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DIMENSIONAL ANALYSIS TO ESTIMATE THE UNSATURATED HYDRAULIC CONDUCTIVITY OF A SANDY LOAM SOIL IN THE AGRICULTURAL FIELD

Naji Mordi Naji Al-Dosary[1*], Abd El Wahed Mohamed Aboukarima[1,2], Mohamed Said El Marazky[2]

[1*]Corresponding author. Department of Agricultural Engineering, College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia. E-mail: nalsawiyan@ksu.edu.sa | ORCID ID: https://orcid.org/0000-0001-9459-4206

KEYWORDS

Electrical conductivity, infiltration rate, mini disc infiltrometer, soil density, water management

ABSTRACT

Hydraulic conductivity in unsaturated soil controls water movement and measuring it in agricultural fields is a challenging task requiring time-consuming, costly, and skilled experimentation. This study was conducted to reduce the cost of experimentation through the development of an estimation model. The developed model is based on dimensional analysis to determine the value of hydraulic conductivity of unsaturated soil as it relates to soil moisture content, irrigation water electrical conductivity, and suction rate (pressure head). Data points were acquired from measurements of cumulative infiltration in the field, using a mini disc infiltrometer. The developed model gave a mean discrepancy ratio of 1.10 (the acceptable range is 0.5–2.0) and a mean percentage of relative errors of 9.96%. These values indicate that the dimensional analysis model is reliable for the prediction of sandy loam soil's unsaturated hydraulic conductivity.

INTRODUCTION

Unsaturated hydraulic conductivity indicates a measure of a soil's water-retaining capability when soil pore space is not saturated with water. The hydraulic conductivity parameter of an unsaturated soil is an independent parameter (or not a constant parameter). It is a parameter which is predominantly a function of the water content or the matric suction of the unsaturated soil (Ramli et al., 2021). Additionally, knowledge about solute transport and water flow in the unsaturated zone is important for drainage and irrigation strategies (Van Dam et al., 2004; Wang et al., 2019). The main property that is considered to govern flow is the soil's hydraulic conductivity. However, there are many obstacles to measuring it accurately (Rasoulzadeh, 2011). Since hydraulic conductivity controls water movement through soil (Fatehnia et al., 2014), measuring its value is a challenging and costly task and requires cleverness and experimental experience (Wösten & Van Genuchten, 1988; Malaya & Sreedeep, 2013). Therefore, the use of models that estimate hydraulic conductivity from more easily measured properties is common (Perkins, 2011). Thus, scientists have been establishing numerical and analytical methods to determine hydraulic conductivity that is difficult to measure in the field (Mollerup et al., 2008; Tao et al., 2019; Amer, 2020; Davis, 2020; Guellouz et al., 2020; Modaresi Rad et al., 2020; Peng et al., 2020; Sariyev et al., 2020; Scherger et al., 2020; Garcia & Galang, 2021; Walle et al., 2021; Ahmed & Hossain, 2022).

Doussan & Ruy (2009) predicated unsaturated soil hydraulic conductivity based on electrical conductivity. Moosavi & Sepaskhah (2012a) established a model for the prediction of unsaturated hydraulic conductivity of soil based on pedotransfer functions. The study revealed that the investigated model was precise at all soil tensions, except for soil tensions of 0.1 m and to some extent 0.3 m. At those tensions, the investigated model gave less accurate prediction values of unsaturated soil hydraulics.

Moosavi & Sepaskhah (2012b, c) performed field experiments at soil water tensions of 0.0-0.2 m, to study the effects of water quality on the hydraulic conductivity of a sandy clay loam soil. The results showed that the mean unsaturated hydraulic conductivity of soil correlated with changes in electrical conductivity of water, as a power or quadratic equation and with the higher electrical

[1] Department of Agricultural Engineering, College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia.
[2] Agricultural Engineering Research Institute (AEnRI), Agricultural Research Center, Giza, Egypt.

