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COMPARISON OF EMPIRICAL MODELS AND LABORATORY SATURATED HYDRAULIC CONDUCTIVITY MEASUREMENTS

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Abstract

Numerous methods for estimating soil saturated hydraulic conductivity exist, which range from direct measurement in the laboratory to models that use only basic soil properties. A study was conducted to compare laboratory saturated hydraulic conductivity (K_{sat}) measurement and that estimated from empirical models. Soil samples for the study were collected from four sites at varying depths (15cm, 30cm, 45cm and 60cm) at the Faculty of Agriculture Teaching and Research Farm, University of Maiduguri. The K_{sat} value for each sample was determined in the laboratory using the falling head permeameter method. Soil physical properties (bulk density, porosity, gravimetric water content, % sand and % silt) required by the models were also determined. A refined Kozeny-Carman model and model developed from multiple regression analysis were used to predict K_{sat} which were compared with the results obtained from laboratory measurement. The developed model predicted values of 0.0065, 0.0010, 0.0965 and 0.0048cm/s at 15cm, 30cm, 45cm and 60cm, respectively, that is closer to the value of K_{sat} measured in the laboratory (0.0061, 0.0054, 0.0050 and 0.0048cm/s at 15cm, 30cm, 45cm and 60cm, respectively) while Kozeny-Carman model predicted a value of 0.2208, 0.2161, 0.2020 and 0.1974cm/s at 15cm, 30cm, 45cm and 60cm, respectively, that is far above the one measured in the laboratory. Therefore, K_{sat} estimating models could not fit for all locations very well.

Key Words: *Saturated hydraulic Conductivity, Empirical models, Laboratory measurements*

Introduction

Knowledge of variability of soil physical properties can assist in defining the best strategies for a sustainable soil management through the provision of vital information for estimating soil susceptibility to erosion; hydrological modelling and efficient planning of irrigation projects (Bagarello and Sgroi, 2004). Soil properties such as texture and structure strongly influence water movement within the soil. Saturated hydraulic conductivity depends strongly on soil texture and structure and therefore can vary widely in space. 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 (Fuentes *et al.*, 2004).

Soil hydraulic conductivity is a measure of soil's ability to transmit water. It is influenced by some soil physical properties and chemical properties and is needed for the study of infiltration, drainage, irrigation and solute movement. Also, it is a key parameter for monitoring of soil and water management (Tayfun, 2005). Knowledge of the rate of water permeability through soil types is essential for determining the type of plants to be grown, plant spacing, yield, managing soil – water systems and erosion control. Compacted soils will have less pore volume resulting in lower hydraulic conductivity especially in clayey soils (Lowery *et al.*, 1996).

Many different techniques have been proposed to determine the value of saturated hydraulic conductivity including field methods (pumping test of wells, auger hole test and tracer test), laboratory methods (constant head and falling head permeameter) and calculations from empirical models (Todd and Mays, 2005). However, accurate estimation of hydraulic conductivity in the field environment by the field methods is limited by the lack of precise knowledge of aquifer geometry and hydraulic boundaries (Uma *et al.*, 1989). The cost of field operations and associated well constructions can be prohibitive. Laboratory tests on the other hand,

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presents formidable problems in the sense of obtaining representative samples and very often, long testing times. Alternatively, methods of estimating hydraulic conductivity from empirical models based on grain-size distribution characteristics have been developed and used to overcome these problems (Boadu, 2000). Grain size methods are comparably less expensive and do not depend on the geometry and hydraulic boundaries of the aquifer. Most importantly, the information about the textural properties of soils or rock is more easily obtained.

Hydraulic conductivity can also be estimated by particle size analysis of the sediment of interest using empirical equations relating either hydraulic conductivity to some size property of the sediment (Odong, 2007). Vukovic and Soro (1992) summarised several empirical methods from former studies and presented a general formula:

$$K = \frac{g}{v}.C.f(n).d_e^2 \quad - \quad (1)$$

Where K = hydraulic conductivity, V = Kinetic viscosity, g = acceleration due to gravity C = sorting coefficient f(n) = porosity function and d_e = effective grain diameter

The kinematic viscosity (v) is related to dynamic viscosity (µ) and fluid viscosity (ρ) as follows:

$$V = \frac{\mu}{\rho} \quad \text{..} \ (2)$$

The value of C, f(n) and d_e are dependent on the different methods used in the grain-size analysis. According to Vukovic and Soro (1992), porosity (n) may be derived from the empirical relationship with the coefficient of grain uniformity (U) as :

$$n = 0.255(1 + 0.83^U) \ \text{.........................} \ (3)$$

Where U is the coefficient of grain uniformity and is given by

$$U = \frac{d60}{d10}$$

Here, d_{60} and d_{10} in the formula represent the grain diameter in (mm) for which 60% and 10% of the sample respectively are finer than.

