An Overview of Methods Used in the Determination of Soil Hydraulic Conductivity

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Abstract

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 determining 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 determine the saturated hydraulic conductivity K. Overall, this review explains the various methods that can be used to determine hydraulic conductivity *in-situ* or within the laboratory.

Keywords: Correlation, Conductivity, Field, Laboratory, Permeameter

1.0 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 [1]. 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 [2]. 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 [3].

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 [4]. 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 [5]. Hydraulic conductivity depends strongly on soil texture and structure and therefore can vary widely in space[5]. 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 [5].

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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 [6]. 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 [7]. Laboratory tests, on the other hand, present formidable problems in the sense of obtaining representative samples [6]. 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 [6]. 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 [3].

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 [8].

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 [9]. The accuracy of numerical modeling of infiltration depends on how well the underlying mathematical models describe the physics of the flow in variable soils [3]. 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.

2.0 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 [10-12]. 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 [13]. 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 [10-12]. Ritzema [14] 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 (Fig. 1).

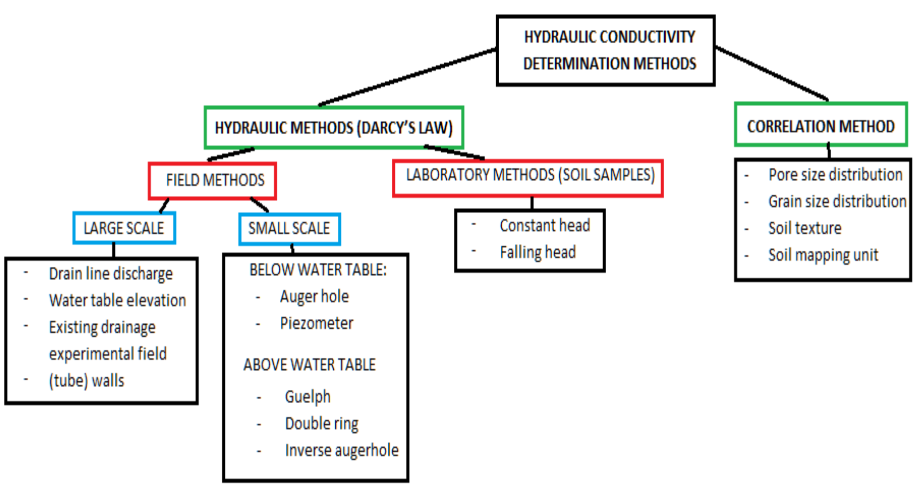

Fig. 1: Overview of methods for determination of hydraulic conductivity

2.1 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 [3]. 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 [3]. 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 [3].

2.1.1 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 equation (1):

$$K = \frac{QL}{Ath} \tag{1}$$

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.

2.1.2 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 [2]. The calculation under falling head method is determined using equation (2).

$$K=\frac{aL}{At} \mathrm{Ln}\left(\frac{h_0}{h_1}\right) \tag{2}$$

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_0 is total head before test; and h_1 is total head after test.

2.2 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 [2]. 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 [2].

2.2.1 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 [3]. 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 [3].

(a) Infiltration Methods

The 'infiltration methods' can be divided into steady-state and unsteady state methods. Steady state methods are based on continuous application of water so that the water level (below which the infiltration occurs) is maintained constant. One then awaits the time when the infiltration rate is also constant, which occurs when a large enough part of the soil around and below the place of measurement is saturated. Unsteady-state methods are based on observing the rate of drawdown of the water level below which the infiltration occurs, after the application of water has been stopped [3]. Most infiltration methods use the unsteady-state principle, because it avoids the difficulty of ensuring steady-state conditions. When the infiltration occurs through a cylinder driven into the soil, one speaks of permeameter methods. A number of unsteady-state permeameter methods have been presented including the double-tube method, where a small permeameter is placed inside a larger permeameter [3].

In general, the infiltration methods measure the K_{sat} value in the vicinity of the infiltration surface. It is not easy to obtain K_{sat} values at greater depths in the soil. Although the soil volume over which one measures the K_{sat} value is larger than that of the soil cores used in the laboratory, it is still possible to find a large variation from place to place. A disadvantage of using infiltration methods is that water has to be transported to the measuring site. The methods are therefore more often used for specific research purposes than for routine measurements on a large scale.

(b) Extraction methods

The most frequently applied extraction method is the 'auger-hole method' which uses the principles of unsteady-state flow. An extraction method based on steady-state flow is called the 'pumped-borehole method' [3]. The 'piezometer method' is based on the same principle as the auger-hole method, except that a tube is inserted into the hole, leaving a cavity of limited height at the bottom. Using the auger-hole method, the values of K_{sat} was reported to be in the range of 0.12 to 49 m/d and 0.54 to 11 m/d in a 7 ha and 5 ha field with sandy loam soil respectively [3].

