ISSN 1023-1072

Pak. J. Agri., Agril. Engg., Vet. Sci., 2014, 30 (2): 205-215

ESTIMATING HYDRAULIC PROPERTIES OF SOME SOIL SERIES OF SINDH

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ABSTRACT

Quantitative description of soil hydraulic properties is necessary for determining the soil water holding capacity, infiltration, percolation, and runoff rates and for modelling water and solute transport in the vadoze zone. Recognizing the key role of soil hydraulic properties in the management of irrigation scheduling, salinity and agricultural drainage, a study was conducted to determine hydraulic properties of the five soil series, commonly found in Sindh, through laboratory method and numerical modeling. Six free drainage experiments were carried out in the laboratory using Jhakkar, Matli, Miani, Sarhad and Sultanpur soil series to estimate their hydraulic properties. Oven dried soil samples of each soil series were filled in 15 plastic pipes of diameter 15 cm and length 30 cm with holes at the bottom for free drainage. Natural soil density and porosity was maintained in pipes by compaction. Tensiometers were installed in the center of each pipe and then pipes were filled with water up to saturation level. Loss in weight of soil filled pipe was measured by weighing and the corresponding tensiometeric reading was recorded. Soil water retention curves were thus drawn from the recorded data. HYDRUS-1D model was used to optimize the van Genuchten-Mualem (VGM) parameters from the physical properties of the considered soil series. To assess the reliability of the model, measured water retention curves were fitted with the predicted curves with HYDRUS-1D model. The measured and predicted soil retention had a strong relationship with the coefficient of determination (R^2) ranging from 0.90 to 0.98. Based on the study, it is concluded that HYDRUS-1D model is a robust tool for determining the hydraulic properties of soil series commonly found in Sindh rather than determining through field methods which are laborious, expensive and time consuming.

Keywords: HYDRUS-1D, soil series, soil water retention curve, VGM parameters.

INTRODUCTION

Mismanagement of fresh water resources in Pakistan has resulted in a twin menace of water shortage and soil salinization and waterlogging. The disastrous

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buildup of salts in soil and increasing waterlogging has compelled to install costly drainage systems and to use large proportion of limited water supply for leaching salts down the profile. Proper and efficient utilization of water resources for optimum crop production requires knowledge of water movement and solute transport into and through the soil. The ability of the soil to retain and conduct water in the vadose zone is a function of its hydraulic properties. The most important soil hydraulic properties are saturated and unsaturated hydraulic conductivity functions and the moisture retention characteristics (Ahuja *et al*., 1980). These soil properties mainly depend on soil structure, soil texture, organic matter content, cation exchange property and bulk density (Hillel, 1998). Quantitative knowledge of the soil hydraulic properties play an important role in assessment of the suitability of land for irrigation of a particular crop and traffic-ability (Schaap, 2005). It is reported (Dane and Topp, 2002) that for modern agricultural, environmental and engineering practices different quantitative aspects about soil hydraulic properties are required for determining the soil water holding capacity, infiltration, deep percolation, and runoff rates, or for quantifying the transport of water and pollutants in soil.

Due to importance of soil hydraulic properties in many fields such as environmental engineering, soil physics (Hopmans *et al*., 2002), agricultural and environmental issues (Vachaud and Dane, 2002), many methods have been developed for easy and cost effective determination of soil hydraulic properties. These soil properties are difficult to measure, therefore direct and indirect methods are employed to describe them adequately and accurately. *In-situ* measurements are more representative of actual field conditions but they are costly, difficult, laborious and time consuming. Whereas, laboratory methods, modeling and simulations are considered to be more convenient with many advantages compared to *in-situ* techniques.

Numerical modeling is widely used to manage soil water content, predict the behavior of soil contaminants and to simulate transport process in vadose zone. These models usually require soil water content (θ), pressure head (*h*) and hydraulic conductivity (*K*) as input parameters. The quality of these input relationships often substantially affect the quality of the simulation results (Leij and van Genuchten, 1999). The HYDRUS-1D is a computer software (Simunek *et al*., 2009) which is widely used to analyze water, solute and heat movement in unsaturated, partially saturated, or fully saturated homogeneous layered porous media.

