capable of changing the hydrology of the affected areas. Thus, land use change policies which are associated with conversion of lands to various other uses and its associated activities have been attributed to change in hydrological pattern of the areas. Soil compaction, therefore, is associated with this urban development, particularly in the areas of road construction and other major Civil Engineering works. Soil compaction can be intentional compacting of a site to increase the structural strength of the soil (Latifi *et al.*, 2015; Zhao *et al.*, 2018) or 'it can be inadvertently caused by the use of heavy equipment and grading of lots' (Sajjadi *et al.*, 2016). Soil compaction influences the soil physical properties by increasing its strength and decreasing its porosity, thereby forcing a smaller distribution of pore sizes within the soil (Jury and Stolzy, 2018). These changes affect the way in which air and water move through the soil and the ability of roots to grow in the soil (Sollins and Gregg, 2017; Lal *et al.*, 2018). This, therefore, explains why flooding has been attributed to soil compaction as reported by Grzesiak *et al.* (2016) and Ferreira *et al.* (2018). A decrease in infiltration rate will result in increased runoff volume, reduced groundwater recharge within watersheds and consequently greater flooding potential.

Various studies have been carried out to check how measured infiltration rates have been related to land development, land use practices, land types, or levels of compaction (Osuji *et al.*, 2010; Ogban and Utin, 2015; Bissadu *et al.*, 2017). According to their conclusions, the soil infiltration rates and soil compaction associated with urban development are negatively correlated. However, there were no established findings that related the dry and wet seasons influence on soil infiltration rate. The hypotheses of this study are that soil compaction as a result of construction practices in societies result in a considerable decrease in infiltration rate on soils and infiltration rate increases during the dry season.

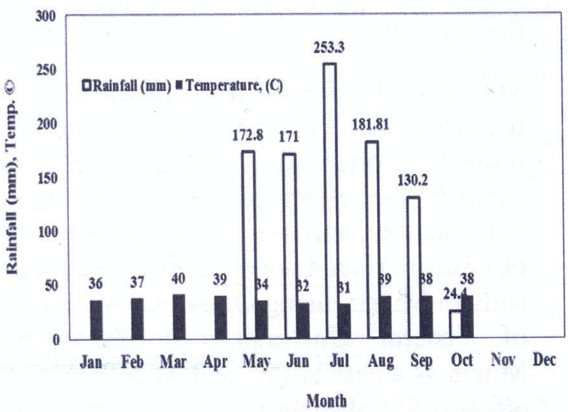
The objectives of this research were, therefore to: 1) determine the seasonal influence on soil infiltration rate, 2) quantify the effect of compaction due to construction activities on infiltration rates of typical urban development sites on sandy soils in Minna, using Gidan Kwano campus of Federal University of Technology, Minna as a case study, and 3) determine the effect of soil compaction on infiltration rates of sandy urban development.

Materials and Methods

Description of study area

Gidan Kwano is located within the basement complex terrain of north-central Nigeria at latitude 9°31'58.57°N and longitude 6°26'41.63° E and is underlain by pre-Cambrian basement rocks of which granite are predominant (Alhassan *et al.*, 2017). The basic lithology of the study area comprises of two rocks types; granite and schist with minor of quartz vein and quartzite. The basement complex includes the Meta sediments, such as Para gneiss, basic and calcareous schist and marble, it also includes Meta intrusive and older granites. The study area enjoys a steady heavy rainfall period from the month of May to September while the temperature ranges between 25 °C to 41 °C (Fig. 1). The dry season lasts from October to April of every year. July, 2017, during the study period, recorded the highest average rainfall depth as 253.3 mm while the highest average temperature was recorded in March as 40 °C (Fig. 1).

The study area was partly made up of areas that had been compacted due to construction vehicle traffic as at the time of the construction of the built-up parts of the institution about 33 years ago. The other portions of the area used for the study were areas that were being used as green areas or lawns that were not in any way compacted.