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conductivity of the water directed to lower soil hydraulic conductivity, as the applied soil water tension was increased. The results showed that, for these categories of soil, the use of water with an electrical conductivity of 10 dSm^{-1} will improve the soil's hydraulic properties. A high positive correlation was noted between soil moisture content and hydraulic soil conductivity values in all investigated soils. It was also recognized that the unsaturated soil hydraulic conductivity drops rapidly with a reduction in soil moisture content, and this decline is influenced by the soil ingredients and properties (Bhatnagar et al., 1979). Nasta et al. (2013) predicted the unsaturated relative hydraulic conductivity from Kosugi's water retention function. Different techniques, including multiple linear regression, adaptive neuro fuzzy inference system, and artificial neural networks, were employed to predict the unsaturated soil's hydraulic conductivity (Moosavi & Sepaskhah, 2012b; Sihag et al., 2017; Sihag, 2018).

Dimensional analysis is a simple, clear, and intuitive method for determining the functional dependence of physical quantities that influence a process (Vekariya et al., 2011). It offers a valuable tool for developing a generalized model for hydraulic conductivity. Ngwangwa et al. (2014) presented a mathematical model based on a dimensional analysis technique for determining the hydraulic conductivity of agricultural soils at 0 to 15 cm soil depths. The model was based on Buckingham's Pi-theorem using the following soil properties: bulk density, porosity, cation exchange capacity (i.e., a positively charged ion that is attracted to the negative electrode in electrolysis.), soil pH, exchangeable sodium percentage, organic matter content, particle density and percentages of clay, silt, and sand, acceleration due to gravity, fluid density, and depth of soil. The dimensional analysis model was tested with data that was not used in building the dimensional analysis model, and the data indicated there was no significant difference between the predicted and measured soil hydraulic conductivity, at a 5% significance level. A high coefficient of determination of 0.940 between the two values was also perceived. Therefore, in this study, field runs in sandy loam soil were undertaken under different water characteristics, to gather data that denote the unsaturated hydraulic soil conductivity. The acquired field data was employed to establish a dimensional analysis model for estimating unsaturated soil hydraulic conductivity based on soil and water properties (i.e., irrigation water's electrical conductivity, moisture content of the soil, bulk density of the soil, and soil suction rate).

MATERIAL AND METHODS

Dimensional analysis

Dimensional analysis (Saadon et al., 2016) is one of the modeling methods used to define the relationships between parameters. It is used to establish, among definite parameters, a dimensionally precise equation. The objectives of dimensional analysis include: i) to decrease the number of parameters for later analysis, ii) to offer dimensionless variables whose numerical value is free of any system of units. It will decrease the quantity of parameters and yield dimensionless variables. However, it is desirable to carry out tests or experiments to confirm these variables. It should be noted that dimensional analysis does not provide the precise form of an equation, but it can produce significant savings in the number of parameters. It is based on two assumptions: i) physical quantities have fundamental dimensions which are length (L), mass (M) and time (T) and ii) physical rules are unchanged when altering the units measuring the dimensions.

Buckingham's Pi-theorem

The Buckingham Pi theorem is a process for defining dimensionless groups from a selection of variables. If the equation $f(q_1, q_2, q_3,..) = 0$ has no shortage, then the answer has the form $f(\pi_1, \pi_2, \pi_3, \ldots \pi_{n-k}) = 0$, wherever the π relations are independent yields of the variables q_1, q_2, q_3, etc., and are dimensionless in the fundamental dimensions (Saadon et al., 2016). To express this differently, a full-dimensional homogeneous equation, relating to the n number of physical quantities that can be expressed in terms of k fundamental quantities, is reduced to a functional relationship between the n-k dimensionless products. For example, if there are nine physical quantities involved in the relationship of the physical problem with three fundamental physical quantities, six set of dimensionless sets will be designed.