Soil salinization and water shortage have seriously affected the crop productivity irrigated agriculture in Pakistan, especially in Sindh. It has been estimated that about 0.2 to 0.4% of the arable land is abandoned each year due to salinity and waterlogging (Khan, 1998). As discussed earlier that soil hydraulic properties have a key role in the management of soil water and solute in the vadoze zone, therefore for efficient and effective management of water, waterlogging and salinity in the province of Sindh there is a dire need to determine hydraulic properties of soils commonly found in Sindh. The present study was thus conducted to determine the hydraulic properties of key soil series commonly found in Hyderabad district using a laboratory method and a numerical model i.e. HYDRUS-1D and evaluate the reliability of the model for determining soil hydraulic properties.

MATERIALS AND METHODS

The experiment

Soil samples of soil series normally found in Sindh i.e. Jhakar, Sultanpur (medium textured); Matli, Miani (moderately fine textured) and Sarhad (medium coarse textured) were collected from different locations of the district Hyderabad as shown in Fig. 1.

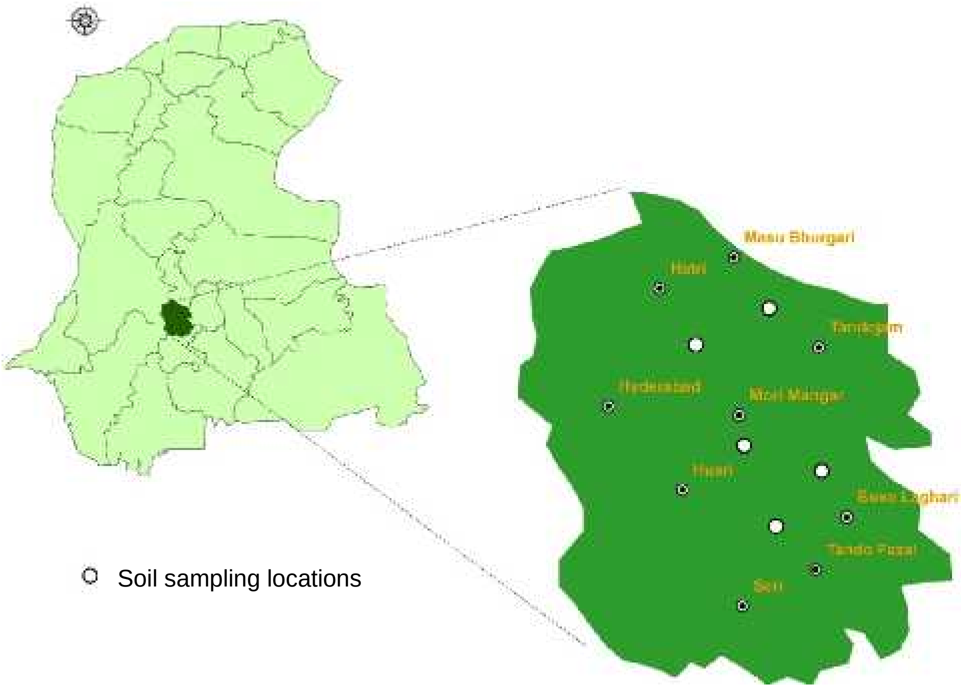

Figure 1. Soil sampling locations in district Hyderabad.

For each soil series, samples were taken from 0-20, 20-40 and 40-60 cm soil depth with the help of auger. The samples were then mixed to get blended sample of each series. Sampling of each soil series was replicated five times, thus in total 25 composite soil samples were collected. The samples were packed in polythene bags separately and then brought to the laboratory of Department of Land and Water Management, Sindh Agriculture University Tandojam for analysis. These samples were oven dried at 105°C for about 24 hours and then cleaned from leaves and pebbles and then ground. Soil texture, dry bulk density, soil water content and saturated hydraulic conductivity were determined using standard methods before initiation of soil retention experimental studies.

