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Pedotransfer functions for prediction of near saturated hydraulic conductivity at different applied tensions in medium texture soils of a semi-arid region

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Abstract

Development of pedotransfer functions (PTFs) for prediction of soil hydraulic properties from readily available soil properties had been received increasing attention due to tedious and time consuming nature of laboratory or field measurements. Multiple-regression-equations were used to link the easily available physico-chemical properties of 138 medium texture soil samples of a semi-arid region to their corresponding measured unsaturated hydraulic conductivity (K_ψ) at six applied tensions of 0.2, 0.15, 0.1, 0.06, 0.03, and 0 m. The most influential physical soil characteristics in prediction of soil hydraulic conductivity using PTFs were the soil particle fractions, bulk density (BD), total soil porosity (F) and initial and near saturated volumetric soil water content (θ_i and $\theta_{s,}$ respectively). The most influential chemical attributes were cation exchange capacity to organic matter content ratio (CEC/OM), CEC to electrical conductivity ratio (CEC/EC_e), OM, and calcium carbonate equivalent (CCE). Some combination of both physic-chemical soil attributes (e.g., their square, logarithm or multiplication etc.) also played key rule in prediction of unsaturated soil hydraulic conductivity. The PTFs predictions of unsaturated soil hydraulic conductivities at all of the applied tensions were enough accurate for the most applications except for the measured K_ψ at applied tension of 0.1 m ($K_{0.1}$) and to some extent at applied tension of 0.03 m ($K_{0.03}$) that were less accurate than the other predictions of K_ψ.

Keywords: Multiple regression equation; unsaturated hydraulic conductivity; soil physical-chemical properties; tension disc infiltrometer.
Abbreviations: ANNs- artificial neural networks; BD- bulk density; CCE- calcium carbonate equilibrium; CEC- cation exchange capacity; ECe- electrical conductivity of saturated paste; EKP- exchangeable potassium percentage; ESP- exchangeable sodium percentage; K_ψ- near saturated soil hydraulic conductivity; OM- organic matter; PTFs- Pedotransfer functions; SAR- sodium adsorption ratio; θ_i- initial water content; θ_s- saturated water content.

Introduction

Modeling of water flow and chemical transport in the vadose zone is recommended as an inexpensive approach to study the problems related to soil and environmental remediation (Merdun et al., 2006). Models require knowledge of soil hydraulic attributes such as soil water retention curve $\theta(\psi)$, and unsaturated hydraulic conductivity function $K(\psi)$ (Mermoud and Xu, 2006). Various methods have been developed to estimate these soil attributes or determine them directly in the field or laboratory such as the crust method, the instantaneous profile method, various unit-gradient type techniques and sorptivity methods (Klute, 1986). Direct field or laboratory measurements of hydraulic attributes are tedious, costly, time-consuming, labor intensive and they give only local scale results (Mermoud and Xu, 2006). Due to the highly spatial and temporal variability, point measurement may not produce accurate results. Therefore, it necessitates a large number of soil samples have to be collected to accurately characterize the field or the watershed systems. Furthermore, 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.

Due to these reasons, recently a great deal of research has been devoted to develop alternative indirect approaches to estimate the soil water retention or unsaturated hydraulic conductivity curves either from widely available or more easily measured basic soil properties, and/or limited data (Timlin et al., 2004).

Attempts have been made to estimate these properties indirectly from readily available soil properties. Such equations are often called pedotransfer functions, PTFs (Rawls et al. 2004). 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 (Bouma, 1989). In general, PTFs transfer the data we have into the data we need (Baker and Ellison, 2008). Numerous PTFs have been developed in recent decades, such as those proposed by Saxton et al. (1986), Vereecken et al. (1990), Wosten (1997), and Zhuang et al. (2001), among the others. A summary of pedotransfer functions (PTFs) and their status is given by and McBratney et al. (2002). Reviews on the development and the use of PTFs, particularly for predicting soil hydraulic properties, have given by Wosten (1997), Wosten et al. (2001) and McBratney et al. (2002). Khodaverdiloo et al. (2011), Mosaddeghi and Mahboobi (2011) and Ghorbani Dashtaki et al. (2010) also developed or evaluated some PTFs for prediction of soil hydraulic/water retention curve properties of semi-arid regions of Iran. Wosten (1997) recognized two types of PTFs based on the amount of available information, namely class and continuous PTFs. Class PTFs predict certain soil properties based on the class (textural, horizon, etc.) to which the soil sample belongs. Continuous PTFs predict certain soil properties as a continuous function of one or more measured variables. There is a small number of PTFs available for estimation of unsaturated hydraulic conductivity especially at different soil water tensions. Therefore, the objective of this study was to develop PTFs for prediction of unsaturated soil hydraulic conductivity (K_ψ) at six applied tensions of 0 to 0.2 m from easily available or measurable physico-chemical attributes for medium texture soil samples of a semi-arid region of IR Iran .

