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Soil hydraulic parameters optimization through inverse modelling using Hydrus-1D to determine unsaturated hydraulic conductivity

Devappa, Ravikumar V, Akshaya KA and Kathirvel L

Abstract

Movement of water in soil is the important processes that influence the quality of soil and water in the environment. Soil water movement occurs under saturated as well as unsaturated conditions. At the start of the experiment, infiltration rate was higher as the free-soil pores allows more water into it. As time passes, the infiltration rate decreased as the soil pores get partially filled with water. The cumulative infiltration flux across a boundary at different time was used as the input variable to optimise the soil hydraulic parameters. The inverse method generally uses a weighted least-squares approach in which numerically simulated data are fitted to the measured data. After 37 min. of the experiment, the observed cumulative infiltration was 7.4 cm and data simulated by Hydrus-1D at 37 min was 7.53 cm which was almost similar to the observed data. Similarly, at 372 min, the observed and fitted data were 57.5 and 58.33 cm respectively and with this, optimized parameter values were confirmed. Hydrus-1D allows the optimization of parameters using Marquardt Levenberg optimization algorithm. The optimised parameter values were fitted in the van Genuchten model for obtaining the unsaturated hydraulic conductivity of the proposed soil.

Keywords: Infiltration, inverse modelling, hydrus-1D, parameter optimization, hydraulic conductivity

Introduction

Due to rising demand brought on by population expansion and intensified agriculture, water resources are under threat. The issue will worsen due to climate change and the desertification that follows, increasing the areas that experience extreme drought (Provenzano *et al*., 2014) [32]. About 70% of freshwater withdrawals worldwide are used for agriculture, with the remaining 80% going toward industry and 10% going toward home use. (Domínguez-Niño *et al*., 2020) [11]. In recent decades, the use of wastewater for irrigation has emerged as an alternative technique due to water scarcity and the consequences of climate change (Hamilton *et al*., 2007) [16]. Nonetheless, research is ongoing to determine whether long-term wastewater application may have detrimental impacts on soil and plants (Assouline and Narkis, 2013) [3]. Thus, the need for more efficient and optimized use of water in irrigation is still critical (Morianou *et al*., 2021) [28]. Quantifying soil moisture content under a micro irrigation system is a challenging task due to variations in soil hydraulic properties, emitter discharge rates, irrigation volume and frequency and water uptake by roots. One of the key mechanisms influencing the quality of soil and water in the environment is the movement of water in the soil. Both saturated and unsaturated conditions lead to soil water flow. The unsaturated zone is crucial to the hydrologic process because it affects soil growth, nutrient cycling, ecosystem health and function, flooding and landslides, and the relationship between atmospheric and terrestrial processes. Thus, knowledge of the hydraulic characteristics of unsaturated soils is necessary for any studies involving water flow and solute transport in the vadose zone (Bitterlich *et al*., 2004) [6]. Simunek *et al*. (1999) [38] used the Hydrus-1D and Hydrus-2D algorithms to predict the hydraulic and solute transport characteristics of unsaturated soil. They used a parameter estimation procedure that combines the Levenberg-Marquardt nonlinear parameter optimization method involving weighted least squares with either a one-dimensional numerical model (Hydrus-1D) or a two- or quasi three-dimensional model (Hydrus-2D) in order to solve the governing equations for water flow and solute transport in variably-saturated porous media.

The process by which water enters the soil via the earth's surface is known as infiltration. Gravity and the forces of the soil particles on the water both contribute to the passage of water into the soil. The maximum rate of water entry into the soil under certain conditions, such as the presence of excess water, is determined by the infiltration rate of the soil. One of the main factors impacting decisions about irrigation, drainage, water harvesting, and ground water recharge is the infiltration characteristics of the soil. The process of infiltration is non-linear and time-dependent. The infiltration intensity of unsaturated soil is greatest at the start because the gradient of water at the soil surface is greatest. The rate of reduction is quick at first, but eventually approaches a constant value. The basic infiltration rate or steady state infiltration rate is the virtually constant rate that develops at the conclusion. Water flow into the soil is aided by adsorption and capillary forces. Many physical factors of soil influence infiltration rate, including moisture content, degree of compaction, structure, texture, porosity, and so on. All of these characteristics vary from location to location, resulting in variation in infiltration rate. Infiltration is affected by water availability at the soil surface as well as soil properties that influence water retention capacity and hydraulic conductivity.

Hydraulic conductivity is a physical property that assesses a material's capacity to transport fluid via pores and cracks in the presence of a hydraulic gradient. Soil water movement occurs under saturated as well as unsaturated conditions. Under saturated conditions the water flow is in horizontal direction which occurs below the water table, but in the case of unsaturated conditions water flow is in vertical direction which occurs above the water table. In agricultural and environmental studies, unsaturated soil hydraulic conductivity is a crucial metric for water management and prediction. Water flow is determined by unsaturated soil hydraulic conductivity (Escoba, 2014) [13], which can be difficult to measure and necessitates expensive, labour-intensive, and specialized experiments (Wosten and Van Genuchten, 1988; Malaya and Sreedeep, 2013) [44, 26]. Numerous methods have been devised to quantify unsaturated hydraulic conductivity both in the field and in the laboratory. Furthermore, field studies and measurements to detect water velocity and chemical concentration take a long time and are costly (Phogat *et al*., 2012) [30]. As a result, mathematical or conceptual models for estimating water and solute transport in the vadose zone have been created (Arbat *et al*., 2013, Communar *et al*., 2010, van Dam *et al*., 2008) [2, 7, 40]. Although the modeling approach is thought to be a helpful alternative to field measurements, it is fraught with uncertainties. To overcome these disadvantages several models are introduced. Through numerical inversion, Simunek and van Genuchten (1996) [36] determined the hydraulic characteristics of unsaturated soil from tension disc infiltrometer data. Kodesova *et al*. (2004) [23] used inverse modeling and a modified cone penetrometer to determine the hydraulic characteristics of unsaturated soil. Simunek *et al*. (1999) [38] estimated the hydraulic and solute transport parameters of unsaturated soil using the Hydrus-1D and Hydrus-2D algorithms.