Twenty five plastic pipes, each of height 40 cm and diameter 15 cm were purchased. One side of pipes was closed with plastic disk using glue and small holes in the disk were drilled in order to allow free drainage of water. Soil from each soil series was filled in five pipes. It was then packed manually in order to maintain density similar to that observed under field conditions. The pipes filled with soil were weighed on balance and total weight was recorded. Soil filled pipes were placed in an open air during the experiment in order to get environment similar to the field conditions. Before installing tensiometers in pots, they were calibrated and zero reading was adjusted at saturation. They were filled with distilled water and then were inserted in the soil at the center of pipes and the nearby soil was firmed. The water was then applied to soil in pipes until soil was completely saturated *viz.* until tensiometers showed zero reading. Any change in soil matric potential was continuously monitored using tensiometers. Also loss in total weight of the soil filled pipes due to water evaporation from surface of soil and free drainage from the bottom of pipes was also measured using weighing balance. The soil water content of each pipe was determined by gravimetric method corresponding to the measured matric potential of tensiometers. The process of measuring matric potential and corresponding soil water content was continued until the soil water suction in pipes reached to the 1bar. Beyond 1 bar, the tensiometeric reading would be unreliable due to air entry into the soil. By plotting the soil water matric potential (suction) against soil water content, soil water retention curves of all soil series were prepared.

Saturated hydraulic conductivity of all the 25 soil samples was measured using falling head permeameterin the laboratory using relation:

$$K = \left(\frac{al}{At}\right)\ln\left(\frac{h_1}{h_2}\right) \qquad (1)$$

Where, K is hydraulic conductivity (cm/sec), a is area of the standpipe (cm^2), L is length of soil column (cm), A is cross sectional area of the soil column (cm^2), h_1 is initial height of water (cm) in standpipeh_2 is final height of water and t is time required for head drop (sec).

Numerical modeling

The soil hydraulic properties $\theta(h)$ and $K(h)$ were defined using the functions of van Genuchten (1980):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \qquad (1)$$

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

where θ_r and θ_s are the residualand saturated soil water contents (L^3 /L^3), respectively; K_s(L / T) is the saturated soil hydraulic conductivity; α (/L), n (unitless) and ℓ are empirical curve shape parameters; m = 1–1/n, and S_e is effective soil saturation:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

The parameters K_s, θ_r, θ_s, α *and* n are called as van Genuchten-Mualem (VGM) parameters.

The soil hydraulic parameters (θ_r, θ_s, α, n, K_s and ℓ) required for the simulations were estimated using the Rosetta pedotransfer functions (Schaap *et al*., 2001), associated with HYDRUS-1D. Rosetta predicts the soil hydraulic parameters when soil texture, relative percentage of soil separates, soil dry density, soil water content at field capacity and wilting point are used as input. The water retention and conductivity functions are derived from more easily measured soil properties, such as soil texture, bulk density, and organic matter content. The collected data (relative percentage of soil separates and dry density) were thus used as an input in HYDRUS-1D model to optimize the VGM parameters and water retention curves of the considered soil series. Measured soil water retention curves were compared with those computed by the model in order to assess the performance of model.

Statistical analysis

Three statistical parameters, the mean bias error (*MBE*), the root mean square error (*RMSE*), and the coefficient of determination (R^2) were also determined. These statistical parameters are defined as (Willmott, 1982):

$$MBE = \frac{\sum_{i=1}^{n}\left(P_i - O_i\right)}{n} \qquad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{n}} \qquad (4)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2} \qquad (5)$$

Where n is the number of data points; P_i is the ith simulated data point; O_i is the ith observed data; and $\overline{O}$ is the mean of observed data. *MBE* can identify potential bias (i.e., underestimation and overestimation) in the predicted values, *RMSE* gives an overall measure of the degree in which the measured data differ from the model predictions and R^2 assess how well model fits the observed data?