Characteristics of water and soil samples

Field experiments were performed in a field located in Huraimla Governorate, Riyadh, Saudi Arabia (coordinates: 11.22° N, 21.21° E, captured using a Garmin GPS 60 with a positional accuracy of 15 m). Three soil samples were collected from the top 20 cm of the soil and analyzed in the laboratory of the Soil Department at the College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia. The soil in the experimental field was sandy loam soil, with a silt content of 28%, sand content of 67%, and clay content of 5%. Soil electrical conductivity was 2.65 dSm^{-1}, organic matter was 1.95%, and soil pH was 8.90. The soil moisture content [%, dry basis (db)] was acquired using an electric oven for 24 h at 105°C. The bulk density of the soil was determined, based on the volume of the core sample and dried soil mass. Eight water samples were utilized and analyzed by the IDAC laboratories (Riyadh, Saudi Arabia) to get the water sample properties, such as electric conductivity of water (ECw), and Mg, Ca, HCO_3, Na, Cl, pH, SO_4 content. Table 1 indicates the chemical properties of water samples, water pH, and electrical conductivity used in the infiltration experiments.

TABLE 1. The properties of water samples used in the infiltration experiments.

Water samples	(meq L^{-1})						ECw	pH
	Ca	Mg	Na	HCO_3	Cl	SO_4	(dSm^{-1})	(-)
W1	6.61	6.48	6.30	2.40	11.97	5.10	4.72	6.83
W2	4.77	2.56	5.74	2.09	5.89	4.09	1.32	7.15
W3	11.62	7.09	10.20	8.00	17.95	8.50	1.77	7.33
W4	10.02	4.46	11.10	4.40	13.96	7.30	3.02	7.40
W5	10.42	3.42	11.33	3.69	9.49	8.14	1.56	7.70
W6	11.41	4.65	13.58	3.98	11.49	14.20	2.38	7.75
W7	14.34	11.28	20.56	5.33	15.47	22.00	3.89	8.00
W8	20.87	10.78	23.56	3.20	19.48	27.04	2.60	8.20
Mean	11.26	6.34	12.79	4.14	13.21	12.05	2.66	7.55
Minimum	4.77	2.56	5.74	2.09	5.89	4.09	1.32	6.83
Maximum	20.87	11.28	23.56	8.00	19.48	27.04	4.72	8.20

Measurement of hydraulic conductivity of unsaturated soil

A mini disk infiltrometer (MDI, Decagon Devices Inc., Pullman, Washington, USA) was used to measure the hydraulic conductivity of unsaturated soil. The MDI consists of two chambers (a bubble chamber and water reservoir), linked through a Mariette pipe, which provided a constant head of water pressure of −0.5 to −7.0 cm (equivalent to −0.05 to −0.70 kPa). The end of the MDI consists of a porous sintered steel disk. The water-filled pipe was positioned on the surface of the soil, and water allowed to infiltrate into the soil, with the volume of water and speed of infiltration dependent on the hydraulic conductivity and sorptivity of the soil. The suction rates were represented as water pressure heads of −1, −2, −3, −4, and −5 cm in this study. At all test locations, the infiltration experiments were carried out without any alteration of the soil surface. The soil moisture content and bulk density of the soil were detected in undisturbed spots. No rainfall occurred during the experiments. The MDI was placed on the soil surface as depicted in Figure 1. The infiltration experiment was repeated seven times for each water sample and the mean value was used.

FIGURE 1. Mini disk infiltrometer used for field infiltration measurements.

The respective measuring spots were typically several metres apart. During the infiltration test, the water volume in the tank chamber was recorded at steady intervals. Infiltration was computed using [eq. (1)], from the cumulative infiltration accounts against time following Zhang (1997), Carsel & Parrish (1988), and recommendations from Decagon Devices Inc. (2016).

$$I = C_1 t + C_2 \sqrt{t} \tag{1}$$

where t is the time (s), I is the cumulative infiltration (cm), and C_1 (cms^{-1}) and C_2 ($(cms^{-1})^{-0.5}$) are parameters. C_1 is associated with hydraulic conductivity and C_2 is linked to soil sorptivity. The hydraulic conductivity (KU) of the soil was then calculated from [eq. (2)].