2.2.2 Large Scale Method

Large scale method can be determined majorly through the use of drain line discharge/water-table elevation measurements and tube wells. The large-scale *in-situ* methods can be divided into those that use pumping from wells and pumping or gravity flow from (horizontal) drains. The method uses observations on drain discharges and corresponding elevations of the water table in the soil at some distance from the drains [3]. The hydraulic conductivity, K values can be calculated with a drainage formula appropriate for the conditions under which the drains are functioning. Since random deviations of the observations from the theoretical relationship frequently occur, a statistical confidence analysis accompanies the calculation procedure. The advantage of the large-scale determinations is that the flow paths of the groundwater and the natural irregularities of the hydraulic conductivity, K values along these paths are automatically taken into account in the overall K value found using this method for a given catchment. It is then not necessary to determine the variations in the K values from place to place, in horizontal and vertical direction, and the overall value found can be used directly as input into the drainage formulas. This field method guarantees the representative K-values, where the problem of variation is eliminated as much as possible. However, the large-scale field methods are rather expensive and time-consuming. Determination of hydraulic conductivity for a silt loam soil in field and laboratory conditions under two vegetative covers (meadows and forest) is shown in Table 1 [15].

Table 1: Comparison between field hydraulic conductivity (wet and dry conditions) (K_{fs}) and laboratory scale (Ks)

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

K_{fs} = field saturated hydraulic conductivity; K_s= laboratory scale

In both cases, mean K_{fs}/K_s was 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 K_s 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 K_{fs} 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 macrospores, 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.

2.3 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 [16]. The advantage of the correlation methods is that it is a faster method of estimating K-value, than the direct measurement. A deflect 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 [17]. 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 [18].

Numerous investigators have studied this relationship and several formulae have resulted based on experimental work [19]. 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 [20]. 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 [21]. 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.

2.3.1 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 [21]. There are several empirical methods which are presented as follows:

$$\mathrm{K} = \frac{g}{v} \cdot c \cdot f(n) \cdot {d_e}^2 \qquad (3)$$

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

The kinematic viscosity (v) is related to dynamic viscosity (μ) and the fluid (water) density (ρ) and it is given as follows:

$$v = \frac{\mu}{\rho} \qquad (4)$$

The values of C, f(n) and d_e are dependent on the different methods used in the grain-size analysis.

According to Odong [19], porosity (n) may be derived from the empirical relationship with the coefficient of grain uniformity (U) as follows:

$$n = 0.255(1 + 0.83^{U}) \tag{5}$$

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

$$U = \left[\frac{d_{60}}{d_{10}}\right] \tag{6}$$

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 (equation 7) which take the general form presented in equation (3) but with varying C, f (n) and $d_e$values and their domains of applicability.

Hazen

$$K = \frac{g}{v} 6 \times 10^{-4}[1 + 10(n - 0.26)]de^2 \tag{7}$$

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.

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 [21].

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

Breyer

$$K = \frac{g}{v} \times 60 \times 10^{-4} log \frac{500}{u} de^2 \tag{9}$$

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 0.06 mm and 0.6 mm.

Slitcher

$$K = \frac{g}{v} 1 \times 10^{-2} n^{23.287} de^2 \tag{10}$$

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

Terzaghi

$$K = \frac{g}{v} \cdot c_t \left[\frac{n - 0{\cdot}13}{\sqrt[3]{1-n}}\right]^2 de^2 \tag{11}$$

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 [7].

USBR

$$\mathrm{K} = \frac{g}{v} \times 4.8 \times 10^{-4} d20^{0.3} \times d20^{2} \tag{12}$$

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 [7].

Alyamani and Sen

$$\mathrm{K} = 1300[I_0 + 0.025(d_{50} - d_{10})]^2 \tag{13}$$

Where K is the hydraulic conductivity (m/day), I_o 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 (13) bear the stated units for consistency. This formula therefore, is exceptionally different from those that take the general form of equation (3). 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 [19].

Table 2: Hydraulic conductivities calculated from grain-size analysis using empirical formulae [19]

Sample & its classification	d_{10} (mm)	d_{20} (mm)	d_{50} (mm)	(U)	(n)	(I_o) (mm)	Hazen (m/da)	K-C (m/da)	Breyer (m/da)	Slitcher (m/da)	Terzahi (m/da)	USBR (m/da)	A/S (m/da)
1-Gravelly sand	0.339	0.468	1.180	5.309	0.349	0.249	NA	80.139	114.009	30.249	51.630	NA	94.788
2-Medium sand	0.180	0.220	0.330	1.917	0.433	0.157	44.454	56.882	39.347	17.327	NA	12.356	33.593
3-Coarse sand	0.310	0.400	0.720	3.226	0.395	0.254	113.500	112.495	105.787	38.001	66.381	NA	90.776
4-Medium sand	0.157	0.189	0.258	1.783	0.438	0.139	34.439	45.591	30.324	13.689	NA	8.713	26.038

Key: K-C = Kozeny-Carman; A/S = Alyamani & Sen

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.

3.0 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.