As a result, utilizing the best-fit model can provide more trustworthy results for policymakers interested in sustainable agriculture. HYDRUS 1D/2D/3D is the most comprehensive, dependable, and frequently used software program for simulating water movement in one-, two-, and three-dimensional variably saturated porous surfaces. When compared to other similar models, one significant advantage of HYDRUS 1D/2D/3D is that there are no restrictions on spatial or temporal scale (Šim˚unek *et al*., 2016) [37]. Over the years, the model has been employed for a variety of applications, most notably agricultural applications. Compared to other unsaturated zone models, HYDRUS provides users with more options for evaluating different irrigation schedules (Cote *et al*., 2003, Kandelous *et al*., 2010, Autovino *et al*., 2018) [8, 20, 4], studies on root water uptake (Vrugt *et al*., 2001, Saitta *et al*., 2021, De silva *et al*., 2008, Han *et al*., 2015) [42, 35, 9, 17] and leaching of nutrients and contaminants (Gärdenäs *et al*., 2005, Li *et al*., 2004, Li *et al*., 2005, Hanson *et al*., 2006, Ajdary *et al*., 2007, Wehrhan *et al*., 2007, Engelhardt *et al*., 2015) [15, 24, 25, 18, 1, 43, 12]. It has also been used extensively to evaluate the effects of different irrigation and fertigation strategies/treatments (Gärdenäs *et al*., 2005, Karandish and Šim ˚unek, 2019, Karandish and Šim ˚unek, 2017, García Morillo *et al*., 2017) [15, 22, 23, 14]. Version 4.17 of the Hydrus-1D software suite simulates the transport of water in one-dimensional variably saturated media.The Richards equation for variable saturated water flow are numerically solved by the HYDRUS program. Water and solute flow in unsaturated, partially saturated, or fully saturated porous media can be examined with this application. It's possible that the flow region is made up of uneven soils. Transport and flow can happen in a horizontal direction, vertically, or generally inclined. The model's water flow section can handle free drainage border circumstances, boundaries governed by atmospheric conditions, and predefined head and flux boundaries. For the purpose of estimating soil hydraulic and/or solute transport and reaction parameters inversely from recorded transient or steady-state flow and/or transport data, HYDRUS additionally incorporates a Marquardt-Levenberg type parameter optimization technique. The present study aims to optimize the hydraulic parameters, to determine the infiltration characteristics, unsaturated hydraulic conductivity of experimental site with the help of Hydrus 1D software package.

Materials and Methods

Study Area Description

Various methods and techniques used in the data generation and analysis are described in this chapter. The field experiment was conducted at AEC and RI, TNAU campus, District of Tamil Nadu state in India and is situated at 11^{0} 12' 39" North latitude and 76^{0} 55' 20'' East longitude.

Infiltrometer test

At the location selected, infiltration data was measured using a double ring infiltrometer. The double ring infiltrometer features two concentric rings with a depth of 30 cm apiece with an outer ring diameter of 30 cm and an inner ring diameter of 20 cm. Using a hammer to consistently hit a wooden plank on top of each ring, the rings were driven approximately 10 cm into the earth, avoiding unnecessary disruption of the soil's surface. The rings were filled with water to the same depth, and the initial water level reading was taken. To avoid the initial water loss error, experiment was started by keeping a small patch of polythene sheet within the inner ring and sheet was removed once after filling the buffer ring. At regular intervals, the depth of the water in the infiltrometer was measured, and the water was refilled to the initial depth each time. The infiltration data at different time periods were noted and the cumulative infiltration was calculated. Total 372 minutes were spent to note all the readings.

Bulk density and Moisture content

Using the core cutter method, the bulk density of the surface soil samples was determined. The core cutter with a height (H) of 13 cm and diameter (d) of 10 cm was used for the purpose. A dolly of 25 mm high and 100 mm internal diameter placed on top of the core cutter. A small area of 30 cm^2 to be tested was cleared and levelled. The core cutter-dolly assembly drove into the soil with the help of hammer until the top of the dolly protrudes about 15 mm above the surface. Then the core cutter with soil was taken out by removing surrounding soil. The dolly was removed and top end of the cutter trimmed flat using straight edge shovel. The weight of the core cutter along with the soil sample was taken as W_1. The sample was dry in hot air oven at 105 °C for 24 hours. After drying, the dry weight of soil was taken as W_2. A soil pit of dimensions 60 cm width, 60 cm length and 50 cm deep was created and bulk density (BD) at depth 50 cm was determined. The BD of the soil was calculated as follows:

$$\text{Volume of core cutter (V)} = \pi \times \frac{D2}{4} \times H \qquad (1)$$

