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Comparison of Infiltration Rate and Hydraulic Conductivity of Three Dominant Soil Series for Irrigation Planning in Federal University of Agriculture, Abeokuta Southwestern Nigeria

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Abstract
Infiltration rate and hydraulic conductivity are important hydraulic parameters for flow and transport related phenomena in soil, but results vary from different measuring methods and field conditions. To evaluate the reliability of field method using the double ring and laboratory methods using the falling head permeameter, Infiltration and hydraulic conductivity tests on the three dominant soil series in the Federal University of Agriculture, Abeokuta i.e. Ekiti, Iseyin and Iwo were investigated. The constants of linear regression of the infiltration rate were obtained using Kostiakov's and Phillips equations as a and n to be 0.01 and 0.598 for Ekiti, 0.063 and 0.627 for Iseyin and 0.173 and 0.648 for Iwo soil series respectively. For Philip's equation, a and b were found out to be 9.73 and 8.981 for Ekiti, 7.1 and 7.603 for Iseyin and 12.87 and 18.79 for Iwo soil series respectively. The average infiltration rates and cumulative infiltration were found to be 20.03, 15.93, and 34.77 cm/hr for Ekiti, Iseyin, and Iwo soil series respectively. The average values of hydraulic conductivity for Ekiti, Iseyin and Iwo were found to be 11.12, 10.07, and 22.6 cm/hr respectively. Iwo soil series was the most suitable for sprinkler irrigation due to its high infiltration rate while Ekiti and Iseyin soil series will suit drip irrigation adequately. This study also established that based on the derived relationships, permeability or hydraulic conductivity tests can be easily done in the laboratory rather than the cumbersome activity of carrying out infiltration on the field with a double ring infiltrometer.

Keywords: Double ring infiltrometer, soil series, falling-head permeameter, infiltration rate, irrigation planning.

1.0 INTRODUCTION

The management and use of water flowing in soils is of utmost importance if an increase in agricultural production is to be achieved globally (Mirzaie *et al*., 2019). For water to be applied to soils as irrigation during periods of scacity, there must be good knowledge of the infiltration characteristics of the soil. Precision agriculture can be achieved successfully if water application rates are monitored (Bastiaaanssen *et al*., 2000) . This will also improve on the management of water resources on farmlands for crop productivity and optimum yield. The amount of water entering into a soil is largely dependent on the rate and duration of water application, slope, vegetation density, surface roughness physical properties of the soil strata and the infiltration capacity of the soil (Assouline, 2013; Raghunath, 2006; Bagarello *et al*., 2017).

Several infiltration measurements methods have been developed in the past for flow and transport related activities in the soil most especially when it relates to irrigation procedures, the reliability and implementation of these methods for different field conditions is of utmost importance to engineers. Gupta *et al*. (1993) conducted a study with four field methods using the double ring infiltrometer, rainfall simulator, Guelph permeameter and Guelph infiltrometer in Canada to access the reliability and variability of each method under different field conditions. He reported that soil and field conditions were the major factors responsible for the variations. Mohanty *et al*. (1994) also compared four in situ methods: Guelph permeameter (Xu and Mermoud, 2003), velocity permeameter, disk permeameter, double tube and the laboratory constant head permeameter to estimate saturated hydraulic conductivity in a glacial-till soil and the study revealed that better estimation of saturated hydraulic conductivity with little variation was achieved with the velocity permeameter and the laboratory method using the constant-head permeameter. It can also be said that many of these methods showed different trends of saturated hydraulic conductivity under various soil types due to flow geometry, characteristics of the soil, size of samples (Sarki *et al.*, 2014) and irrigation system (Messing and Jarvis, 1990; Mubarak *et al*., 2009a).