$$KU = \frac{C_1}{A_0} \tag{2}$$

where C_1 is the slope of the curve of the cumulative infiltration against the square root of time and (A_0) is a value relating the Van Genuchten parameters for a given soil type to the head of water pressure and radius of the infiltrometer disk. The values of A_0 can be calculated by [eq. (3)] and [eq. (4)] (Carsel & Parrish, 1988; Decagon Devices Inc., 2016).

$$A_0 = \frac{11.65\left(n^{0.1}-1\right)\exp\left[2.92(n-1.9)\alpha\,h_o\right]}{(\alpha\,r_o)^{0.91}} \qquad n \geq 1.9 \tag{3}$$

$$A_0 = \frac{11.65\left(n^{0.1}-1\right)\exp\left[7.5(n-1.9)\alpha\,h_o\right]}{(\alpha\,r_o)^{0.91}} \qquad n < 1.9 \tag{4}$$

where the symbols n and α are the Van Genuchten parameters for the soil, r_o is the disk radius and h_o is the suction at the disk surface. The Van parameters for the 12 texture classes were gained from Carsel & Parrish (1988). Sporadically occurring negative values for hydraulic conductivity indicate unsteadiness of the particular measurement and were ignored in further calculations (Schacht & Marschner, 2015).

Dimensional variables

Based on the previous investigations, the primary factors which have impacted the field unsaturated hydraulic conductivity (KU) are the hydraulic conductivity of the soil, soil texture, the existing quantities of gypsum and lime, soil water properties, and the apparent and actual distributions of particle size (Zhuang et al., 2001). In addition, acceleration due to gravity, water viscosity, ratio of total volume of pores, water density, and the radius of equivalent cylindrical pore size impact the field unsaturated hydraulic conductivity (Amer et al., 2009). Moreover, water quality has an impact on KU, along with soil bulk density and soil moisture content; several studies reported significant effects on unsaturated soil hydraulic conductivity (Bhatnagar et al., 1979; Dec et al., 2008; Xiao et al., 1992; Crescimanno et al., 1995; Springer et al., 1999; Moosavi & Sepaskhah, 2012c). Suction rate also has a strong effect on the unsaturated hydraulic conductivity of soil (Moosavi & Sepaskhah, 2012c; Simunek et al., 1999; Matula et al., 2015). In this study, the selected variables which influenced the field unsaturated soil hydraulic conductivity were water electric conductivity, suction rate, soil moisture content, and soil bulk density.

Development of model equation

The mathematical methodology used in this work is dimensional analysis (the Buckingham pi-theorem regarding dimensionally homogeneous equations). Dimensional analysis is a technique that helps to define functional relations. It provides a method for joining various variables, which are thought to denote a system, into set of dimensionless terms, nominated as pi terms, which lessens the number of parameters in a multifaceted phenomenon to a smaller group of dimensionless ratios (Nkakini et al., 2019). The basic unit of electrical conductivity in water is the Siemen per metre (Sm^{-1}). The Siemen expression, in terms of other SI units, is AV^{-1} and the Siemen expression, in terms of SI base units, is $m^{-2}\,kg^{-1}\,s^3\,A^2$. Thus, the SI base unit for water's electrical conductivity (electrical conductivity means a salt tolerance in the water) is $L^{-2}\,M^{-1}\,T^3\,A^2\,L^{-1}$ in the MLT dimension system or $L^{-3}\,M^{-1}\,T^3\,A^2$ in the same system, where L is length, T is time, M is mass and A is amperes. The ampere dimension is Coulombs per second and the electric charge (Q, Coulomb) dimension is $M^{1/2}\,L^{3/2}\,T^{-1}$ (derived by balancing Coulomb's law). Thus, the dimension of water electrical conductivity is T. The basic unit of soil moisture content (MC) is kilograms of water per kilogram of dry soil ($M_wM_s^{-1}$). The basic unit of suction rate (SR - pressure head) is m, the basic unit of soil bulk density (BD) is kilograms per cubic metre (kgm^{-3}) and the basic unit of hydraulic conductivity (KU) is metres per second (ms^{-1}). Table 2 shows some variables affecting the field unsaturated hydraulic conductivity of a soil. Mathematically, KU is a function of ECw, SR.BD, and MC, as follows (Equation 5).

