

# METHODS FOR PREDICTING HYDRAULIC CONDUCTIVITY OF NIGERIAN AGRICULTURAL SOILS

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**Abstract.** Accurate prediction of hydraulic conductivity is very crucial for infiltration and runoff estimation. Factors which affect water infiltration in the soil include hydraulic conductivity, wetting front and soil sorptivity, ponding depth, depth to water table and impact of rain drops. Amongst these factors, the importance of hydraulic conductivity cannot be overemphasized. Hydraulic conductivity is one of the most important parameter for flow and transport related phenomena in soil. There is concern arising from the suitability, efficiency and ease of the different measuring methods under different conditions. The various methods of predicting hydraulic conductivity include field; laboratory and correlation methods each with individual merits and demerits. Although selection of a specific method for a particular application will depend on the objectives to be achieved, most researchers prefer direct measurement of soil hydraulic conductivity. The estimation of soil hydraulic conductivity using correlation method depends on the local soil maps, soil particle size distribution, organic matter content and bulk density. Field methods are usually more expensive than laboratory methods. Consequently, when the question of cost becomes decisive, or when actual representation of field conditions is not of fundamental importance and in-situ hydraulic conductivity is not available, laboratory methods may be used to predict the saturated hydraulic conductivity  $K$ . This study explains the various methods that can be used to predict hydraulic conductivity in-situ or within the laboratory.

**Keywords:** *methods, predicting, hydraulic, conductivity, agricultural, soils*

## Introduction

The importance of hydraulic conductivity cannot be over emphasized as it is an important hydraulic property frequently used in hydrological modelling and water flow related studies in soils such as irrigation, drainage system design and infiltration modelling. It is a key parameter for monitoring soil and water management (Tayfun, 2005). 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 (Osunbitan et al., 2005). It was observed that most of its measurement methods are neither appropriate for all applications nor accurate for all soil types and conditions. Studies have shown

that regardless of land practices, a small portion of the soil volume transports a large portion of the water flow, indicating that spatial hydraulic characteristics of soils are highly variable (Ibrahim and Aliyu, 2016).

Knowledge of variability of soil physical properties can assist in defining the best strategies for sustainable soil management through the provision of vital information for estimating soil susceptibility to erosion, hydrological modeling and efficient planning of irrigation projects (Bagarello and Sgroi, 2004). Hydraulic conductivity of soil is one of the most important soil properties controlling water infiltration and surface runoff, leaching of pesticides from agricultural lands, and migration of pollutants from contaminated sites to the ground water (Fuentes et al., 2004). Hydraulic conductivity depends strongly on soil texture and structure and therefore can vary widely in space (Fuentes et al., 2004). 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. Furthermore, the hydraulic conductivity (K) of soil is of great significance in hydrogeology. The development, management and protection of groundwater and the prediction of contaminant transport need reliable estimates of K (Post et al., 2007). Hydrogeologists and water engineers have searched for reliable techniques to determine the K of soils for better groundwater development, management and conservation. Different techniques have been presented including field, laboratory and empirical methods. However, precise estimation of K by field techniques is limited by lack of accurate information of the aquifer geometry and hydraulic boundaries; and they are always prohibited by high cost for the construction of observation wells (Post et al., 2007).

Laboratory tests, on the other hand, present formidable problems in the sense of obtaining representative samples. It has long been recognized that K is statistically related to the grain-size distribution of granular porous media. As a result, numerous models estimating K from empirical formulae based on grain-size distribution have been developed and used to overcome these problems (Šimůnek et al., 2003). Determining the hydraulic conductivity, K of soils can also be done with correlation methods which are based on predetermined relationships between an easily determined soil property (e.g. texture) and the K value (Ibrahim and Aliyu, 2016). There are two types of hydraulic conductivity (K) namely saturated and unsaturated hydraulic conductivity. In saturated hydraulic conductivity ( $K_{sat}$ ), 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. For 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 (Edoga, 2010). Many techniques have been proposed to determine the saturated hydraulic conductivity of soils, including field methods (pumping test of wells, auger hole test and tracer test), laboratory methods and calculations from empirical formulae (Todd and Mays, 2004). The accuracy of numerical modeling of infiltration depends on how well the underlying mathematical models describe the physics of the flow in variable soils (Ibrahim and Aliyu, 2016). The best choice of methods for the above applications must optimize several interrelated factors including accuracy, speed, simplicity, portability, manpower, capital costs, etc. To this effect, this paper seeks or aims to review the different methods used to measure this important soil

property so as to ascertain the most preferred method based on ease of measurement, applicability and reliability of results obtained based on existing literature.