Determination of infiltration rate is slow and relatively tedious on the field using the double ring approach (Waduwawatte *et al*., 2004). The hydraulic conductivity of a soil gives an indication of the soil's ability to imbibe and transmit available water to crops root zones and to drain excess water from root zones. It is not a property of the soil alone but it also depends on the permeability of the soil, density, moisture content, particle size distribution, structure and fluid type (Hillel, 1998; Choong-Ki *et al*., 2018). Hydraulic conductivity determination in the laboratory can be used to plan for water application rates for drip and sprinkler irrigation design systems (Islam *et al*., 2017; Zeng *et al*.,2013). This will ensure that waterlogging and excessive runoff is minimised. Hydraulic conductivity is a very important factor to consider when studying the infiltration capacity of soils. It is the measure of the soil's ability to transmit water when subjected to a hydraulic gradient (Damiani and Somella, 2004).

The objective of this study was to compare infiltration rates and hydraulic conductivities of three dominant soil series in Abeokuta and to develop models useful for irrigation planning and management.

2.0 MATERIALS AND METHODS

2.1 Study Area

The study site was located in the Federal University of Agriculture, Abeokuta (Latitude 7°14' N and longitude 3°21' E). The annual rainfall of the study area is 1200 mm with mean annual temperature of about 27°C. The vegetation is mainly of secondary forest and mixed cropping is the dominant farming practice in the study area and most of the farmers in the locality grow maize intercroped with cassava, yam and vegetables. Seven soil series were identified in the study area (Figure 1). They are Apomu, Egbeda, Ekiti, Iseyin, Iwo, Jago and Okemesi (Aiboni, 2001; Sotona *et al*., 2014). However, the three dominant soil series in the study area are:

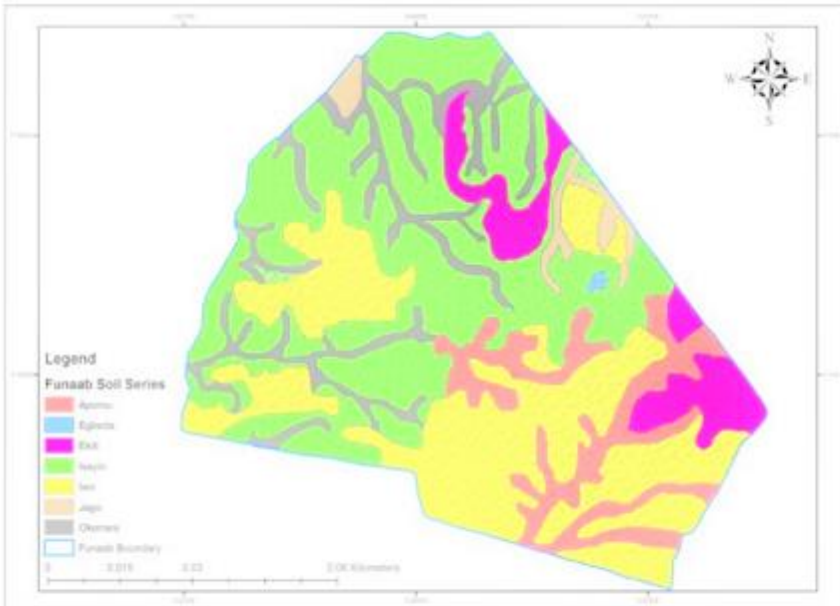

Figure 1. Map of soil series in Federal University of Agriculture, Abeokuta

i. **Iseyin soil series**: this soil series is excessively well drained very sandy with dark brown quartz gravel up to about 50% by weight of the soil. It has high gravel content in the subsoil. It is located all over the lecture hall areas and the hostel area within the University premises.
ii. **Iwo soil series**: this soil series is also well drained and is developed from relatively coarse grained granite and gneisses. It is located about 15 kilometers from the main campus of the University at the Institute of Human Resources and Development (INHURD) village at Mahuko, Abeokuta.
iii. **Ekiti soil series**: this soil series is shallow, consisting of dark, humid, fine earth material overlying unweathered granite or gneiss. It is located where University fence terminates along Alabata road, Abeokuta.

2.2 *Soil Sampling and Protocol*

Particle size analysis was determined using the hydrometer method (Gee and Or, 2002), bulk density was determined by the method of Blake and Hartge (1986) and gravimetric water content (initial and final) of the soil was determined using standard procedures.