$$KU = f(ECw,\ SR.BD,\ MC) \tag{5}$$

The total number of parameters n = 5, and the total number of vital dimensions m = 3, therefore, the number of π- terms = n – m = 2. Then, [eq. (5)] can be written as:

$$f_1 = (\pi_1, \pi_2) \tag{6}$$

Each π term comprises (m + 1) variables, where m = 3 and this is also equal to repeated variable picking from SR, BD, and ECw to get two π- terms, as:

$$\pi_1 = ECw^a.SR^b.BD^c.KU \tag{7}$$

$$\pi_2 = MC \tag{8}$$

The model for the unsaturated hydraulic conductivity equation developed, is represented as follows (Nkakini et al., 2019):

$$KU = \varphi \times \frac{MC \times ECw}{SR} + \beta \tag{9}$$

Besides this, the linear form (Equation 9) can be written as:

$$KU = \varphi \times Z + \beta \tag{10}$$

where KU is the unsaturated soil hydraulic conductivity (mh^{-1}), MC is the soil moisture content (decimal, db), SR is the water pressure head (suction rate, cm), ECw is the electric conductivity of water (dSm^{-1}), φ is the slope coefficient of the regression line for each field test variable (slope parameter), β is the regression constant (intercept parameter), and Z is the mean of the field test results ($\frac{MC \times ECw}{SR}$), with units of ($dSm^{-1}.cm^{-1}$) (Table 3).

TABLE 2. Some variables affecting the field unsaturated hydraulic conductivity of a soil.

Variables	Symbol	Unit	Dimensions
Dependent Variable			
The field unsaturated soil hydraulic conductivity	KU	ms^{-1}	M^0LT^{-1}
Independent Variables			
Water electrical conductivity	ECw	Sm^{-1}	M^0L^0T
Suction rate	SR	m	M^0LT^0
Soil bulk density	BD	kgm^{-3}	$ML^{-3}T^0$
Soil moisture content	MC	%	$M^0L^0T^0$

Suitability analysis

The unsaturated soil hydraulic conductivity computed from the established formula can give vastly different results from each other and from field measurements. So, the performance of predicting the unsaturated hydraulic conductivity of field soil was verified by discrepancy ratio and relative error. Consequently, for this study and for the measured unsaturated soil hydraulic conductivity, the discrepancy ratio (DR, dimensionless) was determined by comparing the computed and measured unsaturated soil hydraulic conductivity using [eq. (11)] (Yu & Woo, 1994).

$$DR = \frac{KU_{predicted}}{KU_{measured}} \quad (11)$$

When the acceptable range of the discrepancy ratio (DR) was between 0.5 and 2.0, then the average value of the discrepancy ratios was calculated. The closer the value is to unity, the better the equation can be applied to the data set. Equation 12 was used to calculate the percentage of relative errors (RE) of the predicted values, with respect to the measured values:

$$RE = \frac{(KU_{predicted} - KU_{measured})}{KU_{measured}} \times 100 \quad (12)$$

RESULTS AND DISCUSSION

Table 3 depicts the values of Z, unsaturated hydraulic conductivity (KU) in sandy loam soil, and variables that were used for determining the unsaturated soil hydraulic conductivity model equation. The unsaturated hydraulic conductivity model equation was developed using dimensional analysis (Buckingham pi-theorem) to analyze the results from field tests. The experimental field test results (Z) are shown in Table 3. From Table 3, a regression graph was plotted for measured unsaturated hydraulic conductivity (KU, mh^{-1}) against (Z, $dSm^{-1}.cm^{-1}$) that was created from field test results and the values for the constants (φ and β) which are appeared in eq. (10) were established (Figure 2). The linear regression equation was built into the unsaturated hydraulic conductivity equation model. The result showed a perfectly acceptable agreement with the coefficient of determination R^2 = 0.9083. As a result, the established predictive unsaturated hydraulic conductivity is as follows:

$$KU = 0.1375 \times Z + 0.0142 \quad (13)$$

TABLE 3. Values of variables, Z, and unsaturated hydraulic conductivity (KU) in sandy loam soil.