4.0 References

[1] Tayfun, A. (2005). Saturated Hydraulic Conductivity: A Study of Path Analysis in Clayey Soils. Ataturk University ZiraatFak Derg,Vol. 36, No. 1, pp. 23–25.

[2] Sarki, A., Mirjat, M., Asghar, A., Shafi, M., Kori, M. and Qureshi, L. (2014). Determination of Saturated Hydraulic Conductivity of Different Soil Texture Materials. Journal of Agriculture and Veterinary Science, Vol. 7, No. 12, pp. 56-62.

[3] Ibrahim. M.M. and Aliyu, J. (2016). Comparison of Methods for Saturated Hydraulic Conductivity Determination: Field, Laboratory and Empirical Measurements. British Journal of Applied Science and Technology, Vol. 15 No. 3, pp. 1-8.

[4] Bagarello, V. and Sgroi, A. (2004). Using the single-ring infiltrometer method to detect temporal changes in surface soil field-saturated hydraulic conductivity. Soil Tillage Research Journal, Vol. 76, pp. 13–24.

[5] Fuentes, J.P., Flury, M. and Bezdicek, D.F. (2004). Hydraulic properties in a silt loam soil under natural prairie, conventional tillage and no-till. Soil Science Society of America Journal, Vol. 68, pp. 1679–1688.

[6] Shipeng, Q.I., Zhonghui, W.E., Chengpeng, L.U., Longcang, S.H.U., Jianwei, S.H., Huang, Y.I.N. and Shuo, Z. (2014). A new empirical model for estimating the hydraulic conductivity of low Permeability. Hydrology of Water Resources Publication, pp. 368.

[7] Cheng, C. and Chen, X. (2007). Evaluation of Methods for Determination of Hydraulic Properties in an Aquifer-Aquitard System Hydrologically Connected to River. Hydrogeology Journal, Vol. 15, pp. 669-678.

[8] Edoga, R.N. (2010). Comparison of saturated hydraulic conductivity measurement methods for Samaru - Nigeria soils. Agriculture Research Center Journal International Vol. 1, No. 4, pp 269-273.

[9] Todd, D.K. and Mays, L.W. (2005). Groundwater Hydrology. John Wiley and Sons Inc., pp. 125-142.

[10] Post, V., Kooi, H. and Simmons, C. (2007). Using Hydraulic Head Measurements in Variable-Density Ground-Water Flow Analyses. Ground Water, Vol. 45, No. 6, pp. 664–671. doi: 10.1111/j.1745-6584.2007.00339.

[11] Simůnek, J., Jarvis, N.J., van Genuchten, M.T. and Gärdenäs, A. (2003). Review and comparison of models for describing non-equilibrium and preferential flow and transport in the vadose zone. Journal of Hydrology, Vol. 272, pp. 14–35. doi.org/10.1016/S0022-1694(02)00252-4.

[12] Scanlon, B.R., Mace, R.E., Barrett, M.E. and Smith, B. (2003). Can we simulate regional groundwater flow in a Karst system using equivalent porous media models? Case study, Barton Springs, Edwards Aquifer, USA. Journal of Hydrology, Vol. 276, pp. 137–158. doi:10.1016/S0022-1694(03)00064-7.

[13] Fetter, C.W. (2001). Applied hydrogeology, 4th edn., Prentice Hall, New Jersey.

[14] Ritzema H.P. (2006). Drainage Principles and Applications, 2nd edn., ILRRI Publication, India, pp. 283-294.

[15] Osunbitan, J.A., Oyedele, D. J. and Adekalu, K.O. (2005). Tillage effects on bulk density, hydraulic conductivity and strength of a loamy sand soil in southwestern Nigeria. Soil and Tillage Research, Vol. 82, pp. 57–64. doi:10.1016/j.still.2004.05.007.

[16] Stibinger, J. (2014). Examples of Determining the Hydraulic Conductivity of Soils: Theory and Applications of Selected Basic Methods. University Handbook on Soil Hydraulics, pp 6-72.

[17] Cirpka, O.A. (2003). Environmental Fluid Mechanics I: Flow in Natural Hydro systems. Journal of Hydrology, Vol. 283, pp 53-66
[18] Pinder, G.F. and Celia, M.A. (2006). Subsurface Hydrology. John Wiley & Sons Inc. Hoboken, New Jersey.
[19] Odong, J. (2008). Evaluation of Empirical Formulae for Determination of Hydraulic Conductivity based on Grain-Size Analysis. Journal of American Science, Vol. 4, No. 1, pp 1545-1003.
[20] Idris-Nda, A. (2013). Estimating Aquifer Hydraulic Properties in Beda Basin, Central Nigeria Using Empirical Methods. Department of Geology Federal University of Technology, Minna, Nigeria, Vol. 2, No. 1, pp 210-211.
[21] Carrier, W.D. (2003). Goodbye, Hazen; Hello, Kozeny-Carman. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 129, No. 11, pp 1054-1056.