Comparison of Methods for Saturated Hydraulic Conductivity Determination: Field, Laboratory and Empirical Measurements (A Pre-view)

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Authors' contributions

This work was carried out in collaboration between both authors. Author MMI designed the study and wrote the first draft of the manuscript and managed literature searches. Author JA managed literature searches and read through the manuscript for corrections. Both authors read and approved the final manuscript.

Article Information

Review Article

ABSTRACT

Hydraulic conductivity is the single most important hydraulic parameter for flow and transport-related phenomena in soil, but there is concern arising from the suitability, efficiency and ease of the different measuring methods under different conditions. The various methods of determining saturated hydraulic conductivity; the field methods, laboratory methods and empirical formulae were reviewed so as to ascertain the suitability of the various methods and their acceptability based on literature. This review shows that all the methods have their individual merits and demerits. Most researchers however, prefer the use of empirical data to data from both field and laboratory conditions; and that the direct measurement of soil saturated hydraulic conductivity is very difficult, laborious, and costly under field or laboratory conditions, and even often impractical for many hydrologic analyses. However, it has been agreed that the estimation of soil saturated hydraulic conductivity using empirical formulae depends on the local soil maps and published data which often has limited accuracy and range in many cases. This is the main reason why many soil

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scientists and engineers have tried to develop models to determine soil saturated hydraulic conductivity with readily obtained soil survey data, with emphasis that all the empirical formulae are to be used strictly within their domains of applicability.

1. INTRODUCTION

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 [1]. Soils saturated hydraulic conductivity (Ksat) indicates how quickly water will infiltrate when applied to the soil surface. The measurements of soil hydraulic properties are very essential to studies in water and solute transport, modelling of heat and mass transport near the soil surface [2], and management of irrigation water. Finding Ksat is needed in various geotechnical applications including design of drainage systems, measurement of seepage from canals, reservoirs, detention ponds, or wastewater lagoons, monitoring the movement of leachate into the ground below sanitary landfills, assessment of groundwater recharge and surface runoff, in prediction of soil erosion and soil compaction generally in water management problems. Soil hydraulic properties are also used as input parameters for process based simulation models [3] and other applications in studies of soil hydrology. Usually the Ksat parameter is directly measured in the field or laboratory. There are several methods for measuring Ksat, but generally they provide differing and often incomparable values. The causes of this may be numerous, in part owing to the measurement technique (procedure of sample acquisition, extreme sensitivity to the given-soil volume dimension, flux geometry, etc.) and in part owing to the soil particularities (different physical and hydraulic characteristics, different structure, texture, etc.), as is well-known and documented in the literature [4-8]. In spite of the methods, comparisons of results are generally uncertain and linked to the specific measurement conditions. Determining the Ksat 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 Ksat value. The accuracy of numerical modeling of infiltration depends on how well the underlying mathematical models describe the physics of the flow in variably saturated soils [9]. The best choice of method(s) for the above

applications must optimize several interrelated factors, including accuracy, speed, simplicity, portability, manpower, capital costs, etc. To this effect, this paper seeks 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 literature.

2. EMPIRICAL FORMULAE

The tasks of using empirical formulae appear rather straight forward but its correlation is not easily established [10]. Published information for soils around the world may have data on soil particle size distribution, organic matter content and bulk density, but the data on soil hydraulic properties may be incomplete or missing. Attempts have been made to estimate these properties indirectly from readily available soil properties. Such equations are often called pedotransfer functions (PTFs) [11]. Pedotransfer functions indeed aim to predict hard-to-measure soil properties that are required by the soil data user, from primary soil properties. They have become an interesting topic in the area of soil science and environmental research [12]. In general, PTFs transfer the data we have into the data we need [13]. The correlation methods for determining Ksat in drainage surveys are frequently based on relationships between the Ksat value and one or more of the following soil properties: texture, pore-size distribution, grain-size distribution, or with the soil mapping unit. Numerous investigators have studied this relationship and several formulae have resulted based on experimental work. [14] proposed a formula which was then modified by Carman in 1937 and 1956 to become the Kozeny-Carman equation. Other attempts were made by [15-24] and so many others. The applicability of these formulae depends on the type of soil for which hydraulic conductivity is to be estimated. Moreover, few formulas give reliable estimates of results because of the difficulty of including all possible variables in porous media. [25] noted that 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.

