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Comparison of Saturated Hydraulic Conductivity Measurement Methods for Samaru-Nigeria Soils

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Abstract: There are numerous methods for estimating saturated soil hydraulic conductivity (Ks), ranging from direct measurement in the laboratory, to models that use only basic soil properties e.g. texture or water retention curve. In this study, the saturated hydraulic conductivity of four sites with samples taken at different depths (15, 30, 45, 60 cm) on the Institute for Agricultural Research (IAR) field, Samaru, Zaria was determined in the laboratory using the constant head permeameter method. The results were compared to selected soil physical properties (bulk density, porosity, percentage clay etc..). A redefined Kozney Carman model and Yannopoulos equation were used to predict Ks. The results obtained from the laboratory were compared with the Kozney-Carman and Yannopoulos prediction models. Yannopoulos model predicted closer to the measured data even though it predicted higher than the measured values. Adjusted factors were determined to enable the model predict as accurately as the measured values. Kozney-Carman predicted far lower than the measured data.

Key words: Saturated hydraulic conductivity % Empirical models % Soil moisture characteristics curve

INTRODUCTION

The soil water movement is of considerable importance to many aspects of agricultural systems. The behaviour of soil water flow systems, such as the flow of water to drains and wells, evaporation from the soil surface, the movement of water to plant roots and many others, are K determined by the soil moisture characteristic curve. Hydraulic conductivity (K) is a measure of soil ability to transmit water while the soil moisture characteristic curve is an expression of its ability to store water in other words; K is a measure of the ability of soil to conduct water under a unit of hydraulic potential gradient.

There are two types of K, namely; saturated and unsaturated hydraulic conductivity. In saturated hydraulic conductivity (Ks), only the solid (soil particles) and liquid (water) states of matter exist. All the pore spaces are completely filled with water and the K is constant.

However, in unsaturated flow, the K is not constant; it decreases as the water content decreases because the pore spaces are not completely filled, and there is the existence of air in some pore spaces. Here, three states of matter (solid, liquid and air) exist.

Determination of Hydraulic Conductivity: Mohanty *et al.* [1], outlined various methods of determining K as:

- Guelph Permeameter method: This is a constant head permeameter that measures a composite of vertical and horizontal Ks in the field.
- Constant – head permeameter method: This is carried out in the laboratory and it is based on the direct application of Darcy's equation to a saturated soil column of uniform cross- section area.
- Disk Permeameter method: This is a constant – head infiltrometer that can operate at either a positive or a negative head.
- Double tube method: This method uses two concentric cylinders installed in an auger hole.
- Velocity permeameter method: This is a falling head permeameter method.

Mbagwu [2] showed that saturated hydraulic conductivity (Ks) could be approximated from infiltration data in two ways:

Firstly, that the hydraulic gradient in the transmission zone approaches unity and the final infiltration rate equals Ks. Secondly, from pure theoretical analysis that for long infiltration times, the transmissivity term (A) in the infiltration model is thus:

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$$I = St^{1/2} + At \quad (1)$$

Where
I = measured cumulated infiltration.
t = time
S = fitted sorptivity
A = fitted transmissivity

Dunn and Philips [3], estimated Ks from an equation obtained from Darcy's and Poiseuille's equations, assuming laminar water flow:

$$Ks = Dgr2 + 8\mu \quad (2)$$

Where
D = density of water
g = gravitational constant
r = equivalent pore radius of a non uniform macro pore
μ = dynamic viscosity of water

Under saturated conditions all the macro pores are assumed to be conducting water in direct proportion to their sizes. In this case, equation (2) will hold and the larger the pores, the faster the rates of water flow through the soil.

Ks has been estimated from porosity (P) by Ahuja *et al*. [4]. Mbagwu [2], Rawls *et al*, [5] using a generalized Kozney-Carman equation of the form:

$$Ks = CPn \quad (3)$$

Where:
C and n = constants
P = effective porosity

P is given by total porosity minus volumetric water content held at –33kPa matric potential. Mbagwu [2] derived and exponetial function from equation (3) in the form:

$$Ks = 0.07e^{0.08}Pe \quad (4)$$

Where Pe = macroporosity

He concluded that at zero macroporosity, there is movement within the soil through the meso- and micro pores but at slow rates. Rawls *et al*. [5] found n in equation (3) to be equal to 3 – 8, equation (2) was then expressed thus.

$$Ks = CP\ 3 - 8 \quad (5)$$

Where, 8 = Brooks and Corey pore size distribution index.