(Source: Department of Geography, FUT, Minna)

Fig. 1: Annual Rainfall and temperature pattern of the study area

These areas were undisturbed and therefore, will be referred to as non-compacted areas. The research areas were further divided into three (3) stations with each station having both compacted and non-compacted plots within it. The three stations chosen have similar hydrological characteristics as they all fall within same watershed with equal rainfall pattern. The study period ran from the dry season to the wet season, precisely between January to June, 2017 (both months inclusive).

Field experiment

Infiltration rates on compacted and non-compacted soil

Infiltration rates were measured in both compacted and non-compacted soil according to Gregory *et al.* (2006) using a double ring infiltrometer with inner and outer ring diameters of 30 cm and 60 cm respectively that was inserted to a depth of approximately 15 cm. Water intake of the soil was read off with the help of the rule. A 2cm of sand layer was spread at the bottom of the rings to minimize soil surface disturbance when pouring water into the rings. The outer ring was first filled with water so that the soil profile around the inner ring would be wet. This is done in order to ensure that only vertical flow (one-dimension) occurs in the inner ring. The reference levels of the water poured into the rings were recorded at the start of the experiment as indicated by the measuring rule in the inner ring. The infiltration tests were conducted for at least 60 min. Infiltration rates were found to become constant within the first 10 to 15 minutes of the test. Cumulative infiltration was plotted against time and the data was fitted to the Horton's infiltration equation as shown in equation 1. Two sets of data were taken: one in dry season and the other in rainy season, between January and June, 2017. The infiltration measurement between January and April represents the dry season sampling while the measurement between May and July represented the wet season measurement.

$$f_t = f_c + (f_o - f_c)\, e^{-kt} \qquad [1]$$

where;

f_t= infiltration rate at a time t,

f_o= initial or maximum infiltration rate

f_c = equilibrium or constant infiltration rate after the soil has been saturated or minimum infiltration rate.

k = saturated hydraulic conductivity ($mm.hr^{-1}$).

Soil classification and hydraulic conductivity test

The soil classification for the study from the three stations area was obtained using particle size distribution in accordance with ASTM (2007) approach. The permeability test was carried out on soils of the three different stations within the study area. Falling head method of permeability test (Qin *et al.*, 2015) was used in both compacted and non-compacted soil.

Results and Discussion

Soil classification and permeability

Fig. 2 shows the grading curves of the particle size distribution of the soil samples from all the stations in the study area. From the figure, the particle size of the soil samples for both compacted and non-compacted soils range from 0.01 mm to 5 mm which classified the soils as fine/silty sand to coarse sands and fine aggregate. The curves clearly show that compacted soils contain smaller particles than non-compacted soil mass as it is evident in the figure.

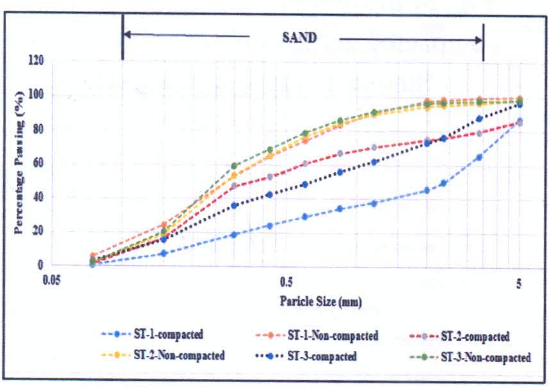


Fig. 2: Particle size distribution of Compacted and Non-compacted soil in all Stations