Results and discussion

Most influential physical and chemical soil attributes

Table 1 shows the derived PTFs for prediction of unsaturated soil hydraulic conductivity (K_ψ) at applied tension of 0.2, 0.15, 0.1, 0.06, 0.03, and 0 m. The most influential investigated physical soil attributes in prediction of K_ψ were soil particle fractions (% sand, silt, and clay), BD, F, θ_i and θ_s and the most influential investigated chemical attributes were CEC/OM, CEC/EC_e, OM, CCE, K_{sol}, and some of their combinations. Wagner et al. (2001) also reported that the bulk density and organic matter content were influential input variables in prediction of soil hydraulic conductivity using eight well known equations. Saxton and Rawls (2006) developed some new statistical regression equations for soil water characteristic equations and also for soil saturated hydraulic conductivity from a broad range of soils provided by the current USDA soils database using only readily available variables of soil texture and OM. They concluded that these equations were similar to those previously reported by Saxton et al. (1986), but include more variables and application range. Saxton and Rawls (2006) included organic matter in their regression equations and stated that soil density strongly reflects a soils structure and large pore distribution, thus has a particularly significant effect on soil saturation and hydraulic conductivity. Saxton and Rawls (2006) reported that water content at high tensions, for example, 1500 kPa, is determined largely by texture, thus there is minimal influence by aggregation and OM. They stated that the effects of OM changes for wetter moisture contents varied with the soil texture, particularly clay. They reported that OM effects were similar to those of clay, thus those textures with high clay content masked the effects of increased OM. Vereecken (2002) stated that the estimation of the saturated hydraulic conductivity, K_s, from basic soil properties is a difficult issue and PTFs still show a considerable amount of unresolved variability in the estimates of K_s. Vereecken et al. (1990), e.g., published PTFs for K_s with a coefficient of determination of about 20% using clay, sand, and organic matter content and bulk density. Vereecken (2002) stated that large differences in estimation of K_s may result in large differences between the estimates of the unsaturated hydraulic conductivity. He stated that the minimization of the unresolved variability in K_s combined with a better characterization of the wet range is, therefore, a key issue to improve our estimates of K_s. He believed that because the definition and use of K_s is problematic, more effort needs to be invested in an appropriate characterization of the wet range part of the $K(\psi)$ function and the way to incorporate this in a mathematical description of the $K(\psi)$ relation. Gijsman et al. (2002) reported an extensive review of eight modern estimating methods applicable to hydrologic and agronomic analyses. They observed significant discrepancy among the methods due to the regional data basis or methods of analyses thus creating doubt on the value of lab-measured water retention data for crop models. They concluded that the method of Saxton et al. (1986) performed the best. There are a few or no PTFs that predict near saturated or unsaturated soil hydraulic attributes especially hydraulic conductivities at different applied tensions using the chemical soil properties. However, some investigators like Bruand and Tessier (2000) reported acceptable relations between some of chemical soil attributes and the hydraulic soil properties or water retention characteristics. Bruand and Tessier (2000) studied the water retention properties of clayey subsoil's' horizons that developed on a large range of age of calcareous or calcium-saturated clayey sediments according to the variation of clay characteristics. Their results showed that the water-retention properties of the clay vary greatly from one soil to another with respect to the clay fabric that depends on the CEC, the size of elementary particles and hydric stress history of the clay. Bruand (2004) reported that the closeness of relationships between the water retained at a given water potential and CEC increased when the water potential decreased. Bruand (2004) stated that the consequences of chemical and mineralogical characteristics for soil hydraulic properties are often linked, and the effect of chemical characteristics on hydraulic properties are closely related to the mineralogical composition of the clay fraction. Rajkai and Varallyay (1992, referenced by Bruand, 2004) showed that for salt-affected soils, water retention was primarily affected by soil chemical properties, while soil physical variables were found to play only a secondary role. They developed pedotransfer functions (PTFs) for prediction of water retention characteristics with the exchangeable sodium Na and bulk density as predictors for ψ of -50 to -1 kPa with Na and the clay content for ψ of -250 kPa and the total salt content and the clay content for ψ of -1500 kPa. Thus, they found chemical properties and bulk density, but not the textural components to be the necessary inputs in their PTFs to estimate water retention in salt-affected soils. Bruand (2004) used the values of sodium adsorption ratio, SAR, and total electrolyte concentration, C, or solute ionic strength, i, to estimate the effect of salinity and solution composition on soil hydraulic properties. His Results showed plugging of the pores by dispersed clay particles were the major cause of reduced K_s. He reported that the sensitivity to excessive exchangeable sodium and small electrolyte concentration increased with clay content and bulk density. Furthermore, the kaolinitic soil was less sensitive than montmorillonitic and vermiculitic soils, the difference between the latter remaining small. Lenhard (1984, referenced by Bruand, 2004) was able to estimate 95% of variation in changes in water retention of clay samples from SAR and C values. Changes in soil-water retention were attributed to soil mineralogical composition in the work of Jayawardane and Beattie (1978). Lima et al. (1990) demonstrated that values of C and SAR affect parameters of van Genuchten's equation (van Genuchten, 1980) in a regular manner and can be in principle used to modify these parameters. Baumer et al. (1994, referenced by Bruand, 2004) suggested including the product of SAR and clay content in PTFs to estimate residual water contents and water content at 21500 kPa, and to include SAR in the PTFs to estimate the bubbling pressure in