Three locations were used as sampling points for the infiltration runs for each soil series. The infiltrometer used for the study has an inner diameter of 23 cm and outer diameter of 36 cm respectively. Height of both ring infiltrometers is 30 cm. Each ring was supplied with a constant head of water and this was achieved with the use of the connected Mariotte's bottle. The rate of infiltration was determined by the amount of water that infiltrated into the soils per surface area, per unit of time. Infiltration was measured by double ring infiltrometer, because the outer ring helps in reducing the error that may result from lateral flow in the soil. The outer ring virtually turns a 3D single ringed system of looking at infiltration into a one dimensional model by allowing water in the centre ring to flow nearly exclusively straight down. This allowed much easier calculation by taking out the need to account for lateral flow. Before the double rings can be placed in position the ground cover (vegetation) was removed without disturbing the soil surface. Once this was done the rings were set in position and knocked into the ground to a depth of 10 cm while making sure that the rings were set firmly in the ground.

Water was supplied inside the rings manually. When filling up the rings the outer ring was filled first so that the soil profile around the inner ring would be wet and only vertical flow would occur when the inner ring is filled later. When filling the inner ring water is poured in on a textile cloth which was to prevent the soil surface pores from being disturbed during the introduction of water in the ring then once the desired amount of water is in the ring on the sheet, the cloth is removed quickly. The level of the water was recorded with a ruler at this point and the commencement of infiltration noted on the stop watch.

In obtaining the infiltration functions of the soil series, the Kostiakov and Phillip's equation given in equations (1) and (2) were used (Kostiakov, 1932; Phillips, 1957).

$$F = at^n \qquad 1$$

where,
F = infiltration rate mm/day or cm/hr
t = time since the start of infiltration
a and n are constants.

$$F = \frac{St^{-\frac{1}{2}}}{2} + c \qquad 2$$

where,
S = soil sorptivity (cm/hr$^{0.5}$)
T = time to reach constant infiltration rate (hr)

Hydraulic conductivity tests were carried out in the laboratory using the falling-head permeameter. The permeameter used was the K-605A combination permeameter designed to determine the permeability of both fine grained and coarse grained soils. The falling head which is usually good for fine grained soils was used in this study based on the fact that the soils under investigation were fine grained.

Vertical hydraulic conductivity was investigated using equations (3) and (4).

$$K = \frac{2.3aL}{At} \times log1_{10}\frac{h_0}{h_1} \qquad 3$$

Since, A= $31.65cm^2, then$

$$K = \frac{aL}{13.76t} \times \log_{10}\frac{h_0}{h_1} \qquad 4$$

where,
K = the coefficient of permeability (cm/s)
L = length of sample in (cm)
a = area of cross section of burette (cm^2)
A = the area of permeameter (cm^2)
t = time (s)
h_0 = initial hydraulic head difference across length L

h_1=final hydraulic head in cm of water.

Three replicates of detached soil cores; 8 cm long and 6 cm diameter were collected from each soil series using a core sampler. Soil filled cores were saturated in the laboratory by wetting from the bottom. Saturated hydraulic conductivity was measured under a falling head. Falling head permeability test was used to determine the hydraulic conductivity of the fine grained soil, with more than 10 percent of its particle passing through a No. 200 sieve. The soil sample was compacted in the lower chamber of the permeameter, in layers approximately 1.25 cm deep, to within about 2 cm of the lower chamber rim. An appropriate tamping device was used to compact the sample to the desired density. The length of the sample was measured and recorded.

The clamp was used to attach the falling head burette to the support rod. The height of water in burette above the chamber outflow was measured using a meter rule. The soil samples were saturated, after a steady flow has been established, the time required for the water level to fall from one convenient selected level to another level was noted using a stop watch. The height of the two levels from the outflow level was measured.

Measurement of hydraulic conductivity was based on the direct application of Darcy's equation to a saturated soil column of uniform cross-sectional area. A specific hydraulic head difference was imposed on the soil column and the resulting flux of water was measured.