**Determination of hydraulic conductivity**

In the field of hydrogeology, it is important to know how easy water (or other fluids) can move through a porous media, i.e. hydraulic conductivity. Hydraulic conductivity describes a material’s ability to let water through. This is defined in terms of volume per area and time,  $m^3/m^2/s=m/s$ , which should not be confused with meter per second as a velocity (Fetter, 2018). This parameter is not always easily measured, but often has to be predicted by using basic information and translating it into estimates of hydraulic conductivity. Hydraulic conductivity can be estimated by using methods based on grain size analysis or determined by the use of experimental in situ or laboratory methods (Scanlon et al., 2003). Ritzema (2006) presented a schematic diagram of the various methods employed in the determination of hydraulic conductivity, the various instruments used and the various levels for which the determination processes are carried out (Figure 1).

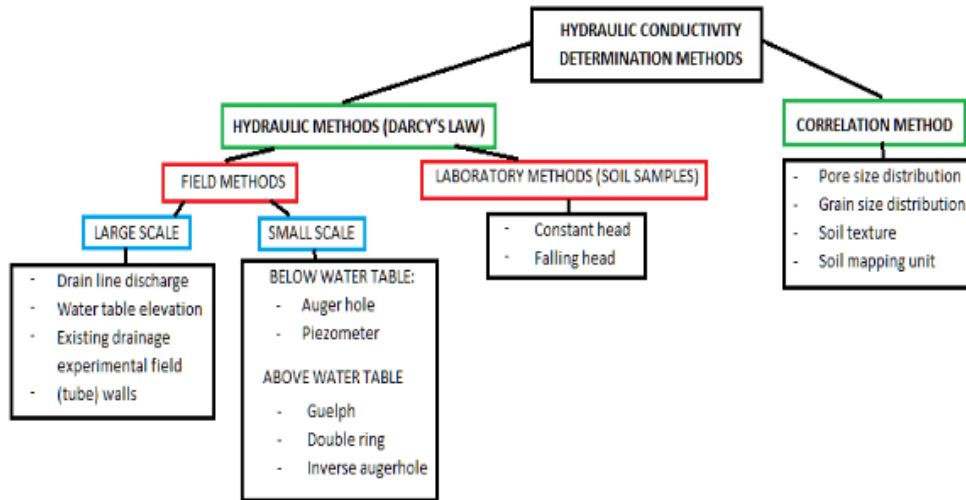


Figure 1. Overview of methods for determination of hydraulic conductivity.

**Materials and Methods**

**Laboratory method**

The laboratory method of determining the value of K can be carried out through the constant head and falling head techniques using several instruments such as permeameter, pressure chamber and consolidometer. A common feature of these methods is that a soil sample is placed in a small cylindrical receptacle representing a one dimensional soil configuration through which the circulating liquid is forced to flow. Depending on the flow pattern imposed through the soil sample, the laboratory methods for measuring hydraulic conductivity are classified as either a constant head with a steady-state flow regimen or a falling-head test with an unsteady-state flow regimen (Ibrahim and Aliyu, 2016). Because of the small sizes of the soil samples handled in the laboratory, the results of tests are considered a point representation of the soil properties (Ibrahim and Aliyu, 2016). If the soil samples used in the laboratory test

are truly undisturbed samples, the measured K value is expected to be a true representation of the hydraulic conductivity at that particular sampling point. The conductivity of disturbed samples of cohesionless soils obtained in the laboratory can be used to approximate the actual value of K in the undisturbed (natural) soil in the horizontal direction (Ibrahim and Aliyu, 2016).

### ***Constant head method***

Constant head method allows water to move through the soil under a steady state head condition while the quantity or volume of water flowing through the soil specimen is measured over a period of time. The coefficient of permeability (K) using constant head method can be calculated using the following Eq (1):

$$K = \frac{QL}{Ath} \quad \text{Eq. (1)}$$

Where, Q is quantity of water discharged; L is distance between manometers; A is cross-sectional area of specimen; t is total time of discharge; and h is difference in head on manometers. This method 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 (Post et al., 2007).

### ***Falling head method***

Falling head is similar to the constant head method in its initial setup; however, it has the advantage that it can better be used for fine-grained soils. The soil sample is first saturated under a specific head condition. The water is then allowed to flow through the soil without maintaining a constant pressure head (Post et al., 2007). The calculation under falling head method is determined using Eq. (2).

$$K = \frac{aL}{At} \ln\left(\frac{h_0}{h_1}\right) \quad \text{Eq. (2)}$$

Where, a is cross sectional area of stand pipe; L is length of soil column; A is cross section area of soil column; t is time interval to head drop; h<sub>0</sub> is total head before test; and h<sub>1</sub> is total head after test.