Dunn et al. [21] showed that Ksat 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 Ksat. Secondly, from pure theoretical analysis of infiltration times. [20] estimated Ksat from an equation obtained from Darcy's and Poiseuille's equations assuming laminar water flow. Ksat has been estimated from porosity by [26]. [22] derived a simple closed-form expression for Ksat using [17] model in conjunction with the [16] water retention curve. However, most of the value gotten using empirical formulae do not give the approximate or the same values when compared to the laboratory and field determination. Some values are either below or above the values [27].

3. FIELD METHODS

3.1 Small-scale *in-situ* Methods

Bouwer and Jackson [28] have described numerous small-scale *in-situ* methods for the determination of Ksat. The methods fall into two groups: those that are used to determine Ksat 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. These methods are called 'infiltration methods' and use the relationship between the measured infiltration rate and hydraulic head to calculate the Ksat. The equation describing the relationship has to be selected according to the boundary conditions induced. 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'. The Ksat value can then be calculated with an equation selected to fit the boundary. The small-scale *in-situ* methods are not applicable to great depths. Hence, their results are not representative for deep aquifers; unless values measured at shallow depth are also indicative of those at greater depths and that the vertical Ksat values are not much different from the horizontal values. In general, the results of small-scale methods are more valuable in shallow aquifers than in deep aquifers.

3.1.1 Extraction methods

The most frequently applied extraction method is the 'auger-hole method'. It uses the principles of unsteady-state flow. An extraction method based on steady-state flow has been presented by [29] and is called the 'pumped-borehole method'. 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, [30] found Ksat values ranging from 0.12 to 49 m/d in a 7 ha field with sandy loam soil. Similarly, [30] also found auger-hole Ksat values in the range of 0.54 to 11 m/d in a 5 ha field with sandy loam soil.

3.1.2 Infiltration methods

The 'infiltration methods' can be divided into steady-state and unsteady state methods. Steady-state methods are based on the 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. An example of a steady-state infiltration method is the method of Zangar or 'shallow well pump-in method' (e.g. [28]). A recent development is the 'Guelph method', which is similar to the Zangar method, but uses a specially developed apparatus and is based on both saturated and unsaturated flow theory [31]. 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. 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'. [28] presented a number of unsteady-state permeameter methods. They also discussed the 'double-tube method', where a small permeameter is placed inside a large permeameter. The unsteady-state method whereby an uncased hole is used is called the 'inversed auger-hole method'. This method is similar to the Zangar and Guelph methods, except that the last two use the steady-state situation. In general, the infiltration methods measure the Ksat value in the vicinity of the infiltration surface. It is not easy to obtain Ksat values at greater depths in the soil. Although the

soil volume over which one measures the Ksat 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 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.

3.2 Large-Scale *in-situ* Methods

The large-scale *in-situ* methods can be divided into methods 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. From these data, the Ksat 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 Ksat values along these paths are automatically taken into account in the overall Ksat value found with the method. It is then not necessary to determine the variations in the Ksat 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.

3.3 Laboratory Methods

In the laboratory, the value of Ksat can be determined by several instruments and methods such as the permeameter, pressure chamber, and consolidometer. A common feature of all 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. Because of the small sizes of the soil samples handled in the laboratory, the results of these tests are considered a point representation of the soil properties. If the soil samples used in the laboratory test are truly undisturbed samples, the measured Ksat value should be a true

representation of the *in-situ* saturated hydraulic conductivity at that particular sampling point. The conductivity of disturbed (remolded) 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. For fine-grained soils, the undisturbed cohesive sample can be oriented accordingly, to obtain the hydraulic conductivity in either the vertical or horizontal direction.