3.0 RESULTS AND DISCUSSION

3.1 Particle Size Analysis and Bulk Density

Particle size analysis was determined on all the three soil series used for the study. Iwo, Iseyin and Ekiti soil series were all sandy (Table 1). Iseyin series had the highest bulk density and this can be attributed to its high clay content and this had an effect on the infiltration rate and hydraulic conductivity. Iwo series also had a similar property to the Iseyin series and this was due to the high clay content (Table 1). Ekiti series had low bulk density thereby having a fairly strong influence on the infiltration rate (Figure 1).

Table 1: Soil physical properties of dorminant soil series in study area

Soil Series	Particle Size Distribution (g/kg)			Mean Bulk Density (g/cm^3)	Textural Class
	Sand	Silt	Clay		
Iwo	750	76	174	1.203	Sandy loam
Iseyin	830	16	154	1.304	Sandy loam
Ekiti	790	154	56	0.933	Loamy sand

3.2 Effect of Moisture Content on Soil Series

It was observed that Iwo soil series has very low initial moisture content which consequently makes the initial infiltration rate to be very high (Tables 2 and 3) and better ability to absorb water. Ekiti soil series had very high final moisture content which revealed high saturation state of the series which ultimately lowers the infiltration rate and high infiltration capacity. Consequently, Iseyin soil series had a little difference between initial moisture content and final moisture content, leading to a high infiltration rate and low water retention ability.

Table 2: Effect of moisture content on soil series

Soil Series	Initial moisture content (%)	Final moisture content (%)
Iwo	2.43	31.9
Ekiti	6.9	60.57
Iseyin	10.2	19.9

3.3 Mean cumulative and constant infiltration rate of different soil series

The mean cumulative infiltration of Ekiti soil series was 18.65 ± 2.71 cm/hr while final infiltration rate was 4.0 cm/hr. For the Iwo series the mean cumulative infiltration was 34.77 ± 2.35cm/hr and the final infiltration rate was 7.0 cm/hr while for the Iseyin series the mean cumulative infiltration was 16.6 ± 2.22cm/hr and the final infiltration rate was 4.0 cm/hr (Figures 2-4).

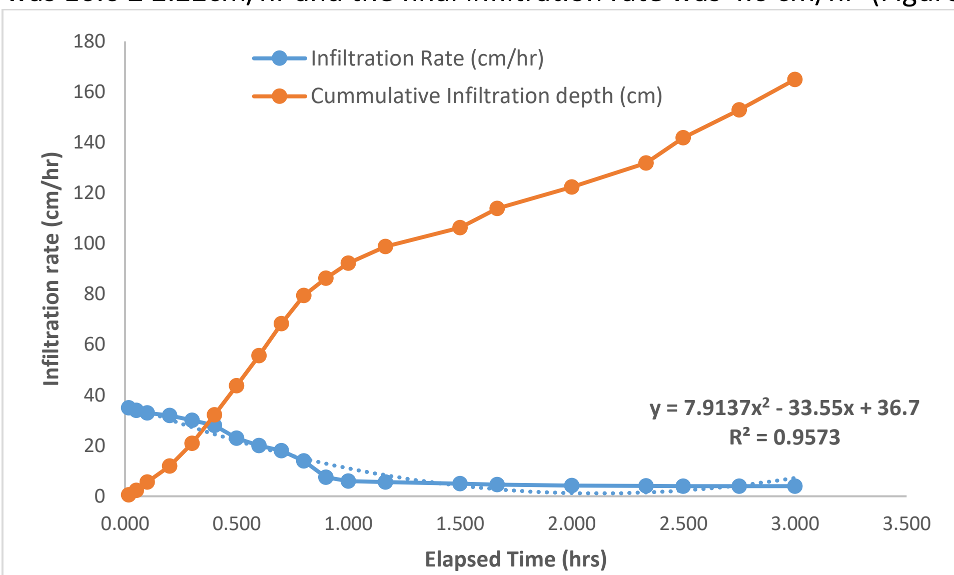

Figure 2: Mean infiltration rate (cm/hr) and cumulative infiltration depth (cm) of Ekiti soil series against elapsed time (hrs)