Where,
D is the diameter of the cylinder, cm
H is the height of the cylinder, cm.

$$\text{Dry Bulk density} = \frac{W2}{V} \qquad (2)$$

Where,
W_2 is the dry weight of soil
V is the volume of the core cutter, cm3

The dry bulk density of surface soil was calculated as 1.552 g cm^{-3} and that for 50 cm deep was 1.488 g cm^{-3}. Gravimetric method of estimating soil moisture content at surface and at 50 cm soil depth is given by

$$\text{Soil moisture } (\theta_g) = \frac{W1 - W2}{W2} \qquad (3)$$

Where,
W_1 = Fresh soil weight (g)
W_2 = Dry soil weight (g)

Parameter estimation by inverse modelling

For this work, a Hydrus-1D numerical model based on Richards' equation was employed. The components of Hydrus-1D are the Hydrus computer software and the interactive, graphics-based Hydrus1D user interface, which are connected via FORTRAN code. Hydrus optimizes the objective function by using the numerical solution of Richard's equation using finite elements. Inverse modelling is a numerical modelling approach, which determines causes of a problem based on observation of their effects. It is an alternative to direct measurement and can be used for indirectly estimating soil hydraulic parameters. By modifying in-situ measurements of hydraulic characteristics, the inverse technique may prove to be particularly appropriate for predicting effective soil hydraulic parameters. The data input to the model for inverse modelling were soil physical properties, initial estimates of soil hydraulic parameters, cumulative infiltration data and initial conditions in terms of pressure head or water content.

The option to choose a suitable model for the simulation of the accessible data is included in Hydrus-1D. The van Genuchten model was selected for this investigation in order to simulate the intermittent water flow in the soil. The model optimises six soil hydraulic parameters *viz*. (θr) residual water content, (θs) Saturated water content, (α) Inverse of air entry value, (l) Pore connectivity parameter, (n) Water retention parameter and (Ks) saturated hydraulic conductivity, which are necessary to calculate the unsaturated hydraulic conductivity. The initial estimates for the parameters were estimated from Rosetta Lite v.1.1 module incorporated with Hydrus-1D. The expressions for hydraulic functions (Equation 6 to 9) by Van Genuchten (1980) [41] was used to calculate the initial pressure head at the top (i.e., soil surface) and the bottom (50 cm below the soil surface) of the soil profile were determined.

The Hydrus-1D run window shows the optimized parameters for each iteration. Since, no further reduction in the Sum of Squares (SSQ) was obtained, the optimization of the objective function had stopped with 6 iterations for loamy sand soil. The simulated cumulative infiltration, optimized final estimates of soil hydraulic parameters and soil characteristics curve (relating moisture content, head, time, Ks and depth of soil profile) were the expected output from the model. The cumulative infiltration flux across a boundry at different times was used as an input variable in inverse modeling to optimize soil hydraulic parameters. Unsaturated hydraulic conductivity cannot be directly given by the model. The inverse method consists of three interconnected functional parts, including a controlled transient flow experiment in which boundary and initial conditions are prescribed and flow variables such as cumulative infiltration and/or drainage cumulative and/or matric head and/or water content are measured and other two parts are as follows.

Numerical flow model

The transient flow through unsaturated zone was simulated using the numerical model proposed by Richard (1931) [34]:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial \left(K(h)\frac{\partial h}{\partial z}\right)}{\partial z} + \frac{\partial K(h)}{\partial z} - S(h) \qquad (4)$$

Where,
θ: Soil moisture content (cm^{-3} cm^{-3})
K (h): Unsaturated hydraulic conductivity function
S (h) is the sink term,
h: Pressure head
t: time. This partial differential equation is the equation governing variably saturated flow in unsaturated zone. Eq. (4) is the mixed form of the Richard's equation having two dependent variables: θ and h.

Optimization algorithm

Hydrus-1D numerical model which uses the one-dimensional Richard's transient flow equation has an inverse modelling capability. Deviations between observed and predicted variables, such as pressure heads or water contents at various depths and times, are included in the minimized objective function. A penalty function for discrepancies between the final estimations and past knowledge of the soil hydraulic parameters may be included in this function. Hydrus-1D uses a Marquardt-Levenberg nonlinear minimization (Marquardt 1963) [27] for the minimization of the objective function. The soil hydraulic function parameters are updated iteratively in the optimization routine, thereby continuously reducing the residuals until a predetermined convergence criterion has been achieved. In order to calculate the desired hydraulic parameters, the disparities between the simulated and observed state variables are minimized. An objective function (Φ) that can be defined as follows expresses the sum of these differences:

$$Ø(\beta, y) = \sum_{j=1}^{j=m_y} v_j \sum_{i=1}^{i=n_j} W_{ij}[y_{j^*}(z,t_i) - y_j(z,t_i,\beta)]^2 \quad (5)$$

Where, the right-hand side reflects the residuals between the measured (y_{j^*}) and matching model-predicted (y_j) space-time variables using the soil hydraulic parameters of the optimized parameter vector, β. The first summation sign sums the residual for all measurement types m_y, whereas the variable in the second summation denotes the number of measurements for a certain measurement type j. Usually in water flow studies, y_{j^*} may represent water flux density, cumulative water flow, soil water matric head, or soil water content values. Weighting factor values for v_j can be chosen such that data types are weighted equally using a normalization process or such that they are equal to the reciprocal of the variance of measurement type j; additional weighting W_{ij} can be provided to individual data (Hollenbeck *et al*., 2000) [19]. In addition to the transient measurements, the objective function can also include independently measured soil water retention or unsaturated hydraulic conductivity data points. Levenberg–Marquardt method is the most widely used minimize the objective function. This method is based on Marquardt's maximum neighbourhood method and employs a weighted least-squares approach.