### ***Field method***

Field method (in-situ methods) can be divided into small-scale and large-scale methods. The small-scale methods are designed for rapid testing at many locations. They impose simple flow conditions to avoid complexity, so that the measurements can be made relatively quickly and cheaply. A drawback of the small-scale in-situ methods is that they imposed flow conditions are often not representative of the flow conditions corresponding to the drainage systems to be designed or evaluated (Post et al., 2007).

### ***Small scale methods***

Small scale methods refer to numerous small-scale in-situ methods for the determination of K-values. The methods fall into two groups namely those that are used to determine K above the water table and those that are used below the water table.

Above the water table, the soil is not saturated. To measure the saturated hydraulic conductivity, one must therefore apply sufficient water to obtain near-saturated conditions (Ibrahim and Aliyu, 2016). These methods are called "infiltration methods" and the measurement is done using the infiltrometer and inverted auger hole. Below the water table, the soil is saturated by definition. It then suffices to remove water from the soil, creating a sink, and to observe the flow rate of the water into the sink together with the hydraulic head induced. These methods are called "extraction methods" and the measurement is done through the auger hole, piezometer, double tube, Guelph and pumped borehole (Ibrahim and Aliyu, 2016) (Table 1).

**Table 1.** Comparison between field hydraulic conductivity (wet and dry conditions) (Kfs) and laboratory scale (Ks).

Soil Depth	Field ( $k_{f3}^{wet}$ )	( $k_{f3}^{Dry}$ )	Laboratory ( $k_2$ )	Wet Condition ( $k_{fs}/k_s$ )	Dry Condition ( $K_{fs}/k_s$ )
15cm	4.6	8.3	32.2	0.14	0.26
25cm	1.3	32.1	-	-	-
50cm	0.3	1.0	11.1	0.03	0.09
Meadows	2.1	7.5	26.1	0.10	0.35
15cm	2.2	18.2	27.6	0.08-0.66	-
25cm	2.1-2.5	-	8.7	0.24	0.29
50cm	0.1	2.3	-	-	-
Forest	1.7	7.7	18.2	0.09	0.42

In both cases, mean Kfs/Ks were 0.10 in wet conditions, and 4 times greater in dry conditions. These differences could be explained considering the possible alterations suffered by the samples during the extraction. In fact, the extraction of samples to perform laboratory analyses could involve the formation of preferential flow paths, and therefore increase Ks values. Differences may perhaps be explained by some characteristics of the processes. Constant head permeameter measured Ks in a vertical direction, where preferential flows, due to the macro-porosity or the conducts produced by bioturbation and roots plants could be important. On the contrary, Guelph permeameter measured the Kfs of a wetting bulb, which included horizontal and vertical directions. In addition, the swelling-shrinking processes observed in these soils, could entail collapses of the macropores, and as a consequence a reduction of the hydraulic conductivity. Finally, textural homogeneity in the first 15 cm depth, determined a rapid steady-state conditions of the water flow, and fewer variations of the process (Qi et al., 2014).

**Correlation method (empirical)**

The correlation methods can be carried out using the pore size and grain size distributions, grain size distribution, soil texture and soil mapping. These methods originated from predetermined relationship between soil property (e.g. grain size distribution, texture etc.) and K-value (Stibinger, 2014). The advantage of the correlation methods is that it is a faster method of estimating K-value, than the direct measurement. A defect is a fact that the application of relationship can be incorrect and can be a reason of random errors. Accurate estimation of hydraulic conductivity in the field environment by field methods is limited by lack of precise knowledge of aquifer geometry and hydraulic boundaries. The cost of field operations and associated wells constructions can be prohibitive as well. Laboratory tests on the other hands, presents formidable problems in the sense of obtaining representative samples and, very often, long testing times.

Alternative methods of estimating hydraulic conductivity from empirical formulae based on grain-size distribution characteristics have been developed and used to overcome these problems. Grain-size methods are comparably less expensive and do not depend on the geometry and hydraulic boundaries of the aquifer. Most importantly, since information about the textural properties of soils or rock is more easily obtained, a potential alternative for estimating hydraulic conductivity of soils is from grain-size distribution. Although in hydromechanics, it would be more useful to characterize the diameters of pores rather than those of the grains, the pore size distribution is very difficult to determine. Hence, approximations of hydraulic properties are mostly based on easy-to-measure grain size distribution as a substitute (Cirpka, 2003). Consequently, groundwater professionals have tried for decades to relate hydraulic conductivity to grain size. The tasks appear rather straight forward but it found that this correlation is not easily established (Pinder and Celia, 2006). Numerous investigators have studied this relationship and several formulae have resulted based on experimental work (Odong, 2007). Kozeny proposed a formula which was then modified by Carman to become the Kozeny-Carman equation. The applicability of these formulae depends on the type of soil for which hydraulic conductivity is to be estimated (Idris-Nda, 2013).