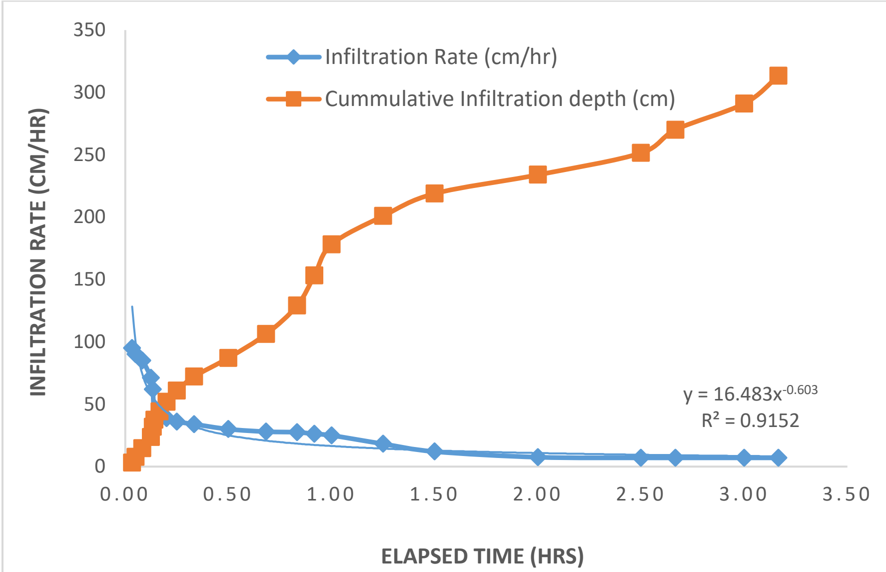

Figure 3: Mean infiltration rate (cm/hr) and cumulative infiltration depth (cm) of Iwo soil series against elapsed time (hrs)

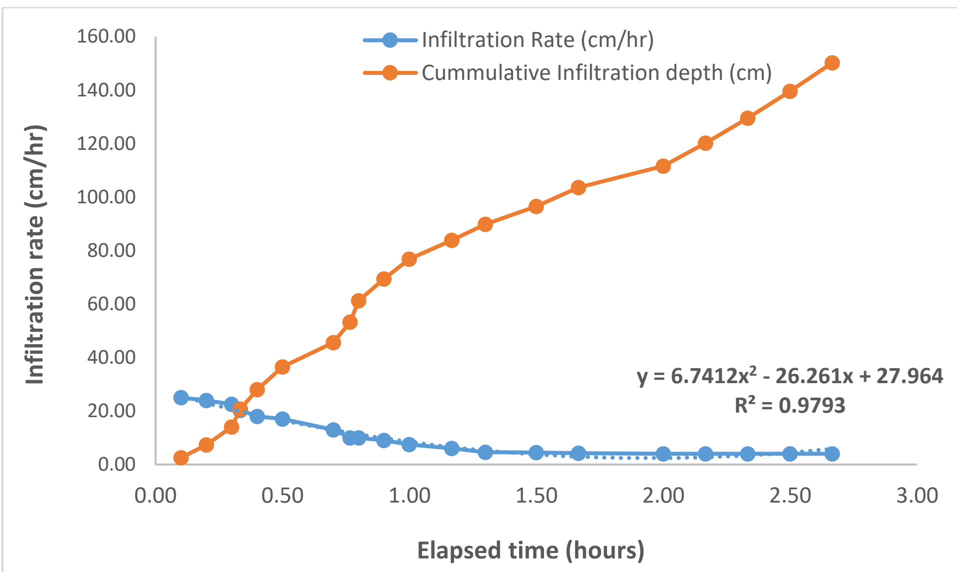

Figure 4: Mean infiltration rate (cm/hr) and cumulative infiltration depth (cm) of Iseyin soil series against elapsed time (hrs)

3.4 Comparison of mean infiltration rate and hydraulic conductivity of the three soil series

The infiltration rate and hydraulic conductivity of Ekiti and Iseyin soil series fall within the same range (Table 3). Also, considering the mean values of infiltration rate and hydraulic conductivity for each series, we observed that a correction factor of 0.6 to 0.7 can be multiplied by the infiltration rate to determine the hydraulic conductivity.