Soil Hydraulic Properties function

Before using the numerical solution of Richard's equation, a model of the hydraulic properties of unsaturated soil must be chosen. Van Genuchten's unsaturated soil hydraulic functions (1980) [41] were employed in this investigation.

The van Genuchten-Mualem model is a set of equations that is frequently used to describe the unsaturated retention and hydraulic conductivity functions. The following are the equations:

$$K(h) = K_s S_e^l \left(1 - \left(1 - S_e^{1/m}\right)^m\right)^2 \quad (6)$$

$$h = -\frac{1}{\alpha}\left[\left(\frac{\theta_s - \theta_r}{\theta - \theta_r}\right)^{\frac{1}{m}} - 1\right]^{\frac{1}{n}} \text{ for } \theta < \theta_s \quad (7)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \text{ or } S_e = \frac{1}{\left(1 + (-\alpha h)^n\right)^m} \quad (8)$$

$$m = 1 - \frac{1}{n};\ n > 1 \quad (9)$$

Where,
θ: Volumetric water content ($cm^{-3}cm^{-3}$),
θ_s and θ_r: Saturated and residual water contents ($cm^{-3}cm^{-3}$)
h: Pressure head (cm),
Se: Effective saturation
K_s: Saturated hydraulic conductivity ($cm\ d^{-1}$)
α: Inverse of air-entry value or (bubbling pressure (1/cm)
n: Pore size distribution index
l: Pore connectivity parameter. 'l' is conventionally taken as 0.5. The density of the water is 1 g cm^{-3} and the dry density of soil was determined using core cutter method.
The volumetric moisture content of the soil,

$$\theta_h = \theta_g \times \text{Specific gravity} \quad (10)$$

$$\text{Specific gravity} = \frac{\text{Dry density of soil}}{\text{Density of water}} \quad (11)$$

θ_g: Gravimetric water content ($cm^{-3}\ cm^{-3}$)

Soil texture identification

Texture is relative proportion of various sizes of soil particles. Figure 1 is intended to provide a comprehensive guide to texturing soil using the feel method. A soil sample and water are the only materials required. The soil at experimental site is classified as loamy sand.

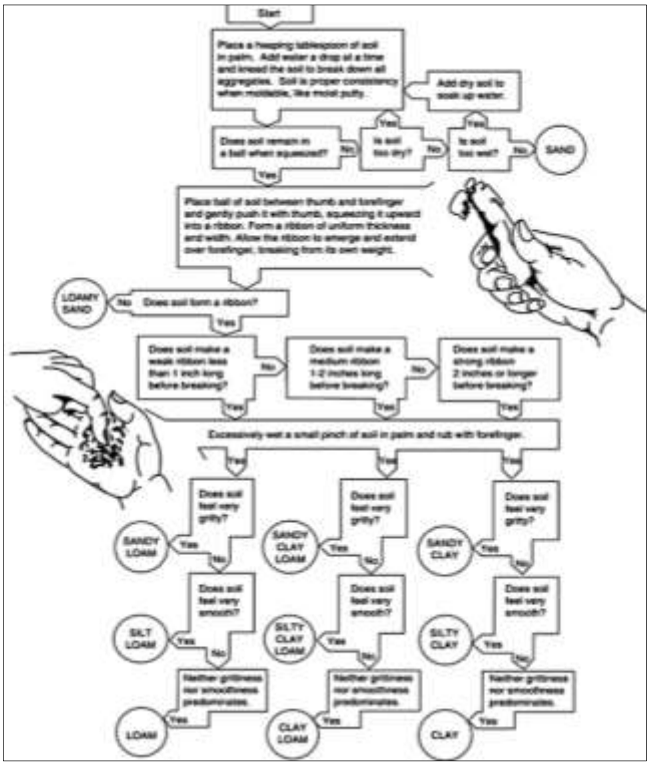

Fig 1: Soil textural classification by feel method (Thien, 1979) [39]

Results and Discussions

These days, inverse approaches are being employed more and more to evaluate the hydraulic characteristics of unsaturated soils. In this work, six soil hydraulic parameters were numerically inverted using the Hydrus-1D numerical code, which employs the one-dimensional Richard's equation.

1. Infiltration characteristics by field experiments

The infiltration rate curve represents the infiltration characteristics of the loamy sand soil with time. At the start of the experiment, infiltration rate was higher as the free-soil pores allows more water into it. As time passes, the infiltration rate decreased as the soil pores get partially filled with water. The infiltration rate becomes constant after some time, which can be taken as the saturated hydraulic conductivity of the soil. The cumulative infiltration was calculated for the different time periods by adding up the successive infiltration depths. The cumulative infiltration (cm) versus time (min) graph was plotted for loamy sand. The cumulative infiltration curve always shows an increasing trend with increase in time. The cumulative infiltration curve is steeper, which might be due to higher percentage of macro pores within the soil caused maximum infiltration rate instead holding the water.