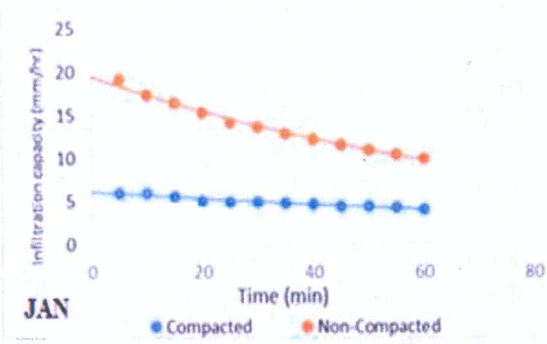
Table 1 presents the comparisons of the coefficients of permeability for various soil classifications and their degrees of permeability for the study areas. Compacted surface in Station 2 has the lowest coefficient of permeability of 8.3×10^{-7} cm/s compared to the non-compacted soil also in Station 2 with coefficient of permeability of 1.1×10^{-3} cm/s. In all the stations, compacted soils recorded the lowest soil permeability compared to non-compacted soils. The lower soil permeability has been attributed to the crushing of aggregates or 'combining them into larger units thereby increasing its bulk density and decreasing the number of coarser pores (Delgado *et al.*, 2007). This has also been known to reduce permeability of water and air into the soil mass (Mooney and Nipattasuk, 2003), increased surface runoff, erosion (Keesstra *et al.*, 2016), leading to flooding and reduction in groundwater recharge (Hamza and Anderson, 2005; Wang *et al.*, 2015).

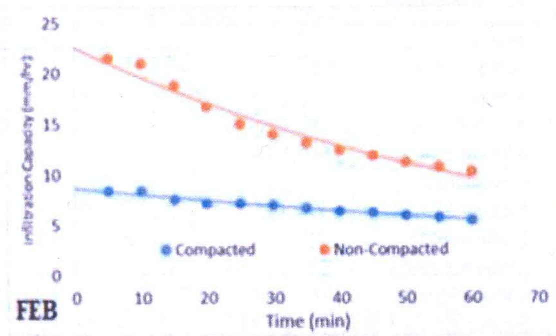
Table 1: Soil Classification according to their Coefficients of Permeability

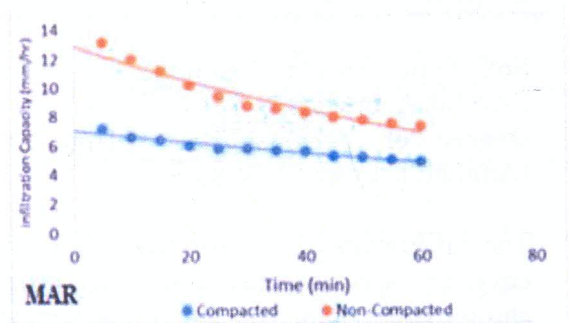
Test value	k (cm/s)	Degree of permeability	Soil type
Station 1 (non-compacted)	2.6×10^{-3}	H/M	F/SS
Station 1 (compacted)	5.1×10^{-4}	Medium	SS
Station 2 (non-compacted)	1.1×10^{-3}	H/M	F/SS
Station 2 (compacted)	8.3×10^{-7}	L/VL	FS/FA
Station 3 (non-compacted)	5.7×10^{-6}	L	FS/FA
Station 3 (compacted)	1.9×10^{-6}	L/VL	S/FA

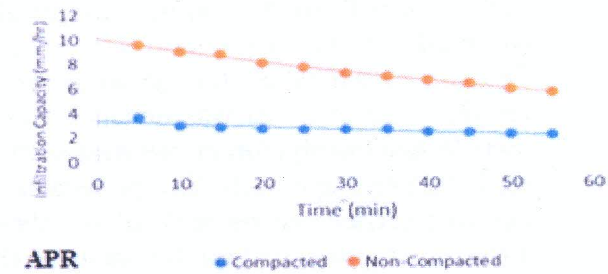
Soil Type: FS-Fine Sand; SS-Silty Sand; FA-Fine Aggregate; S-Sand
Degree of Permeability: H-High; M-Medium; L-Low; VL-Very Low