Moreover, few formulae give reliable estimates of results because of the difficulty of including all possible variables in porous media. The applications of different empirical formulae to the same porous medium material can yield different values of hydraulic conductivity, which may differ by a factor of 10 or even 20. This paper also evaluates the applicability and reliability of some of the commonly used empirical formulae for the determination of hydraulic conductivity of unconsolidated soil/rock materials (Carrier III, 2003).

### ***Empirical formulae***

Hydraulic conductivity (K) can be estimated by particle size analysis of the sediment of interest, using empirical equations relating either K to some size property of the sediment (Carrier III, 2003). There are several empirical methods which are presented as follows (Eq. (3)):

$$K = \frac{g}{v} \cdot c \cdot f(n) \cdot d_e^2 \quad \text{Eq. (3)}$$

Where; K=hydraulic conductivity; g=acceleration due to gravity; v=kinematic viscosity; C=sorting coefficient; f(n)=porosity function; and de=effective grain diameter.

The kinematic viscosity (v) is related to dynamic viscosity ( $\mu$ ) and the fluid (water) density ( $\rho$ ) and it is given as follows (Eq. (4)):

$$v = \frac{\mu}{\rho} \quad \text{Eq. (4)}$$

The values of C, f(n) and de are dependent on the different methods used in the grain-size analysis. According to Odong (2007), porosity (n) may be derived from the empirical relationship with the coefficient of grain uniformity (U) as follows (Eq. (5)):

$$n = 0.255(1 + 0.83^U) \quad \text{Eq. (5)}$$

Where  $U$  is the coefficient of grain uniformity and is given by (Eq. (6):

$$U = \left[ \frac{d_{60}}{d_{10}} \right] \quad \text{Eq. (6)}$$

Here,  $d_{60}$  and  $d_{10}$  in the formula represent the grain diameter in (mm) for which, 60% and 10% of the sample respectively. Previous studies have recommended Hazen formula (Eq. (7) which take the general form presented in Eq. (3) but with varying  $C$ ,  $f$  ( $n$ ) and  $d$  values and their domains of applicability.

## Results and Discussion

### *Hazen*

Hazen formula was originally developed for determination of hydraulic conductivity of uniformly graded sand; but it 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 3 mm.

$$K = \frac{g}{v} \times 10^{-4} [1 + 10(n - 0.26)] de^2 \quad \text{Eq. (7)}$$

### *Kozeny-Carman*

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 and was then modified by Carman to become the Kozeny-Carman equation. It is not appropriate for either soil with effective size above 3mm or for clayey soils (Carrier III, 2003).

$$K = \frac{g}{v} \times 8.3 \times 10^{-3} \left[ \frac{n^3}{(1-n)^2} \right] de^2 \quad \text{Eq. (8)}$$

### *Breyer*

This method does not consider porosity and therefore, porosity function takes on value 1. Breyer formula is often considered most useful for materials with heterogeneous distributions and poorly sorted grains with uniformity coefficient between 1 and 20, and effective grain size between 0.06mm and 0.6mm.

$$K = \frac{g}{v} \times 60 \times 10^{-4} \log \frac{500}{u} de^2 \quad \text{Eq. (9)}$$

### *Slitcher*

This formula is most applicable for grain-size between 0.01mm and 5mm.

$$K = \frac{g}{v} \times 1 \times 10^{-2} n^{23.287} de^2 \quad \text{Eq. (10)}$$

**Terzaghi**

Where; the  $C_t$ =sorting coefficient and 6.1. In this study, an average value of  $C_t$  is used. Terzaghi formula is most applicable for large-grain sand (Carrier III, 2003).

$$K = \frac{g}{v} \cdot c_t \left[ \frac{n-0.13}{3\sqrt{1-n}} \right]^2 de^2 \quad \text{Eq. (11)}$$

**USBR**

U.S. Bureau of Reclamation (USBR) formula calculates hydraulic conductivity from the effective grain size ( $d_{20}$ ), and does not depend on porosity; hence porosity function is a unity. The formula is most suitable for medium-grain sand with uniformity coefficient less than 5 (Post et al., 2007).

$$K = \frac{g}{v} \times 4.8 \times 10^{-4} d_{20}^{0.3} \times d_{20}^2 \quad \text{Eq. (12)}$$