Data points	ECw (dSm^{-1})	MC (decimal)	BD (kgm^{-3})	Suction rate (cm)	KU (mh^{-1})	Z ($dSm^{-1}.cm^{-1}$)
1	1.32	0.10927	1.52	5	0.0092	0.02885
2	1.56	0.10677	1.65	5	0.0095	0.03331
3	1.77	0.10049	1.60	5	0.0098	0.03557
4	1.32	0.11066	1.55	4	0.0145	0.03652
5	1.56	0.10292	1.55	4	0.0223	0.04014
6	1.77	0.10537	1.55	4	0.0233	0.04663
7	1.32	0.11057	1.58	3	0.0246	0.04865
8	1.56	0.10399	1.58	3	0.0252	0.05408
9	2.38	0.10339	1.57	3	0.0306	0.08202
10	1.32	0.12805	1.68	2	0.0271	0.08451
11	2.6	0.10302	1.44	3	0.0276	0.08928
12	1.56	0.12293	1.53	2	0.0284	0.09589
13	1.77	0.11946	1.59	2	0.0331	0.10572
14	2.6	0.11534	1.48	2	0.0339	0.14994
15	1.32	0.13042	1.63	1	0.0398	0.17216
16	1.56	0.11831	1.64	1	0.0454	0.18456
17	1.77	0.13648	1.68	1	0.0481	0.24156
18	2.38	0.10538	1.64	1	0.0552	0.25080
19	2.6	0.11411	1.47	1	0.0599	0.29669
20	3.02	0.12293	1.63	1	0.0647	0.37126
21	3.89	0.11961	1.58	1	0.0675	0.46527

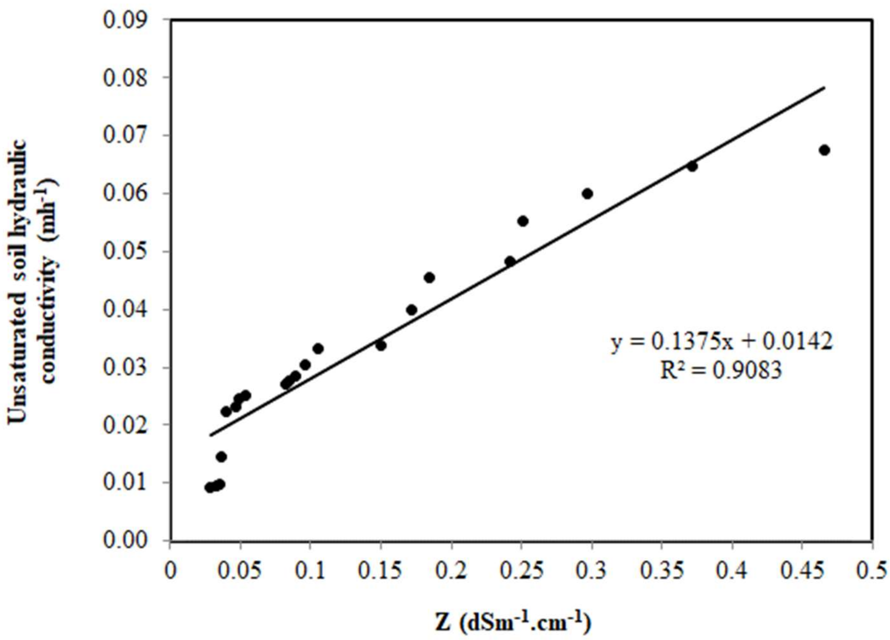

FIGURE 2. Relationship between unsaturated hydraulic conductivity and Z, from field test results.