The methodology used for the experimental determination of Ksat in either laboratory or field experiments is based on the following procedures [32]:

1. Assume a flow pattern (such as one-dimensional flow in a porous medium) that can be described analytically by Darcy's law,

$$Q = AK\frac{\Delta h}{L}$$

Where, Q is the volumetric flow rate, A is the flow area perpendicular to L, K is the hydraulic conductivity, L is the flow path length, h is the hydraulic head and Δ denotes the change in h over path L.

$$h = (p/rg + z)$$

Where p is the water pressure, r is the water density, g is the acceleration due to gravity and z denotes the elevation.

2. Perform an experiment reproducing the chosen flow pattern and measure all measurable quantities in the above equation.
3. Compute the coefficient *K* by substituting the measured quantities into the Equation above.

4. DISCUSSION

In the laboratory, the performance of four *in situ* Ksat measuring methods were evaluated by [33] at four depths (15, 30, 60, and 90 cm) on a glacial-till soil, the methods are (i) Guelph permeameter, (ii) velocity permeameter, (iii) disk permeameter, and (iv) double-tube method with one laboratory method (constant-head permeameter) to estimate Ksat. The Guelph permeameter method was found to give the lowest Ksat values, possibly because of small sample size, whereas the disk permeameter and double-tube methods gave maximum values for

Ksat with minimum variability, possibly because of large sample size. Maximum variability in Ksat values for soil cores at shallow depths may have occurred because of the presence or absence of open-ended macropores. Estimates of Ksat however, are most comparable for the velocity permeameter. For the laboratory method, greatest variability at shallow depths of 15 and 30 cm was produced, perhaps because of smaller sample size, the presence or absence of open-ended macropores, and variable soil compaction during core extraction.

In later years, when a research was conducted by [34] a different Ksat estimate was employed, where two-dimensional numerical model, CHAIN_2D was used to predict water flow into a subsurface tile drain on the same glacial-till soil. For their study, the Ksat measurement techniques used include: (i) an *in situ* Guelph permeameter, (ii) an *in situ* velocity permeameter, (iii) an *in situ* disc permeameter, and (iv) a constant-head permeameter in the laboratory using detached soil cores. Quantitative and qualitative findings suggest that the disc permeameter was best suited for the field site. Their results also indicated that the Ksat estimates obtained with the velocity permeameter and laboratory constand-head permeameter methods led to underpredicted tile flow rates. These two methods yield strictly vertical Ksat measurements. Moreover, it is likely that this result reflects the fact that a disc permeameter better represents the natural flow conditions. Moreover, its ease of operation and minimal pore structure disturbance during the hydraulic conductivity measurements seem to give this technique additional advantage over other methods.

In a research work by [35] that aimed at determining and evaluating the saturated hydraulic conductivity for silt loam soil in both field and laboratory conditions, the hydraulic conductivity was measured in the field in two conditions (dry and wet) using the Guelph permeameter and field saturated hydraulic conductivity based on Elrick equation was calculated. In the laboratory, the saturated hydraulic conductivity (Ksat) was determined using the constant head permeameter. The results indicated significant differences between both methods and between both seasons. 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 special flow paths, and therefore increase Ksat values.

One merit of the laboratory measurement methods is that they could be used to evaluate both the vertical and horizontal hydraulic conductivity in soil samples. If undisturbed samples are collected, the values of Ksat obtained correspond to the direction in which the sample was taken (generally vertical). If however, the samples of the disturbed soils are obtained, it can be used to approximate the actual value of Ksat in the undisturbed (natural) soil in the horizontal direction. Also, in laboratory tests it is necessary to select appropriate fluid for the determination of the saturated hydraulic coefficient. This is because the objective is to have the test fluid that mimics the actual properties of the soil fluid as closely as possible. When an inappropriate test fluid is chosen, there is tendency for the test sample to get clogged with entrapped air.

In contrast to laboratory methods for measuring conductivity in soil samples, field methods, in general, involve a large region of the soil. Consequently, the results obtained from field methods should reflect the influences of both the vertical and horizontal directions and should represent an average value of Ksat. Moreover, owing to the afore-mentioned difficulty in obtaining a perfectly undisturbed sample of soil, the field methods should be used in order to avoid inaccurate estimation of Ksat value. However, field methods are usually more expensive, laborious and difficult than laboratory methods. In this case, laboratory methods may be used to determine the value Ksat especially, when the question of cost becomes significant, or when actual representation of field condition is not of fundamental importance.