They obtained 8 by fitting a log-log plot of water content Vs pressure head using only the – 33 kPa and – 1500 kPa water contents. They also concluded that C ranged from 160 – 34,000 and 3- 8 varied between 1.59 and 3.98 depending on the soil type. Mishra *et al*. [6] derived a simple closed – form expression for Ks using Mualem's [7] model in conjunction with the Van Genuchten [8] water retention curve and presented a simple closed –form equation to estimate Ks.

$$Ks = C\,[\,ES - Er]^{5/12}\,\frac{1}{a}\frac{2}{b}\,B^{2}(P,q) \quad (6).$$

Where;
Ks = saturated hydraulic conductivity.
C = constant
Es = Saturated moisture content
Er = Residual moisture content
B = Beta function
a = Fitting parameter affecting the shape of moisture retention curve.

$$P = 1 + 1/b \text{ and } q = 1 - 1/b$$

Equation (6) has been presented by Yannopoulos [9], Mishra *et al*. [6] presented a Ks model in the form

$$Ks = C[Es - Er]^{5/2}\,\%^{2} \quad (7)$$

Where % = a constant obtained from soil moisture retention curve.
Yannopoulos [9] presented another model in the form of

$$Ks = C[Es - Er]^{5/2}\,\%^{2}\,M_2\,B_2\,(P,q) \quad (8)$$

Where,
P = M + 1/n and q = 1 – 1/n
M and n = empirical constants affecting the shape of moisture retention curve.

B is given by
B (P,q) = ½ yP-1 (1 -y)q-1 äy, P>0, q<0 (9)

Equation (6) by Mishra *et al*. [6] was however, presented by Yannopoulos [9].

Equation (3) and (5) with parameters that are easily determined in Northern Guinea savanna Zone are applied in this work. So the problem is reduced to determining the parameters (P, C and 8) for equation (3) and (C, Es, Er and %) for equation (7).

In the alfisols that predominate Samaru, determination of saturated hydraulic conductivity is either by laboratory or field method.

The objectives of this study were to:

- Estimate saturated hydraulic conductivity using some prediction models and comparing the results obtained with laboratory measurements.
- Identify an accurate and simple empirical method for estimating saturated hydraulic conductivity in under Samaru, northern Guinea Savanna Zone of Nigeria conditions.

MATERIALS AND METHODS

Soil Sampling and Analysis: Soil sample used in this study were collected from Institute for Agricultural Research (IAR) farms, Samaru, Northern Guinea Savanna Zone of Nigeria.

Soil Sampling: Undisturbed core samples were collected at 15 cm depth interval up to 60 cm from four sites on the farm using core samplers.

Soil Preparation: The core samples were weighed and immediately oven dried at 105°C for 24hours. After the oven dried soil had been weighted, the soil bulk density was determined. The duplicated core samples were saturated and used for the determination of hydraulic conductivity. The disturbed soil samples were air-dried, ground with a proclain pestle and mortar to pass through a 2mm sieve.

Particle Size Analysis: For each of the soil sample representing the various profile depth, 50g of the sieved soil was transferred into plastic cups 100 ml of sodium hexametaphosphate solution was added to the soil and the mixture were shaken in an end to end mechanical shaker for 20 minutes before they were transferred into 1000 ml measuring cylinders. Hydrometer and thermometer were used to measure the behaviour of each solution and record their temperatures respectively at 40 seconds and 2 hours interval. Blank of the reagents were also run.

Soil Bulk Density: A double cylinder, hammer driven core sampler was used to sample the soil profile at an interval of 15 cm. The samples were then oven dried at 105 °C for 24 hours after which they were weighed.