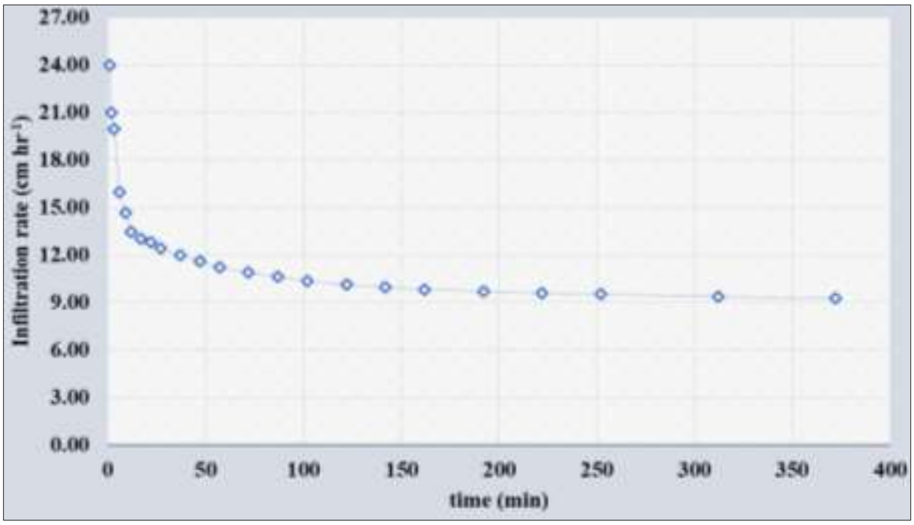

Fig 2: Infiltration rate characteristics at the experimental site

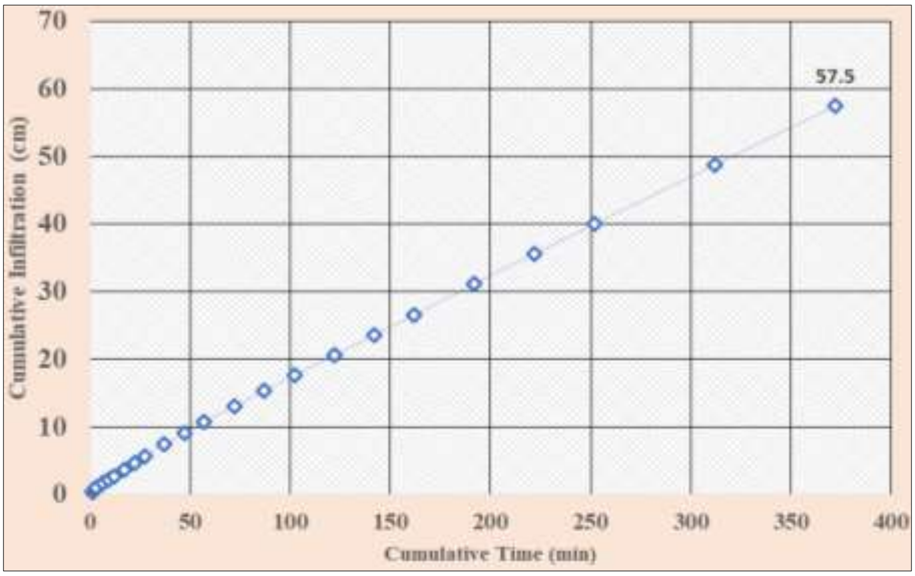

Fig 3: Cumulative infiltration vs. Time curve for experimental loamy sand data

2. Hydrus 1D optimized parameters: Hydrus-1D software was used for inversion of six soil hydraulic parameters including θs, θr, Ks, n, α and l which is further optimized using Marquardt-Levenberg optimization algorithm. Cumulative infiltration data for 26-time intervals is taken as the number of input data points, with a single material having 50 cm depth is considered as the domain of study.

The initial estimates of these parameters were found out by the Rosetta lite v 1.1 module in Hydrus-1D and shown in Table 1. The Hydrus-1D numerical code optimized the initial estimated parameters in consecutive iterations to get an optimum parameter set and solution got converged in 6 consecutive iterations. Until a sufficient degree of convergence is reached, that is, until the absolute change in pressure head (water content) between two consecutive iterations at every node in the saturated (unsaturated) region is less than a small value specified by the imposed absolute pressure head tolerance (1 cm), the iterative process is repeated. The maximum intended absolute change in the pressure head value between two consecutive iterations within a specific time step is represented by the pressure head tolerance. Since no further reduction in sum of squares (SSQ) was possible, the iterations were stopped and after running the Hydrus-1D, the optimized parameters obtained were shown in Table 2 and profile information were shown in Fig.3. The profile information module divides the soil profile into discrete parts. The user can then change the number and position of the nodes to optimize finite element lengths.