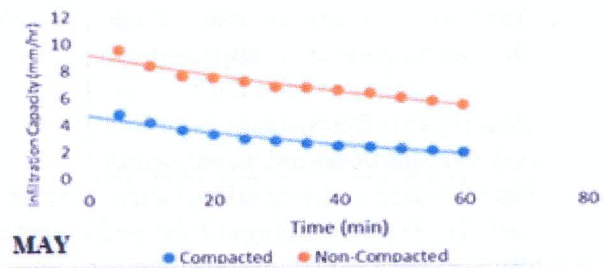
The infiltration curves for Stations 1 to 3 covering both dry season and wet season and for both compacted and non-compacted soils are as shown in Figs. 3 to 5. In all the stations, infiltration rates for compacted soils in both the dry and wet periods were observed to be very low compared to non-compacted soil throughout the sampling periods. This could be attributed to reduction in the permeability of the soil due to frequent compaction of the soil layers by moving vehicular loads around the station. It was also observed that higher infiltration rates occurred during the periods of January to April which represented the dry season as against the infiltration rates observed during the wet season. This has also been attributed to more water filling the voids within the soil mass during the rainy season. The whole analysis took an average of 60 minutes in all the tests carried out before the infiltration rates became constant.











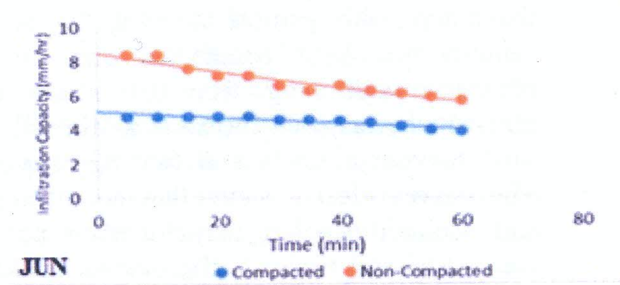


Fig. 3: Infiltration rates (Jan-June) for compacted and non-compacted soil for Station 1 (dry& wet season)

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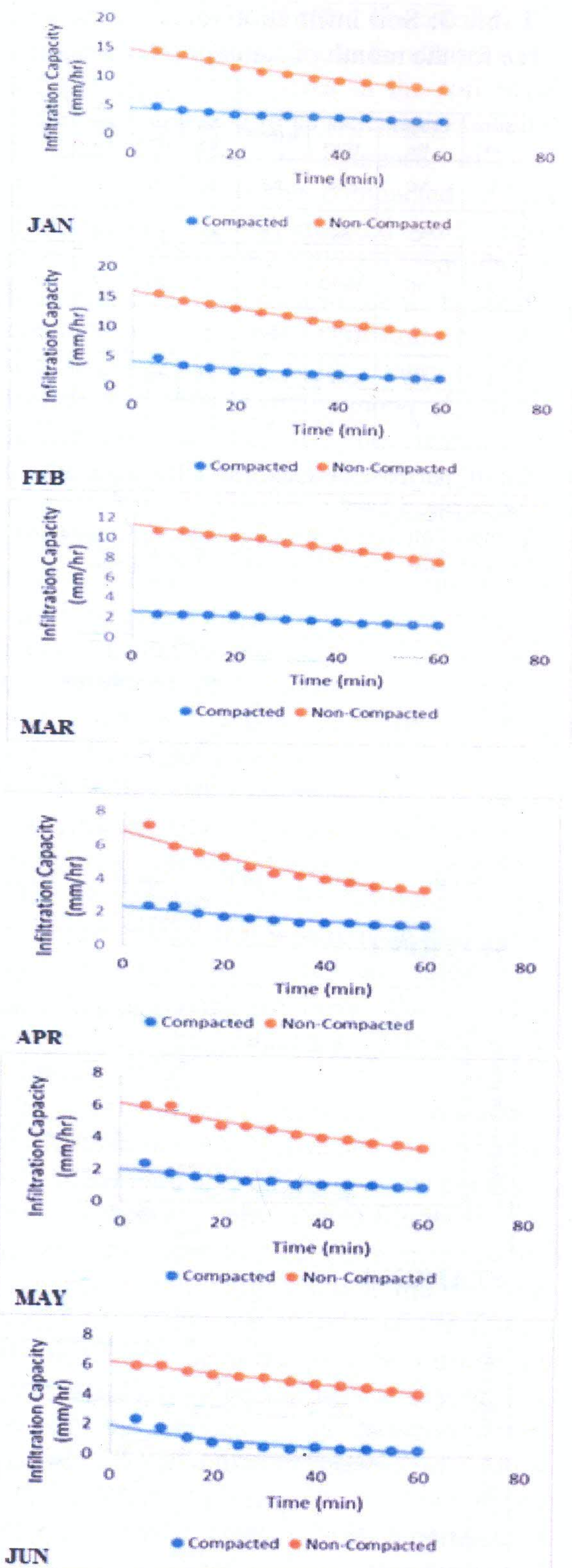