The empirical method was emphasized to be the simplest and most appropriate for estimation of soil hydraulic parameter by the use of average parameter values for soil textural classes [36]. [37] have proposed regression equation for computing soil water relation from particle size distribution data. They described this approach as the simplest estimation of soil hydraulic properties. In addition, [37] using three different models adequately predicted soil saturated hydraulic conductivity on the basis of soil texture of data collected from (field of) grassed soils with healthy grass growing. Also, the performance of the three models was compared with field measured data of soil saturated hydraulic

conductivity. The results showed that two-parameter models, Campbell and Saxton et al. models had better performance than the one-parameter model (Smerttem and Bristow model).

Pandey et al. [36] concluded that accurate determination of saturated hydraulic conductivity leads to precise estimation of unsaturated hydraulic conductivity. It is inferred from the paper that the empirical model termed as Relative Effective Porosity Model (REPM) gives reasonable estimate of Ksat. Due to its simplicity and better estimating capabilities, the empirical equation is recommended for field use. These findings are based on the alluvial soils. The researchers advised that the use of the model should be extended for different soil types so that REPM model can generalized for adoption. It is also recommended that field measured field capacity be used in the equation to give better estimate measured Ksat. [27] studied the Comparison of saturated hydraulic conductivity measurement methods for Samaru-Nigeria Soils. 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. [38] used seven different empirical formulae to determine hydraulic conductivity based on grain-size analysis and noted that Kozeny-Carman formula proved to be the best estimator of most samples analyzed, and may be, even for a wide range of other soil types. However, some of the formulae underestimated or overestimated hydraulic conductivity; even of the same soil in contrast to the findings of [27] on the non-suitability of Kozney-Carman model in estimation of saturated hydraulic conductivity of soil samples in Samaru. The researcher emphasized that all the empirical formulae are to be used strictly within their domains of applicability. For this reason, this paper presumes that the conflict findings of [27] and [38] about non-suitability and excellence of Kozney-Carman model, respectively; in estimation of saturated hydraulic conductivity is due to the differences in terms of the type of soil for which the hydraulic conductivity is to be estimated. Furthermore, [39] in his work on aquifer system supports the view of [40] on the merit and use of empirical formulae to obtain accurate estimation of hydraulic conductivity in field environments.

5. CONCLUSION

Field and laboratory measurements have their merits and demerits because of the procedures upon which the experiments are based, such as assumption of 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. It is emphasized that the use of field methods is limited by the lack of precise knowledge of aquifer geometry and hydraulic boundaries [41]. The cost of field operations and associated wells constructions can be prohibitive as well. Amongst the limitations of the laboratory measurement of Ksat is that laboratory tests are carried out on small samples of soil materials collected during core-drilling programmes as well as formidable problems in the sense of obtaining representative samples and, very often, long testing times. If the soil samples used in the laboratory test are truly undisturbed samples, the measured value of Ksat should be a truly representation of the *in-situ* saturated hydraulic conductivity at that particular sampling point. Unfortunately, it is very difficult if not impossible to get a truly 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 [42]. Alternatively, methods of estimating hydraulic conductivity from empirical formulae based on grain-size distribution characteristics have been developed and used to overcome these problems. On the use of empirical formulae, researchers have established that the estimation of soil saturated hydraulic conductivity has to depend on the local soil maps and published data which often has limited accuracy and range in many cases. This is the main reason why many soil scientists and engineers have tried to develop models to determine soil saturated hydraulic conductivity with readily obtained soil survey data [40] and that all the empirical formulae are to be used strictly within their domains of applicability [27]. Summarily, most researchers preferred the use of empirical data to data from both field and laboratory conditions; and that the direct measurement of soil saturated hydraulic conductivity is very difficult, laborious, and costly

under field or laboratory conditions, and even often impractical for many hydrologic analyses.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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