The authenticity of an established model equation for solving a specific problem depends on its validation and predictions. Table 4 shows the results of the suitability analysis of the established model, based on discrepancy ratio and the percentage of the relative errors. The relative error value ranged between -16.62% and 98.51%, with a mean value of 9.96%. Also, the discrepancy ratio ranged between 0.83 and 1.99, with a mean value of 1.10, which is in the acceptable range. These values are pointers to the fact that the dimensional analysis model is reliable for the prediction of unsaturated hydraulic conductivity of a sandy loam soil. Figure 3 shows the graphical relationship between measured and predicted values, as well as the satisfactory and acceptable agreement with the coefficient of determination $R^2 = 0.9083$.

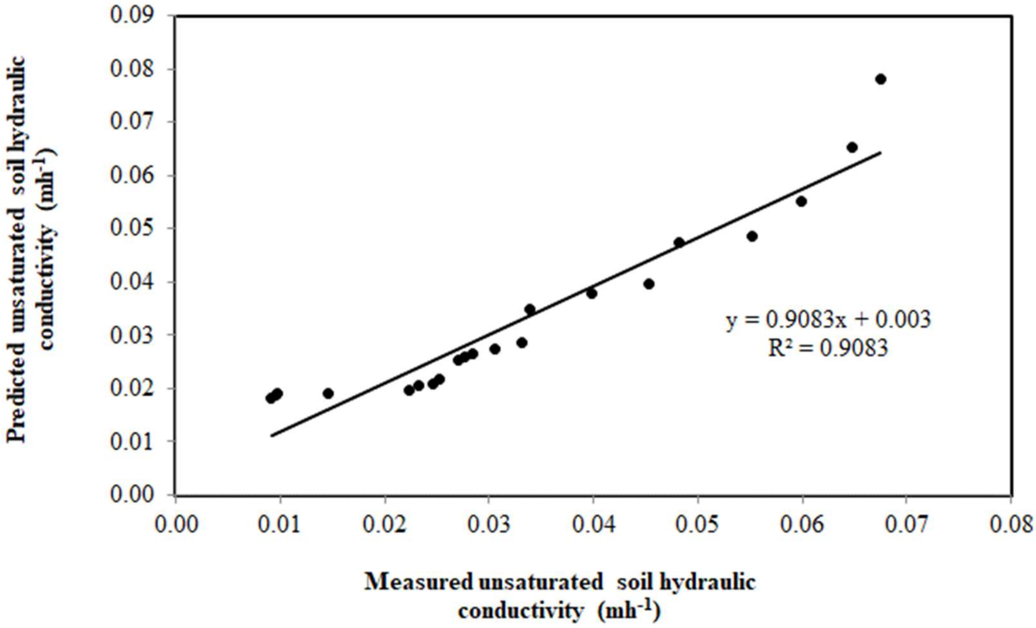

FIGURE 3. Relationship between measured and predicted unsaturated hydraulic conductivity.

TABLE 4. Results of the suitability analysis of the developed unsaturated hydraulic conductivity model.

Data points	Discrepancy ratio	Relative errors (%)
1	1.99	98.51
2	1.97	96.86
3	1.96	95.77
4	1.32	32.33
5	0.88	-11.66
6	0.89	-11.36
7	0.85	-15.02
8	0.86	-14.13
9	0.83	-16.62
10	0.95	-4.77
11	0.96	-4.12
12	0.96	-3.52
13	0.87	-13.30
14	1.03	2.78
15	0.95	-4.88
16	0.87	-12.77
17	0.98	-1.52
18	0.88	-11.87
19	0.92	-8.19
20	1.01	0.83
21	1.16	15.84
Mean	1.10	9.96

CONCLUSIONS

This study has established an appropriate model to estimate the field unsaturated hydraulic conductivity (KU) of a sandy loam soil. The predictive model equation established is $KU = 0.1375 \times Z + 0.0142$. The equation's coefficient of determination was obtained, (R^2) = 0.9083. The results presented satisfactory agreement between the predicted model equation results and measured data. This proved that the dimension analysis model equation can precisely predict field unsaturated hydraulic conductivity of a sandy loam soil. Furthermore, choosing the soil moisture content and the correct water quality, under a specific suction rate, will provide a respectable estimation, saving both cost and time. Also, the established equation can be used to direct decision making related to irrigation research and water management.

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