Fig.4: Infiltration rates (Jan-June) for compacted and non-compacted soil for Station 2 (dry& wet season)

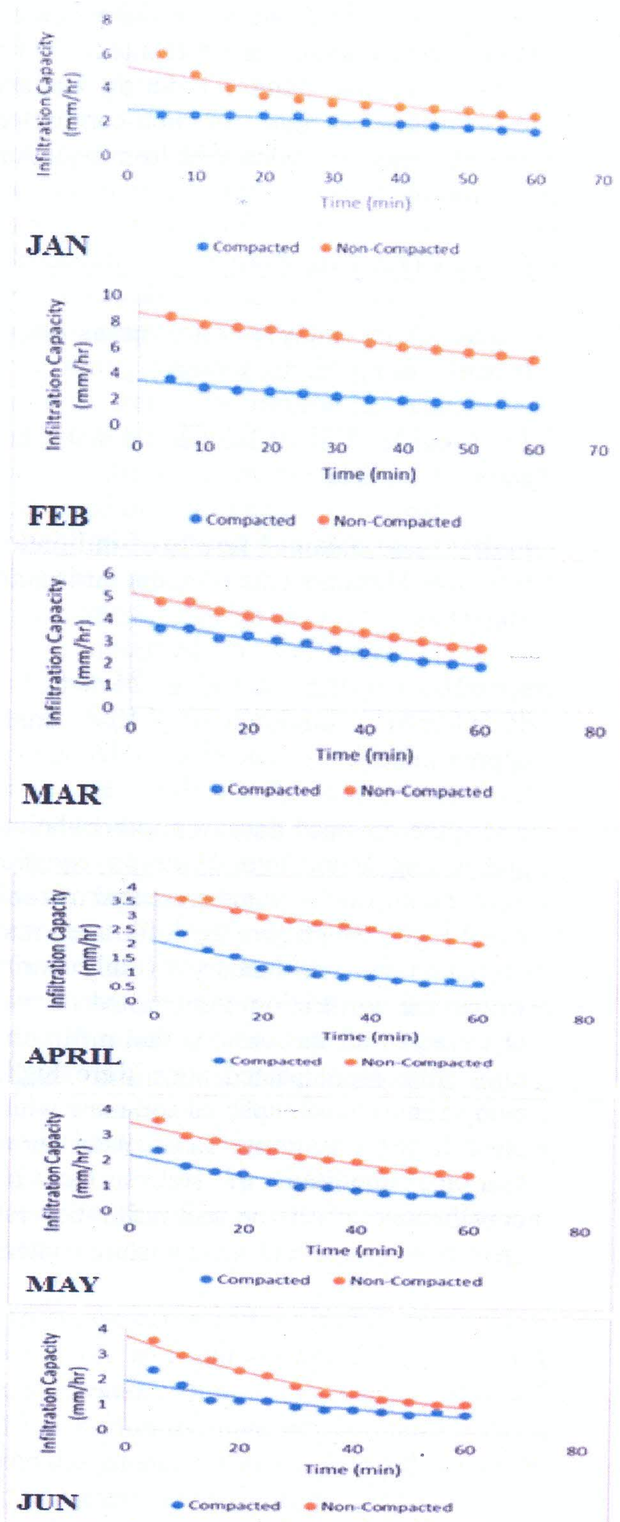


Fig.5: Infiltration rates (Jan-June) for compacted and non-compacted soil for Station 3 (dry& wet season)