The diameters of the core samplers were determined and the volume of the core sampler was assumed equal to the volume of the soil in it.

$$\text{Volume of sample} = Br^2h$$

Bulk density (D) was then calculated as

$$1 = \frac{\text{Mass of oven dried soil}}{\text{Volium of the core sample}}$$

(vi) Totals porosity (F) the total porosity of the samplers was determined using the expression below;

$$F = 100\left(1 - \frac{\text{Buledensity}}{\text{Realdensity}}\right)$$

Saturated Hydraulic

Constant Head Method: The disturbed core samples representing each layered profile were covered at one end, with a piece of Muslin cloth held in place with the aid of rubber bands and allowed to stand overnight in water to ensure complete saturation. These saturated samples were then arranged into a permeameter, velocity of flow and changes in hydraulic heads were determined. Saturated hydraulic conductivity was calculated using Darcy's equation i.e.

$$q = -K\frac{)H}{L}$$

since the minus sign indicates direction only, it can be deleted

$q = K)H/L$
$qL = K)H,$
$K = qL/)H$
Since $q = Q/A$
$q = V/At$

$$K = \frac{VL}{At \Delta H}$$

Where

K = saturated hydraulic conductivity in cm/s
q = Soil water flux in cm/s
Q = Discharge rate in cm/s
V = Volume in cm^3
t = Time in seconds
A = Area in cm^2
L = Length of soil samples in cm
ΔH = change in hydraulic head in cm

Moisture Retention: The data for moisture retention were obtained for each soil depth using the undisturbed samples. Between the suction range of 0.1 – 0.4 bars, moisture characterization of the samples was obtained using a combination of filled glass funnels and a low-pressure plate extractor. Between 1 and 15 bars the samples were run on 15 bar ceramic plate extractors.

RESULTS AND DISCUSSION

From Table 1 it is observed that bulk density (BD) and clay has an impact on Ks. As clay content and BD increases Ks decrease. [5]. Also as total porosity (F) increase. Ks at 45cm is an exception to this due to its low BD in this work. Mbagwu [2] reported that high BD reduced Ks by decreasing drainable porosity through compaction. It can be seen from the table that measured Ks decreased with depth due to an increase in the clay content of the soil. Clay offers a higher resistance to movement of water because of its high proportion of micro pores that store water in film or gyroscopically.

When Ks was correlated with soil properties, it was observed that Ks decreases with depth and has a significant negative correlation with clay (r = 0.80**), [10]. The increasing clay content with depth might have decreased Ks because of increased capillary pores.

Values of BD ranged from 1.12 – 1.54 Kg m^{-3} for all the sites and this showed significant negative correlation with Ks (r = 0.85**). Comparison of measured Ks and unadjusted predicted Ks using both Kozney-Carman equation and Yannopoulos model with regression analysis resulted in R^2 values of 20 and 93 % respectively.

Yannopoulos model with R^2 of 93 % shows a positive correlation with the measured Ks. This model however, over estimated Ks; Yannopoulos model results were adjusted using the adjustment factors in Table2.

There is a close agreement between them. The measured Ks and predicted Ks using Yannopoulos model. The parameters filled in the Yannopoulos model can be easily determined using saturated water content (Es), residual water content (Er), % an empirical constant can be obtained from soil moisture retention curve while C, a constant which depends on the surface tension, viscosity and temperature of water in this study, C was found to be 182.5 cm/ secs.

Table 1: Shows the arithmetic means of measured properties of the soil

Soil Depth	F	Bulk Density	Clay	Water Retained (kpa)		Ks
(cm)	(%)	(gcm^{-3})	(%)	-33	-1500	cm/min
15	44	1.48	8	0.18	0.13	19.2
30	40	1.59	10	0.24	0.19	17.8
45	55	1.20	15	0.22	0.16	31.4
60	39	1.61	28	0.37	0.31	12.8

Table 2:

Soil depth (cm)	Adjustment Factors
15	1.01
30	1.00
45	1.00
60	1.00

CONCLUSION

The results of this study show Kozney-Carman equation might not be very suitable in this ecological Zone, while Yannopoulos model with R^2 of 93% is best fitted for Samaru Soil. Saturated water content (Es) were obtained as follows; 0.24, 0.31, 0.37, 0.48 cm^3/cm^3 and residual moisture content (Er) obtained were 0.13, 0.19, 0.16, 0.31 for 15, 30, 45, 60 cm soil depth, respectively. % was obtained as 0.5 from soil moisture characteristic curve. C, a constant, which depends on viscosity, surface tension and density of water, was obtained as 182.5 cm/secs.

From the results of this study, Yannopoulos model is best suited to Samaru Soil. Adjustment factors were in corporated into Yannopoulos equation (Ks = Y [C (ES – Er) $^{5/2}$ " ^{2}]. So that the equation will predict as accurately as measured Ks and Y= adjustment factor.

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