RESULTS AND DISCUSSION

Soil texture, dry density and saturated hydraulic conductivity

Table 1 shows soil texture and bulk density of the five soil series used in the study. The table indicates that soil texture of Jhakkar soil series and Sultanpur soil series is same i.e. Silt loam with slight variation in relative percentage of soil separates. Similarly the soil texture of Matli and Miani soil series are identical i.e. silty clay loam. Whereas, the texture of Sarhad soil series is coarse (sandy loam) containing higher relative percentage of sand separates. The dry soil bulk density of Jhakkar soil series ranged from 1.31 to 1.35 g/cm^3, Matli soil series from 1.25 to 1.28 g/cm^3, Miani soil series from 1.26 to 1.28 g/cm^3, Sarhad soil series from 1.50 to 1.55 g/cm^3 and Sultanpur soil series from 1.33 to 1.37 g/cm^3. The saturated hydraulic conductivity of Jhakkar, Matli, Miani, Sarhad and Sultanpur soil series was 2x10^{-4} cm/sec, 1.9 x10^{-4} cm/sec, 1.9 x10^{-4} cm/sec, 3.1 x10^{-4} cm/sec and 1.8 x10^{-4} cm/sec, respectively. It indicates that due to higher relative percentage of sand separates in Sarhad soil series, it had more hydraulic conductivity than other considered soil series.

Table 1. Soil texture, dry bulk density and saturated hydraulic conductivity of the different soil series considered in the study.

Soil Series	Sand %	Silt %	Clay %	Soil texture	Dry bulk density (g/cm^3)	Hydraulic conductivity (cm/sec)
Jhakar	8.8±1.14	68.6±1.47	22.6±1.71	Silt Loam	1.32±0.01	2.0x10^{-4} ±1x10^{-5}
Matli	8.8±2.27	57.0±0.62	34.2±1.69	Silty Clay Loam	1.26±0.01	1.9x10^{-4} ±1x10^{-5}
Miani	7.8±1.69	58.6±2.20	33.6±1.00	Silty Clay Loam	1.27±0.00	1.9x10^{-4}± 1x10^{-6}
Sarhad	62.0±1.39	25.2±3.00	12.8±1.69	Fine Sandy Loam	1.51±0.01	3.1x10^{-4}±1x10^{-5}
Sultanpur	19.6±1.47	56.8±2.66	23.6±2.29	Silt Loam	1.34±0.01	1.8x10^{-4}±1x10^{-5}

± = Confidence Interval

Table 2. VGM Parameters optimized by Rosetta pedotransfer functions associated with HYDRUS-1D model.

Soil Series	Θ_r(cm^3/cm^3)	Θ_s(cm^3/cm^3)	α	n	K_s(cm/day)
Jhakkar	0.078±0.002	0.456±0.007	0.005±0.0003	1.63±0.016	20.59±0.821
Matli	0.091±0.002	0.492±0.009	0.008±0.0006	1.497±0.021	18.67±0.318
Miani	0.091±0.001	0.492±0.004	0.008±0.0004	1.504±0.012	18.35±0.240
Sarhad	0.045±0.004	0.378±0.010	0.026±0.0010	1.423±0.007	30.41±1.234
Sultanpur	0.074±0.003	0.433±0.009	0.006±0.0005	1.618±0.025	17.60±1.069

± = Confidence Interval

Soil VGM parameters

Table 2 shows the VGM parameters *(¯$_{r}$, ¯$_{s}$, α, n,* and K_{sat}*)* optimized by Rosetta pedotransfer functions embodied in HYDRUS-1D model when soil texture and dry bulk density were used as input parameter. The table shows that residual moisture content **(**$Θ_r$*)* and saturated water content *(*$Θ_s$*)* for Jhakkar soil series were 0.078 cm^3/cm^3 and 0.456 cm^3/cm^3, respectively whereas *α, n* and K_s were 0.005, 1.630 and 20.594, cm/day, respectively. For Matli soil series, ¯$_{r,}$ ¯$_{s}$*, α, n,* and K_s given by model were 0.091 cm^3/cm^3, 0.492 cm^3/cm^3, 0.008, 1.497 and 18.674 cm/day, respectively. Similarly for Miani soil series ¯$_{r,}$ ¯$_{s}$*, α, n,* and K_s were 0.091 cm^3/cm^3, 0.492 cm^3/cm^3, 0.008, 1.504 and 18.358, cm/day, respectively. VGM parameters; ¯$_{r,}$ ¯$_{s}$*, α, n,* and K_s for Sarhad soil series were 0.045 cm^3/cm^3, 0.378 cm^3/cm^3, 0.026, 1.434 and 30.412 cm/day, respectively. Sultanpur soil series had ¯$_{r,}$ ¯$_{s}$*, α, n,* and K_s as 0.074 cm^3/cm^3, 0.433 cm^3/cm^3, 0.006, 1.618 and 17.602, cm/day, respectively. It suggests that due to higher sand content in Sarhad soil series, the values of ¯$_{r}$, ¯$_{s}$, and *n* are small while ~ and K_s values are higher than the respective values of VGM parameters of other soil series.