**Alyamani and Sen**

Where;  $K$  is the hydraulic conductivity (m/day),  $I_0$  is the intercept (in mm) of the line formed by  $d_{50}$  and  $d_{10}$  with the grain-size axis,  $d_{10}$  is the effective grain diameter (mm), and  $d_{50}$  is the median grain diameter (mm). It should be noted that the terms in equation (Fetter, 2018) bear the stated units for consistency. This formula therefore, is exceptionally different from those that take the general form of equation (Ibrahim and Aliyu, 2016). It is however, one of the well-known equations that also depend on grain-size analysis. The method considers both sediment grain sizes  $d_{10}$  and  $d_{50}$  as well as the sorting characteristics. Results, from which hydraulic conductivities were calculated using the seven empirical formulae discussed above, are presented in *Table 2* (Odong, 2007). For the studied samples, and consequently may be for a wide range of soil type, the best overall estimation of permeability is reached based on Kozeny-Carman’s formula followed by Hazen formula. However, Breyer formula is the best for estimation of highly heterogeneous soil sample.

$$K = 1300[I_0 + 0.025(d_{50} - d_{10})]^2 \quad \text{Eq. (13)}$$

**Table 2.** Hydraulic conductivities calculated from grain-size analysis using empirical formulae (Odong, 2007).

Ct	A	B	C	D	E	F	G	H	I	J	K	L	M
1	0.34	0.47	1.18	5.31	0.35	0.25	NA	80.14	114.01	30.249	51.6	NA	94.79
2	0.18	0.22	0.33	1.92	0.43	0.16	44.45	56.88	39.34	17.327	NA	12.36	33.59
3	0.31	0.40	0.72	3.23	0.40	0.25	113.50	112.50	105.79	38.001	66.4	NA	90.78
4	0.16	0.19	0.26	1.78	0.44	0.14	34.44	45.59	30.32	13.689	NA	8.71	26.04

Note:  $C_t$ =Sample & its\* classification;  $A=d_{10}(mm)$ ;  $B=d_{20}(mm)$ ;  $C=d_{50}(mm)$ ;  $D=(U)$ ;  $E=(n)$ ;  $F=I_0(mm)$ ;  $G=Hazen(m/da)$ ;  $H=K-C(m/da)$ ;  $I=Breyer(m/da)$ ;  $J=Slitcher(m/da)$ ;  $K=Terzahi(m/da)$ ;  $L=USBR(m/da)$ ;  $M=A/S(m/da)$ ;  $1=Gravelly\ sand$ ;  $2=Medium\ sand$ ;  $3=Coarse\ sand$ ;  $4=Medium\ sand$ ;  $K-C=Kozeny-Carman$ ;  $A/S=Alyamani\ \&\ Se$ .

**Conclusion**

Selection of a specific method for the determination of hydraulic conductivity for a particular application will depend on the objectives to be achieved. Because of the

difficulty in obtaining a perfectly undisturbed sample of unconsolidated soil, the  $K$ -value determined by laboratory methods may not accurately reflect the respective value in the field. Therefore, field methods should be used whenever the objective is to characterize the physical features of the subsurface system as accurately as possible. Field methods, however, are usually more expensive than laboratory correlation methods. Consequently, when the question of cost becomes decisive, or when actual representation of field conditions is not of fundamental importance and in-situ hydraulic conductivity is not available, correlation methods should be used. Based on the review of determination of hydraulic conductivity using laboratory, field and correlation methods; the following concluding remarks can be drawn: (1) It is emphasized that the use of field methods is limited by the lack of precise knowledge of aquifer geometry and hydraulic boundaries. The cost of field operations and associated wells constructions can be prohibitive as well; (2) Field and laboratory measurements have their merits and demerits because of the procedures upon which the experiments are based. Such assumptions includes one-dimensional flow pattern measurement of all measureable quantities in the Darcy's equation like fluid density, dynamic viscosity, flow velocity and the gradient of the hydraulic head; (3) Laboratory measurements are carried out on small samples of soil materials collected during core-drilling programs. If the soil samples used in the laboratory test are truly undisturbed samples, then the measured value of  $K_{sat}$  should be a true representation of the in-situ saturated hydraulic conductivity at that particular sampling point. Unfortunately, it is very difficult, if not impossible to get a true undisturbed soil sample because the structure of the sample might be destroyed while being collected. The degree of such disturbance depends on either the sampling method employed or the material used. However, undisturbed sampling of soils is possible, but it requires the use of specially designed techniques and instruments; (4) Alternative methods of estimating hydraulic conductivity using correlation (empirical) formulae based on grain-size distribution characteristics have been developed and used to overcome problems which other methods encounter.

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### **Conflict of interest**

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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