The results of infiltration rates as given by Horton's equation is presented (from equation 1). For Station 1 during January test, infiltration rate for non-compacted fine/silty sands is calculated from equation 1 as follows:

$$f_p = f_c + (f_o - f_c)e^{-kt}$$

where, for the study area for the month of January during the dry season,

f_c=10 cm/hr, f_o= 19.2 cm/hr, k = 9.5 hr^{-1} and t = 0.0833 hr^{-1}

Fitting these obtained results of infiltration rates into Horton's equation, the infiltration rate gives

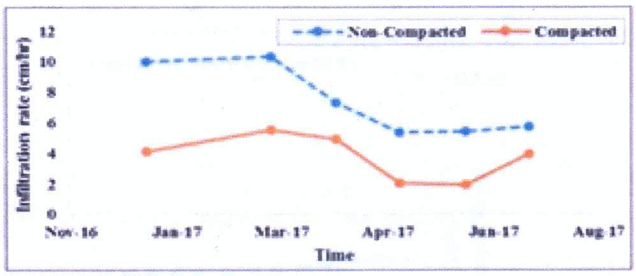
$f_p = 10 + (19.2 - 10)\ e^{-9.5\ (0.0833)} =$ 10.0000574 cm/hr = 10 cm/hr approximately.

Using the obtained data from other stations and fitting them into Horton's equation gave the infiltration rates presented in Table 2 and Fig. 6 which give the infiltration rates as obtained from January to July during which the infiltration tests lasted. It was observed in all the stations that infiltration rates in non-compacted soils were higher compared to the compacted soil mass which gave lower infiltration rates. This shows that the condition of soil surface has considerable effects on soil infiltration rate apart from antecedent soil moisture content.

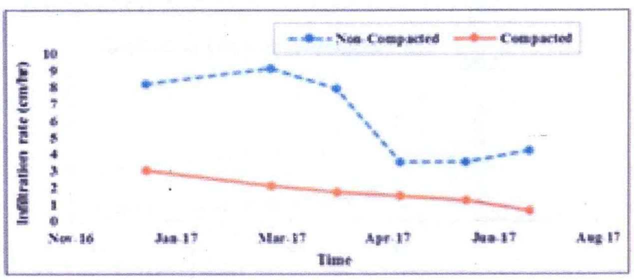
Table 2: Soil Infiltration rates for the study rea for the month of January (Dry season)

				$f_p = f_c + (f_o - f_c)e^{-kt}$ (cm/hr)					
Stations	Compaction	Soil types	k (hr^{-1})	Jan (DS)	Mar (DS)	Apr (DS)	May (WS)	June (WS)	July (WS)
1	NC	F/SS	9.5	10	10.3	7.3	5.3	5.4	5.7
	C	SS	1.9	4.1	5.5	4.9	2	1.9	3.9
2	NC	FS/FA	3.8	8.2	9.1	7.9	3.5	3.5	4.2
	C	FS/FA	0.003	3	2.1	1.7	1.5	1.2	0.6
3	NC	SS/ FA	0.021	2.8	5.6	3	2.2	1.7	1.3
	C	SS/ FA	0.007	1.7	1.9	2.1	0.8	0.8	0.8