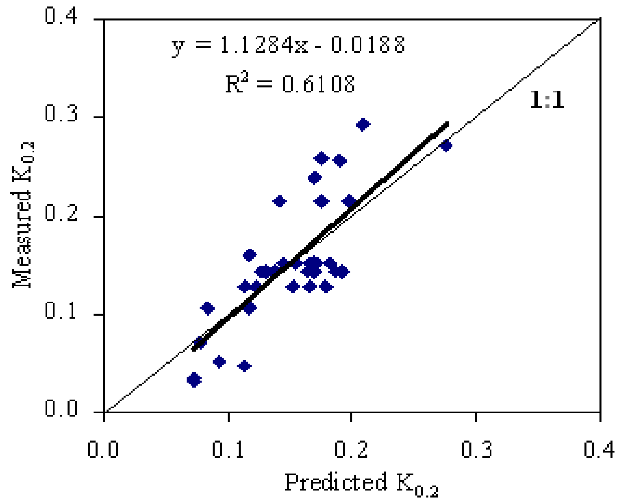
Table 1. Pedotransfer functions (PTFs) for prediction of near saturated soil hydraulic conductivity (K_ψ) at different applied tensions along with the coefficient of determination (R^2), normalized root mean square error (NRMSE), geometric mean error ratio (GMER), and geometric standard deviation of error ratio (GSDER) of predictions for testing dataset (Number of soil data used for PTFs derivation and testing, was 92 and 46, respectively).