Soil moisture retention curves [¯*(h)*]

Fig. 2 shows the plot of soil moisture retention curves of Jhakkar, Matli, Miani, Sarhad and Sultanpur soil series plotted between the measured and predicted soil water contents against soil matric water potential. The solid line in the graph represents the predicted whereas the data points show the measured soil water content. From the moisture retention curves given in Fig. 1, it is obvious that as the matric potential increases; the corresponding soil water content decreases. It may be noted that clay soil has the characteristics to retain more water at lower matric potentials than the coarse textured soils. Jhakkar soil series and Sultanpur soil series both have approximately same pattern of curves due to same soil texture (Silt loam). Similarly Matli and Miani soil series have approximately same pattern of curves due to same soil texture (Silty clay loam) whereas Sarhad soil series has the steep trend of curve compared to other soil series. These graphs show that initially up to 300 matric potential HYDRUS-1D model over estimates the soil water content but later on it slightly underestimates the measured results. The coefficient of determination (R^2) between the measured and predicted water retention curves ranged from 0.90 to 0.98. This indicated the reliability of using the Hydrus-1D model for predicting soil water retention curves for the soils of Sindh.

Soil hydraulic conductivity [K (h)]

Fig. 3 shows logarithm of hydraulic conductivity, predicted with HYDRUS-1D, plotted against matric potential for Jhakkar, Matli, Miani, Sarhad and Sultanpur soil series. The plots show that for all soil series the hydraulic conductivity decreases tremendously when the soil becomes unsaturated (when soil water pressure becomes negative). These results are similar to those reported by Siyal (1998) and Tahir *et al*. (2012). Decrease in hydraulic conductivity with increase in matric potential is more rapid in Sarhad soil series. This suggests that rapid decrease in unsaturated hydraulic conductivity with increase in matric potential depends on relative percentage of sand in the soil. The coarser the soil texture, the rapid the decrease in unsaturated hydraulic conductivity of soil with increase in matric potential.