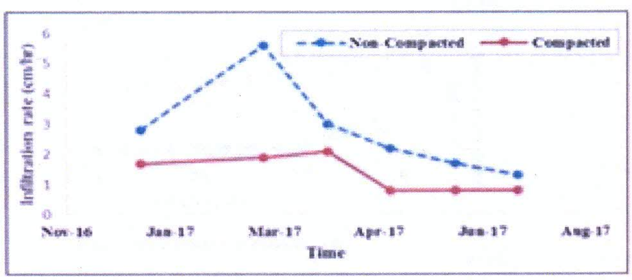
Soil Type: FS-Fine Sand; SS-Silty Sand; FA-Fine Aggregate; S-Sand
Compaction; NC-Non-Compacted; C- Compacted
Season: DS- Dry Season; WS- Wet Season



STATION 1



STATION 2



STATION 3

Fig. 6: Seasonal variability of infiltration rates in both compacted and non-compacted soils for Stations 1 to 3

The lower infiltration rates observed in all compacted soil surfaces can be attributed to a decrease in large pores in the soil mass commonly referred to as macropores. Table 2 also indicated a decrease in soil permeability in all the compacted soil as compared to non-compacted soil. This, therefore, shows that there is correlation between soil compaction, soil hydraulic conductivity and soil infiltration rates which is consistent with Batey (2009), Bailey *et al.* (2015) and Leung *et al.* (2015). In terms of seasonal variability, from Table 2, study periods which ranged from January to July of the water year had major impacts on all the measured infiltration rates as dry season which was between January and April recorded higher infiltration rates in both compacted and non-compacted soils (1.7 cm/hr to 10.3 cm/hr) as compared to wet season which recorded lower infiltration rates ranging from 0.6 cm/hr to 5.7 cm/hr. This shows that there is consistency and correlation between soil infiltration rates and seasonal variability. This, therefore, could be attributed to the high percentage of soil saturation during the wet season as soil pores are filled with water which tends to lower the entry of water into the soil mass (Hazelton & Murphy, 2016).

The relationship between measured infiltration rate during the dry spell and the wet season are also observed to be positive, which explains why the infiltration rate largely and spatially depends on seasonal changes (Fig. 6). Fig. 6 shows the seasonal variability of infiltration rates of the soil in all the three stations. Higher infiltration rates were observed during the dry season in both the compacted and non-compacted soils in all the stations. The soil infiltration rates started declining in the month of March in all the stations for both compacted and non-compacted soils and this continued through the month of June in all the stations.

Conclusions

The effects of soil compaction and seasonal variability on soil infiltration rate have been studied. The infiltration capacities of studied catchments at each station under different soil compaction and types of soil are also discussed. The influence of soil hydraulic conductivity and soil infiltration rates was also studied. The study shows that soil compaction coupled with seasonal variability negatively affect the infiltration rate of soils. The infiltration capacities of the soil for all the studied stations varied and declined at diverse rates due to both seasonal influence and soil compaction. The study also showed that there is correlation between soil compaction and soil infiltration rates as soil infiltration rates were observed to be higher in a non-compacted soils compared to compacted soils. Soil hydraulic conductivity was also observed to influence the soil infiltration rate as soils with higher hydraulic conductivity recorded high soil infiltration rates. The study also established that the sandy nature of the soils in the study area accounts for high infiltration rates in both the dry and wet periods of the water year. On these sandy silty soils, the lowest level of compaction resulted in significantly lower infiltration rates, especially during the wet season. Therefore, runoff mostly experienced in these areas during the wet season could be attributed to soil compaction which results to low infiltration rate.

The measurement of infiltration rate plays a vital role in irrigation development or soil conservation. Since the results obtained from infiltration data are normally used at the design stage, it is recommended that the comprehensive soil compaction studies be carried out on soils being used for agricultural activities. This will enable the determination of water infiltration rate into the soil's root zones which aids the passage of sufficient moisture into the root zones for crops use. Further studies on effects of different levels of soil compaction on soil infiltration are recommended. Also, more stations should be identified for studies to give a good representation of the study area.

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