Soil hydraulic attribute ($K_\psi \times 10^6$, m s^{-1})	Predictor function*	R^2	NRMSE	GMER	GSDER
$K_{0.2}$	= - 0.181 - 2.807×10^{-5} (F^2) + 0.006 (CEC/OM) + 0.515 (θ_s) + 0.057 [CEC/(OM + clay)] - 9.802 (θ_i^2)	0.61	0.33	1.12	1.49
$K_{0.15}$	= - 0.015 - 5.788×10^{-5} (F^2) + 0.008 (CEC/OM) + 0.763 (θ_s) - 0.004 (θ_i)($clay^2$)	0.65	0.33	1.04	1.45
$K_{0.1}$	= 0.813 + 0.0001(F^2) - 0.063 (OM)(BD^2) + 1.13 (θ_s) + 0.0001($Clay^2$)	0.21	2.46	3.72	1.91
$K_{0.06}$	= - 1.81 + 14.024 (θ_s) + 0.012 (CEC/EC_e) -0.167 (θ_i)(sand) + 0.004 (silt)(BD^2) -17.488 (θ_s^2) - 2.02 (K_{sol}) - 0.017 (CCE)	0.67	0.48	1.18	1.72
$K_{0.03}$	= - 0.076 + 4.789 (θ_s) + 0.013 (CEC/EC_e) + 0.0001 (CCE^2) - 3.066 (K_{sol})	0.73	1.29	2.58	1.65
K_0	= - 0.934 + 11.273 (θ_s) + 0.031 (CEC/EC_e) - 0.001 (CCE^2) - 0.006 (θ_s^2)($sand^2$)	0.74	0.56	1.40	1.59
Mean		0.60	0.91	1.84	1.64

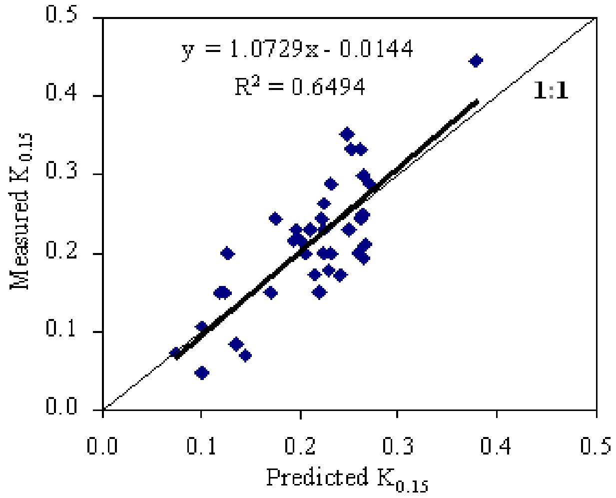
*. Sand, silt, clay, BD, OM, θ_i, θ_s, F, CEC, EC_e, CCE, and K_{sol} are sand, silt, and clay contents (%), soil bulk density (Mg m^{-3}), organic matter content (%), initial and filed saturated volumetric water content (m^3 m^{-3}), total porosity (%), cation exchange capacity [$cmol_+$ kg^{-1}], electrical conductivity of saturated extract (dS m^{-1}), calcium carbonate equivalent, and soluble potassium, respectively.

the Brooks–Corey equation. Naghshineh-Pour et al. (1970) studied the effect of electrolyte composition on soil saturated hydraulic conductivity (K_s) of several soils in Texas. They concluded that the most significant single soil characteristic is soil mineralogy. Changes in K_s as affected by SAR and C were related to clay mineralogy, clay content and bulk density in the work of Frenkel et al. (1978). In the present study the soil saturated hydraulic conductivity (K_0) related to saturated volumetric water content (θ_s), sand content, and the ratio of CEC to EC_e. The amount of sand particles negatively affected K_0 (Table 1) probably due to its negative effect on the soil porosity similar to the findings of Saxton and Rawls (2006) who stated that the soils with gravel-size particles (>2 mm) lose a portion of their water holding and conductance capacity. The negative effect of sand on K_0 (or K_s) was in agreement to the findings of Saxton et al. (1986) and Vereecken et al. (1990), whereas, was in contrary to that of Brakensiek et al. (1984). The positive effect of θ_s on K_0 (Table 1) was probably due to their well known positive relation as previously reported by Brakensiek et al. (1984).