Table 1: Initial Parameter Estimates as per Rosetta Lite for loamy sand

Parameters	Initial estimates	Optimized Parameter
Residual water content, θr (cm^3 cm^{-3})	0.0485	0.0570
Saturated water content, θs (cm^3 cm^{-3})	0.3904	0.2951
Inverse air entry value, α (cm^{-1})	0.0347	0.0958
Soil water retention function, n (-)	1.7466	1.249
Saturated hydraulic conductivity, Ks (cm min^{-1})	0.073	0.1516
Pore connectivity parameter, l (-)	0.50	0.50

The optimised parameters were fitted to the empirical models proposed by van Genuchten (1980) [41] for finding the unsaturated hydraulic conductivity (K) of the proposed loamy sand. The comparison of observed and simulated data is generally termed as Residual Analysis. The curve plotted shows a best fit between the observed and simulated cumulative infiltration (Fig.4). For example, after 37 min of the experiment, the observed cumulative infiltration was 7.4 cm and data simulated by Hydrus-1D at 37 min was 7.53 cm which was almost similar to the observed data. Similarly, at 372 min, the observed and fitted data were 57.5 and 58.33 cm respectively and with this, optimized parameter values were confirmed. Hydrus-1D allows the optimization of parameters using Marquardt Levenberg optimization algorithm. The optimised parameters were fitted to the empirical models proposed by van Genuchten (1980) [41] for finding the unsaturated hydraulic conductivity (K) and the water retention properties of the proposed loamy sand soil. Table 2 displays the field observed data and matching simulation data for various time increments. When the objective function was described in terms of cumulative infiltration depths data, Fig. 4 displays the measured and computed cumulative infiltration curves. Results indicate excellent agreement between the measured and optimized infiltration curves. Since no further reduction in SSQ was possible, the iterations were stopped at 6 iterations and final outputs were obtained. There is a good correspondence between the initial and optimised parameter estimates of θr, θs, α, n and Ks. The close correspondence of the initial and final estimates of Ks lends further credibility to the accuracy of double ring infiltrometer data, for the loamy sand soil used in this study.