$$K = \frac{g}{v} \text{ x } 6 \text{ x } 10^{-4} \, [1 + 10(n - 0.26)]d_{10}^2 \ \ldots \ (4)$$

Hazen formula was originally developed for the determination of hydraulic conductivity of uniformly graded sand but is also useful for fine sand to gravel range, provided the sediment has a uniformity coefficient less than 5 and effective grain size between 0.1 and 3mm.

$$K = \frac{g}{v} \text{ x } 8.3 \text{ x } 1$$

The Kozeny – Carman equation is one of the most widely accepted and used derivations of permeability as a function of the characteristics of the soil medium. This equation was originally proposed by Kozeny (1927) and was later modified by Carman (1937, 1956) to become the Kozeny – Carman equation. It is not appropriate for either soil with effective size above 3mm or for clayey soils. The main objective of this study is to compare laboratory determined saturated hydraulic conductivity with saturated hydraulic conductivity estimated from empirical models and also to show the relationship between some soil physical properties and saturated hydraulic conductivity.

Materials and Methods

Experimental Site

The soil for the study was collected at the University of Maiduguri Teaching and Research Farm. The site is located in the north eastern part of Nigeria between longitudes 13°05′′E and latitudes 11° 50′′N and an elevation of 354m above sea level. The study area has a tropical climate characterised by low and erratic distribution of rainfall. The mean annual rainfall is about 625mm and means annual temperature is between 27 – 32°C (Grema and Hess, 1994). The steady state infiltration varies from 72mm – 220mm/hr with average of 135mm/hr (Folorunso, 1986). Soil of the study area has a sandy loam textures and has been classified as typic ustipsamment according to USDA system of classification (Rayar, 1983).

Sample Collection and Preparation

Undisturbed soil samples were collected at 15cm depth intervals up to 60cm from four sites on the farm using core samplers. The core samples were weighed and immediately oven dried at 105^0C for 24 hours. After the oven dried soil had been weighed, the bulk density was determined. The duplicated core samples were saturated and used for determination of hydraulic conductivity. Disturbed samples were also collected, air–dried, ground with porcelain pestle and mortar, passed through a 2mm sieve and used for the determination of other soil parameters.

Determination of Soil Physical Properties

Soil particle size was determined by the hydrometer method (Gee and Bauder, 1979), bulk density was determined using the core sampler method and water content of the soil at the time of sampling was determined in the laboratory by the gravimetric method (Blake, 1965). Saturated hydraulic conductivity was also determined by falling head permeameter method (Klute, 1986).

Regression Models

Regression equation was developed to predict the K_{sat} using some measured physical properties of the soil as descriptor variables. These soil physical properties include bulk density (BD), porosity (P), volumetric water content (Θv), percent sand (Sa) and percent silt (Si) from particle size analysis. The regression model relates the K_{sat} values to the descriptors via the following equation:

$K_{sat} = a+b_1x_1+b_2x_2+b_3x_3+b_4x_4+b_5x_5$

Where K_{sat} = saturated hydraulic conductivity

a = constant

$b_1 - b_5$ = coefficients determined by regression analysis

x_1 = Bulk Density
x_2 = Porosity
x_3 = Volumetric water content
x_4 = % sand
x_5 = % silt

The resulting regression equation that best relates K_{sat} to the five descriptors of soil properties is given as:

$K_{sat} = 0.07118 - 0.03266BD - 0.00077P + 0.392010\Theta_v + 0.00121Sa + 0.0002572Si$

The above equation describes a model that predicts K_{sat} of a soil using information from soil parameters as bulk density, porosity, water content, percent sand and percent silt.

Statistical Analysis

Experimental data were analysed using descriptive statistics, correlation and multiple regression using Statistix9, statistical software package (Microsoft, 2009).

Results and Discussion

Some Selected Soil Properties of the Study Area

The descriptive statistics on %sand, %clay and %silt, bulk density (g/cm^3), volumetric water content (cm^3/cm^3), porosity (%) and K_{sat} (cm/s) is shown in Table 1. The range values of %sand are 66.9 – 69.4%, %silt is 6.6 – 14.1% and %clay is 19.0 – 24.0%. Hence the textural class of the soil of the study area is described as sandy loam using Marshall's Textural Triangle. The bulk density ranges from 1.46 – 1.62g/cm^3, porosity ranges from 39 – 45% and water content ranges from 0.0149 – 0.0153cm^3/cm^3

Correlation coefficient of Some Soil Properties

The results on the correlation coefficients on selected soil properties and the saturated hydraulic conductivity are given in Table 2. Clay content showed significantly negative correlation with the saturated hydraulic conductivity ($P < 0.01$). This agrees with the findings of Tayfum (2005) who reported significant negative correlation of clay content with soil K_{sat} that, as clay content increases, K_{sat} decreases and vice versa. Also, there is a high negative correlation between bulk density and porosity at $P<0.01$, implying that increase in bulk density will cause a decrease in pore spaces of the soil. This agrees with the findings of Edoga (2010) who reported negative correlation between bulk density and porosity.