Table 3: Relationship between mean infiltration rate and the mean hydraulic conductivity of each soil series

Soil series	Infiltration Rate (cm/hr)	Hydraulic Conductivity (cm/hr)
Ekiti	18.65 ± 2.71	11.12 ± 1.45
Iwo	34.77 ± 2.35	22.60 ± 2.89
Iseyin	16.60 ± 2.22	10.07 ± 1.69

3.5 Models for the different soil series using Regression Analysis

The Kostiakov (1932) and Phillips (1957) equations are developed for infiltration studies to asses and interprete water movement into soils.The Kostiakov equation reveals saturated infiltration appropriately and assumes that the intake rate reduces over time according to a power function as shown below while the Phillips equation separates the infiltration process into two components, that influenced by sorptivity and that influenced by gravity. The Phillip equation takes the form of a power series but under practical situations, an adequate description is given by the two-parameter equation:

$$F = At^{0.5} + bt \qquad 5$$

where,

F is the infiltration rate
A is sorptivity in mm/hr
and *b* is a gravity factor related to hydraulic conductivity at large time.

The Phillips (1957) equation has been shown to be very adequate for predicting infiltration parameters in longer times and it was used in this study based on the fact that sorptivity values which give early infiltration without the influence of gravity can easily be predicted from it.
Regression analysis was done using the Kostiakov's and Philip's equations.
From Kostiakov's equation,

$$F = at^n \qquad 6$$

where,
a and n are constants,
F = the infiltration rate in cm/hr
t = the time in hr.
By finding the log of both sides,

$$\text{Log } F = \log a + n\log t \qquad 7$$

Plotting a graph of log F against log t
Log a= intercept of the graph
n= slope of the graph.
From Philip's equation,

$$F = at^{0.5} + bt \qquad 8$$

where,
a and b are constants,

F = the infiltration rate (cm/hr)
t = the time in sec

Dividing through by t, Philip's equation becomes:

$$\frac{F}{t} = at^{-0.5} + b \quad 9$$

Plotting the graph of F/t against $t^{-0.5}$

a = slope of the graph
b = intercept.
Substituting a and b into equation 2, and vary the values of t to get F.

Using the above, a general equation was postulated for the three soil series.
Using Kostiakov equation;
for Ekiti soil series:

$$F = 0.01t^{0.598} \quad 10$$

for Iseyin soil series:

$$F = 0.063t^{0.627} \quad 11$$

for Iwo soil series:

$$F = 0.173t^{0.648} \quad 12$$

Using Philip's equation,
for Ekiti soil series:

$$F = 9.73t^{0.5} + 8.981t \quad 13$$

for Iseyin soil series:

$$F = 7.1t^{0.5} + 7.603t \quad 14$$

for Iwo soil series:

$$F = 12.87t^{0.5} + 18.79t \quad 15$$

where,

F = infiltration rate in cm/hr
t = elapsed time in hrs.

4.0 CONCLUSION

Based on this study, it can be concluded that the Iwo soil series is the most suitable soil to carry out irrigation practices because of its high infiltration rate. Drip irrigation could be carried out on other soil series which are the Ekiti and Iseyin due to the lower intake rate.
This study has established a relationship between the infiltration rate and the hydraulic conductivity of the soil series using the Kostiakov and Phillip's equations adequately. In essence, while planning for irrigation design on soils with these soil series, field samples can be collected and such samples can be subjected to permeability or hydraulic conductivity tests in the laboratory instead of wasting a lot of time and resources in carrying out infiltration tests with the double ring on the field.

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