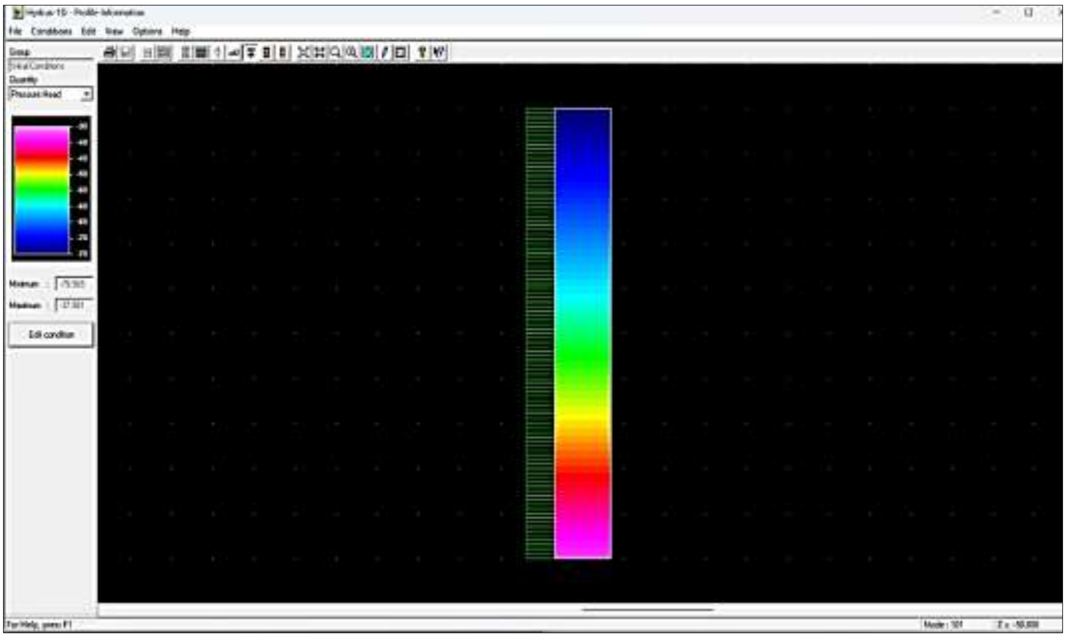

Fig 3: Soil profile information with initial pressure head conditions

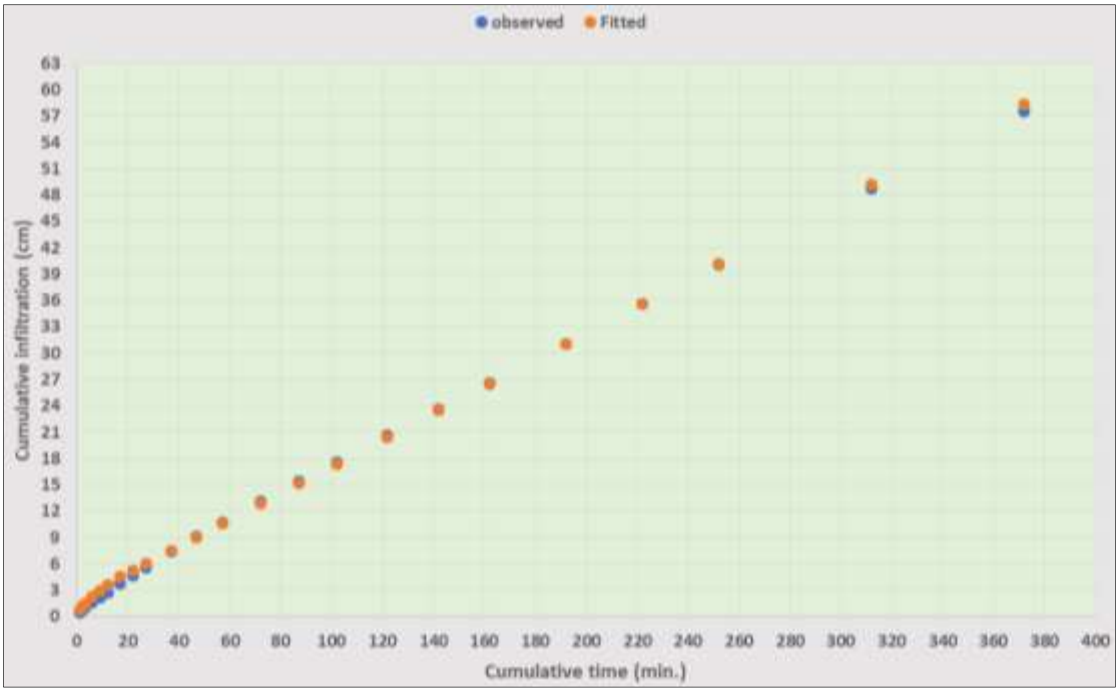

Fig 4: Goodness of parameter estimation

Table 2: Measured cumulative infiltration from field and fitted data using Hydrus-1D

Sl. No.	Time (min)	Observed cumulative Infiltration (cm)	Simulated infiltration (cm)	Residual
1.	1	-0.4	-0.77996	0.37996
2.	2	-0.7	-1.1603	0.46030
3.	3	-1	-1.47712	0.47712
4.	6	-1.6	-2.2694	0.66940
5.	9	-2.2	-2.95786	0.75786
6.	12	-2.7	-3.59506	0.89506
7.	17	-3.7	-4.50733	0.80733
8.	22	-4.7	-5.26543	0.56543
9.	27	-5.6	-6.02353	0.42353
10.	37	-7.4	-7.53973	0.13973
11.	47	-9.1	-9.05596	-0.04404
12.	57	-10.7	-10.57221	-0.12779
13.	72	-13.1	-12.84658	-0.25342
14.	87	-15.4	-15.12095	-0.27905
15.	102	-17.6	-17.39524	-0.20476
16.	122	-20.6	-20.42755	-0.17245
17.	142	-23.6	-23.45986	-0.14014
18.	162	-26.6	-26.49217	-0.10783
19.	192	-31.1	-31.04062	-0.05938
20.	222	-35.6	-35.58953	-0.01047
21.	252	-40.1	-40.13855	0.03856
22.	312	-48.8	-49.2366	0.43660
23.	372	-57.5	-58.33465	0.83465

*Hydrus considers the infiltration data as negative flux

4. Correlation matrix between the optimized parameters

The results reveal that all the parameters exhibit a slightly noticeable change from the initial estimates when the pore connectivity parameter was fixed as 0.5. Hydrus generates a correlation matrix as part of the inverse solution, which details the degree of correlation between the fitted coefficients. The correlation matrix measures how minimal variations in the final estimate of specific parameters affect the model's predictions. The non-orthogonality between two parameter values is shown in the correlation matrix. A perfect linear correlation is indicated by a value of ±1, whereas no correlation is shown by a value of 0. Because of the high correlation, the correlation matrix can be utilized to determine which parameters, if any, should be kept constant in the parameter estimation process (Radcliff and Simunek, 2010) [33]. High correlation causes underestimation of parameter uncertainty, slows down convergence rate, and increases non-uniqueness. The correlation table shows a large correlation (0.6426) between α and θr for the infiltration experiment, a result that is common when fitting retention data to the van Genuchten relationship. A highest negative correlation is observed between (α) and (l) followed by θs and n. Among all optimized parameters, n has strong correlation with K_s as compared to others.

Table 3: Correlation table for optimized parameters

Parameters	θr	θs	α	n	Ks	l
θr	1					
θs	-0.5451	1				
α	0.6426	-0.4589	1			
n	0.3691	-0.8898	0.0153	1		
Ks	-0.0470	-0.0747	-0.0042	0.0699	1	
l	-0.6461	0.0976	-0.8998	0.3133	0.0383	1

The term "soil water retention curve" or "soil moisture characteristic curve" refers to the relationship between a soil's volumetric water content and pressure head. The variations in the distribution of pore sizes among soils are the main cause of the variations in soil water retention curves. The curve is sensitive to changes in bulk densities and the disturbance of soil structure. More water is drawn out of the soil when the pressure is increased, and more of the relatively big pores, which cannot retain water under the pressure, will empty out. Pressure increases gradually, causing progressively smaller holes to empty.