There is a significant negative correlation at $P<0.01$ between porosity and clay content. This means that increase in clay content reduces the soil pore spaces hence the ability of the soil to transmit water is also affected. There is a positive correlation between bulk density and silt and clay contents at ($P<0.05$). Increase in clay and silt contents will cause a resultant increase in bulk density thus affecting saturated hydraulic conductivity.

Bulk density and porosity also showed significant negative correlation with the K_{sat} at $P<0.01$. Thus, the higher the bulk density, the lower the ability of the soil to transmit water, the less the number of macro pores. High bulk density decreases the number of macro pores in the soil thereby making it difficult for water to move through the soil. This agrees with the findings of Edoga (2010) who reported that bulk density and clay content has an impact on K_{sat}, and that as clay content and bulk density increases, saturated hydraulic conductivity decreases. It shows that clay content, bulk density and porosity were the most important soil properties affecting $K_{sat.}$

Comparison between Laboratory Measurement and Empirical Measurement on K_{sat}

Table 3 shows the comparison between K_{sat} measured in the laboratory using falling head permeameter method and K_{sat} estimated from two empirical models (Kozeny-Carman and model developed from multiple regression analysis). The table showed that model developed from multiple regression analysis predicted a closer value of K_{sat} as the one measured in the laboratory, while Kozeny-Carman model predicted a K_{sat} value that is far greater than the one measured in the laboratory. This suggests that Kozeny-Carman equation might not be suitable for predicting the K_{sat} of the study area probably due to difference in climatic and ecological zone. Similar study was carried out in Samaru, Zaria by Edoga (2010) comparing K_{sat} measurement methods with some empirical models as Yannopoulos equation and Kozeny-Carman equation.His results showed that Kozeny-Carman equation is not suitable for the ecological zone but Yannopoulos equation predicted a value of K_{Sat} that is closer to the one measured in the laboratory.

Conclusion

The results of this study showed that Kozeny-Carman equation might not be suitable for the soils of the study area despite its wide usage for predicting K_{sat}, while the model developed from multiple regression analysis with $R^2 = 92\%$ is best fitted for the soils of the study area. The presented regression model is suggested as useful alternative to laboratory analysis especially for soils that may be difficult to prepare for measurements or may take several days or perhaps weeks for K_{sat} measurements. In certain circumstances, the model may also be useful in giving first hand information about hydraulic properties in a field environment.

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Table 1: Descriptive Statistics on Some Selected Soil Properties

Soil Property	Min.	Max.	Mean	SE	SD
Sand (%)	66.900	69.400	67.681	0.299	1.197
Silt (%)	6.600	14.100	11.131	0.521	2.085
Clay (%)	19.000	24.000	21.19	0.459	1.797
BD (gcm^3)	1.460	1.620	1.54	0.015	0.059
Porosity (%)	39.000	45.00	14.750	0.544	2.176
θ_v(cm^3/cm^3)	0.0149	0.0153	0.015	0.00003	0.00011
K_{sat} (cm/s)	0.0045	0.0066	0.0055	0.00018	0.00070

Table 2: Correlation Coefficients on Some Selected Soil Properties

	K_{sat}	BD	Porosity	θv	Sand	Silt
BD	-0.8829**					
Porosity	0.8609**	-0.9931**				
θ_v	-0.1852	0.3181	-0.3713			
Sand	-0.1246	0.1949	-0.2400	0.2308		
Silt	0.8062*	0.7831*	0.8173*	-0.4157	-0.5113	
Clay	-0.8527*	0.7790*	-0.7887*	0.3287	0.0727	-0.8200*

*Significant at P<0.05, ** significant at P<0.01

Table 3: K_{sat} measured in laboratory and prediction from the two models at various depths

Depth	K_{sat} (cm/s)		
	Kozeny-Carman	Regression Model	Laboratory
15cm	0.2208	0.0065	0.0061
30cm	0.2161	0.0060	0.0054
45cm	0.2020	0.0065	0.0050
60cm	0.1974	0.0048	0.0048