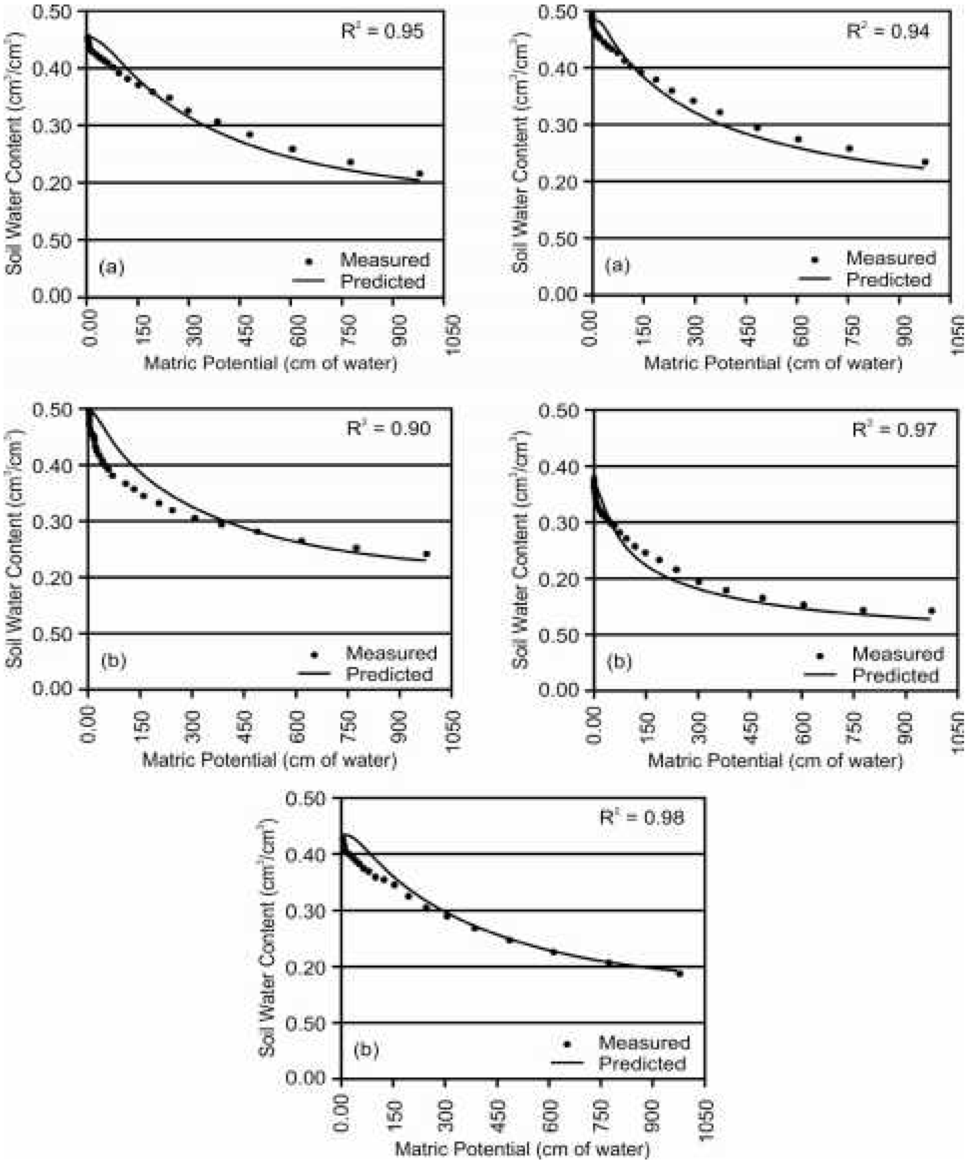

Figure 2. Measured and predicted soil water retention curves (a) Jhakkar soil series (b) Matli soil Series (c) Miani soil series (d) Sarhad soil series and (e) Sultanpur soil series.