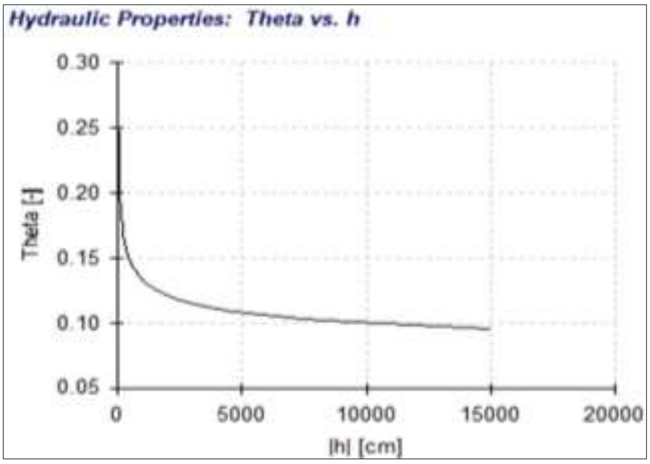

Fig 5: Soil Water Retention Curve

3. Unsaturated hydraulic conductivity

The regression curve (water retention curve) illustrated in fig 5 is obtained by fitting the simulated data of volumetric soil water content (h) and pressure head (h) to the model proposed by van Genuchten (1980) [41]. Continuous fluid routes may not exist at very low water concentrations, and water may travel in the vapour phase. The unsaturated hydraulic conductivity is thus expressed as a function of negative pressure head (K(h)) or water content (K). Substitution of parameters, n and m (1–1/n) into the equation for unsaturated hydraulic conductivity function and plotting the unsaturated hydraulic conductivity versus pressure head gives the Fig. 6, which is the graphical representation of Mualem's model (1976) [29]. Larger pores drain faster than smaller ones in the unsaturated zone. As a result of water passing through smaller holes or as films over the walls of bigger pores, hydraulic conductivity is substantially lower in unsaturated conditions than in saturated situations. Unsaturated hydraulic conductivity (K) and volumetric water content (θh) are shown in the graph as having a direct relationship. Through inverse modelling with Hydrus-1D, the average saturated hydraulic conductivity for the loamy sand soil under study was determined to be 0.1516 cm min^{-1} (218.304 cm d^{-1}). It was discovered that the unsaturated hydraulic conductivity is substantially lower than the saturated hydraulic conductivity, falling between near zero to 0.23 cm d^{-1}. An increase in unsaturated hydraulic conductivity is observed when the negative pressure head decreases. A rapid increase in the K value is observed when the negative pressure head decreases beyond 50 cm.

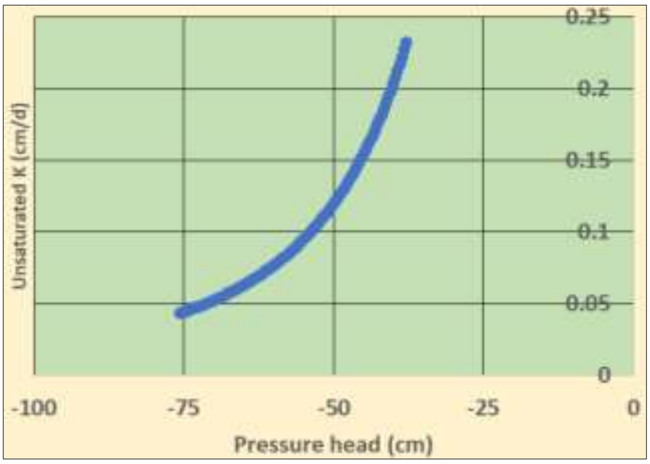

Fig 6: Unsaturated K vs. pressure head curve

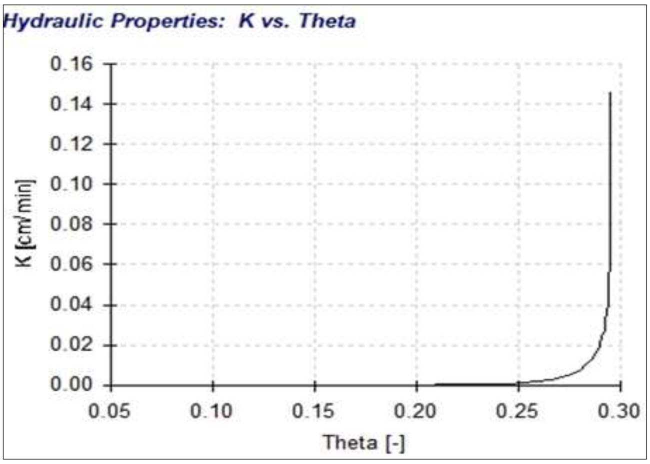

Fig 7: Unsaturated K vs Volumetric Water Content

The relationship between the volumetric soil water content and the unsaturated hydraulic conductivity was well shown in Fig. 7. The volumetric water content and the unsaturated hydraulic conductivity show a direct relationship with each other.

Conclusion

The movement of water in the unsaturated zone is an important process to be considered. In this study, the Hydrus numerical model was effectively utilised for the optimisation of six soil hydraulic parameters including θ_r, θ_s, α, n, K_s and l using inverse modelling. There was a good correspondence between the initial and final parameter estimates. The observed and simulated cumulative infiltration data also revealed a best fit. The optimised parameter values were substituted in the van Genuchten model and found the unsaturated hydraulic conductivity and water retention properties of the loamy sandy soil under study. This study's inverse problem method enabled the determination of soil hydraulic characteristics in loamy sand. The results of this investigation's soil hydraulic characteristics can be used to forecast water dynamics via a vertical soil profile under the effects of irrigation, drainage, and evapotranspiration, which is critical for soil management.

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