Results indicated that the percentage of clay and OM of soil play key rule in prediction of K_ψ at higher applied tensions i.e., $K_{0.2}$, $K_{0.15}$, and $K_{0.1}$ (Table 1) probably due to effect on soil water content via their high specific surface areas regarding that the soil water content at higher applied tensions depends upon the specific surface area of soil. The other investigators like Wosten (1997) reported that the OM and clay contents of soil were two of the most influential variables in prediction of the parameters of van Genuchten (1980) function for unsaturated hydraulic conductivity. Hudson (1994) stated that increased OM generally produces a soil with increased water holding capacity and conductivity, largely as a result of its influence on soil aggregation and associated pore space distribution. Since we used small number of soil data to generate PTFs for prediction of unsaturated soil hydraulic attributes at different applied tensions, therefore, the generated PTFs may not perform acceptably with the other soil data. Our statements are in agreement to that of the other investigators like Saxton and Rawls (2006) who stated that their proposed regression models will approximate each of the measured values (i.e., soil water content at each applied tensions, saturated and unsaturated soil hydraulic conductivities) to a varying degree, thus the user must assess those most important to the application and adjust the model inputs accordingly. The findings of Saxton and Rawls (2006) indicated that the results of their proposed regression equations compared with those of Saxton et al. (1986) provide improved estimates of varying magnitude for both tensions and conductivities depending on the parameters selected and the properties of the soil being evaluated. Generally, review of available literature reveals various modeling approaches for estimating the unsaturated hydraulic conductivity. The first approach estimates K_ψ using parameters obtained from measurements of the retention curve. This approach leads to good results in many cases. Another approach estimates relevant data points of the curve from basic soil properties. A lot of attention has been given to the correlation of K_s with other soils properties, as K_s is often used as a matching factor in the calculation of the K_ψ curve. These modeling attempts, however, have not been very successful, due mainly to the large variability of K_s (Wagner et al., 2001). Wagner et al. (2001) stated that the remaining approaches to predicting the K_ψ can be divided into three groups: i) Estimation of the parameters of functions that are fitted to the measured K_ψ points by relating them to non-hydraulic soil properties. These methods estimate the target variables by (generally multiple nonlinear) regression statistics from input variables such as clay, sand, organic matter content and bulk density. This type includes the methods of Vereecken et al. (1990) and Wosten, (1997); ii) Derivation of a physico-empirical relationship between the particle size distribution and K_ψ. For this purpose, Campbell (1974) described the particle size distribution by a geometric mean particle size and a geometric standard deviation. The required model parameters are then calculated from these two auxiliary variables; and iii) The K_ψ estimation is based on the assumption that the necessary fitting parameters can be calculated from a single data set of measured matric head vs. moisture content (Gregson et al., 1987). This approach represents a special case because all other methods depend on input variables, that can be obtained relatively easily, while the PTFs based on the Gregson–Hector–Mcgowan, GHM, model (Gregson et al., 1987) is not applicable without



(a)



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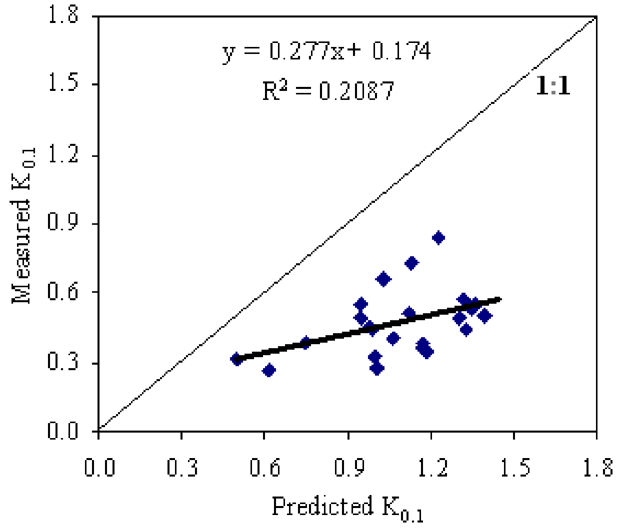