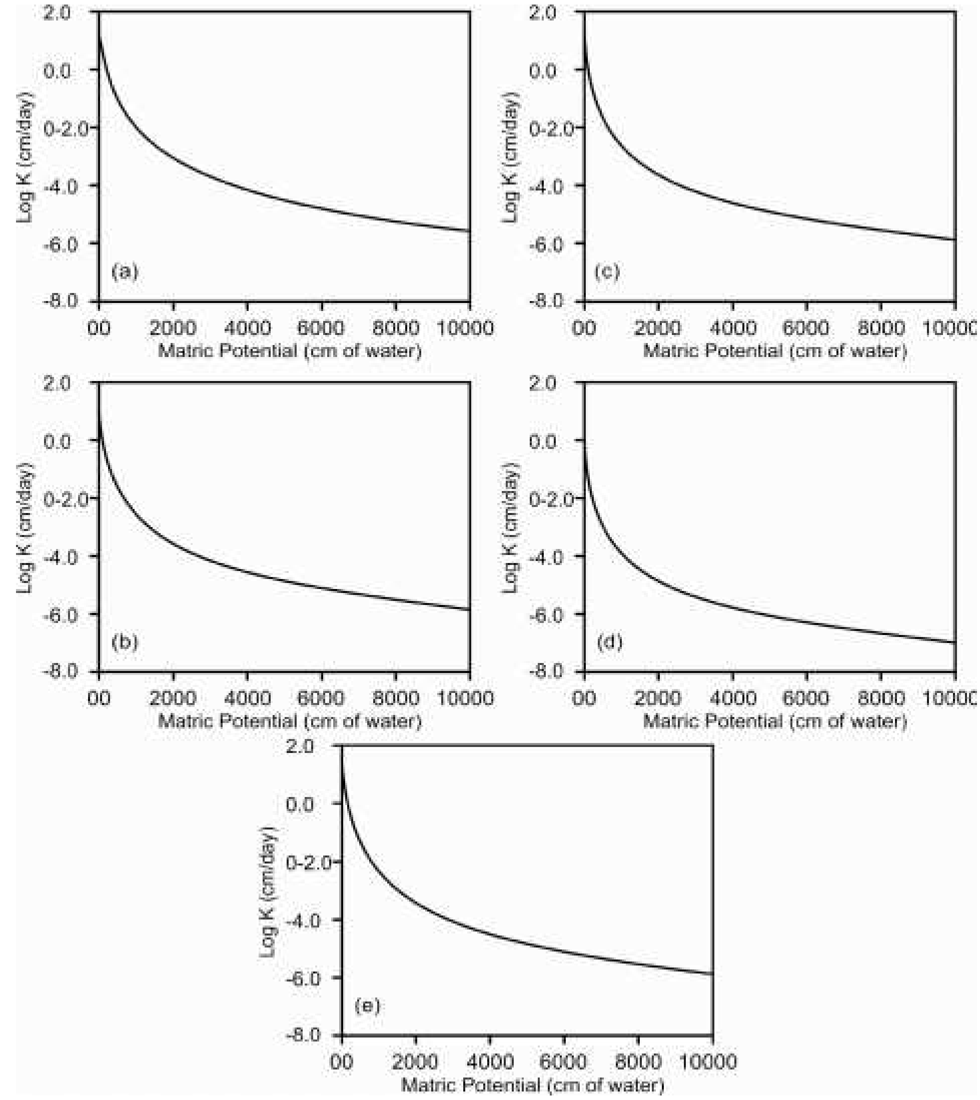

Figure 3. Predicted hydraulic conductivity (log) plotted against matric potential for (a) Jhakkar soil series (b) Matli Soil Series (c) Miani soil series (d) Sarhad soil series and (e) Sultanpur soil series.

Statistical analysis

RMSE (Root Mean Square Error), MBE (mean bias error) and R^2 (coefficient of determination) were determined to evaluate the performance of the HYDRUS-1D model for predicting the soil water retention curves and hydraulic conductivities of soils of Sindh. Table 3 shows that the RMSE, MBE and R^2 of Jhakkar soil series are 0.038, -0.001 and 0.97 respectively. Similarly, RMSE, MBE and R^2 for Matli, Miani, Sarhad and Sultanpur soil series are 0.050, -0.029, 0.90; 0.039, -0.003, 0.94; 0.03, -0.0005, 0.97 and 0.025, -0.004, 0.98 respectively. The MBE shows that initially model overestimates the soil water content but later on (after -300 soil water potential) it underestimates the soil water content.

Table 3. RMSE, MBE and R^2 values for the observed and simulated data of soil water content.

Soil Series	RMSE	MBE	R^2
Jhakkar	0.038±0.00	-0.001±0.02	0.97±0.02
Matli	0.050±0.02	-0.029±0.01	0.90±0.03
Miani	0.039±0.01	-0.003±0.00	0.94±0.01
Sarhad	0.030±0.01	-0.005±0.00	0.97±0.00
Sultanpur	0.025±0.01	-0.004±0.00	0.98±0.00

CONCLUSION

Experimental and simulation study of soil water retention showed that the soil water content of the all the considered soil series decreased with increase in soil water matric potential. As the soil water content decreased, the unsaturated hydraulic conductivity decreased tremendously. Tensiometeric reading becomes unreliable beyond 1bar due to air entry into soil. Based on the simulations and statistical analysis, it is concluded that HYDRUS-1D model initially slightly over estimates the soil water content but later on (when matric potential is greater than -300 cm of water) it under estimates the soil water content. The coefficient of determination (R^2) of the experimental and predicted water content for the considered soil series ranged from 0.90 to 0.98. It is suggested to determine soil hydraulic properties and VGM parameters using HYDRUS-1D model rather than determining in field which is a laborious and time consuming process. Farmers can optimize irrigation water use, minimize waterlogging and salinity and develop an efficient irrigation scheduling for their crops once they know soil hydraulic properties using HYDRUS-1D model.

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(Received January 28, 2014; Accepted November 27, 2014)