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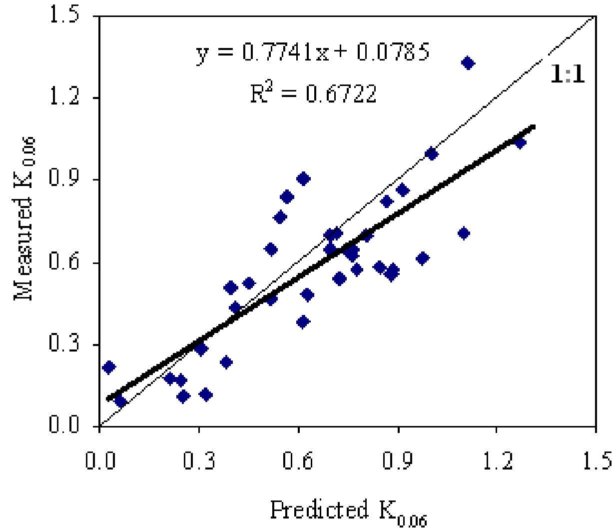

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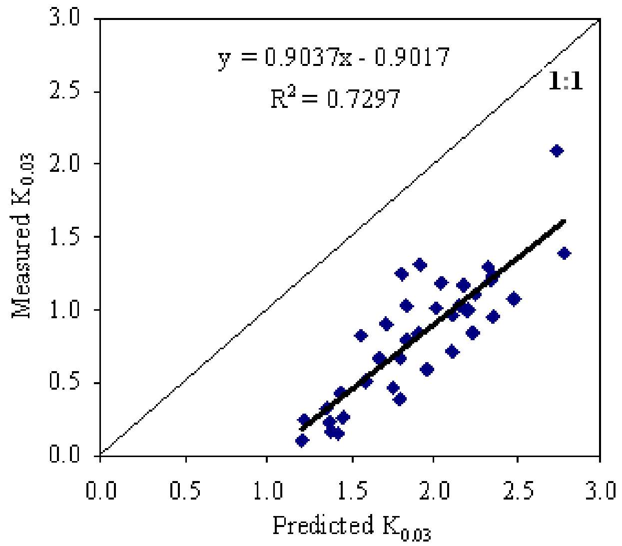

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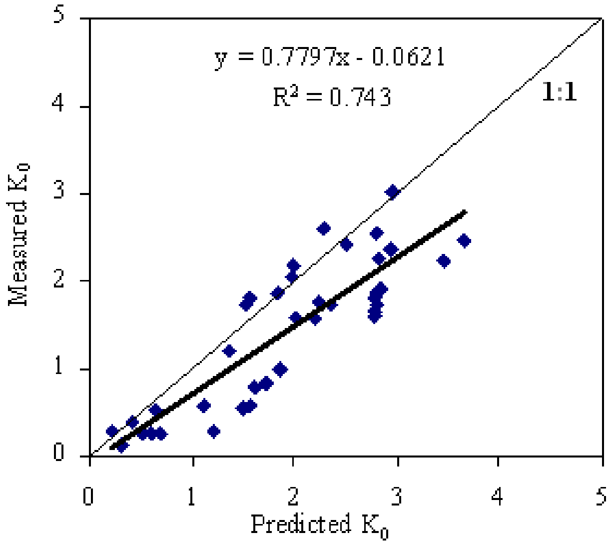

(f)

Fig 1. Measured vs. PTFs predicted values of near saturated soil hydraulic conductivity ($K_\psi \times 10^6$, m s^{-1}) at different applied tensions (ψ, m) for testing dataset.

laboratory measurements on undisturbed samples. On the other hand, single measurements of pressure head vs. water content are often available in soil screening data.

Comparison of the measured and PTF_s-predicted hydraulic conductivities at different applied tensions

Figure 1 gives a comparison of measured K_ψ values vs. their corresponding predictions by the proposed regression PTFs models at different applied tensions. The slope of the regression models for $K_{0.15}$, $K_{0.03}$, and $K_{0.2}$ were somehow similar to that of 1:1 line, but the absolute values may vary. Whereas, for the other K_ψ values the slope of the regression models were largely different to that of 1:1 line, furthermore, the absolute values may vary. Since the GMER equal to 1 corresponds to an exact matching between measured and predictive data; the GMER < 1 and GMER >1 indicate that predicted values are generally under-estimated and over-predicted, respectively. Therefore, it can be concluded that the predicted values of K_ψ were generally over-predicted; however, the GMER values obtained for $K_{0.2}$, $K_{0.15}$, $K_{0.06}$, and K_0 were somehow close to one, indicating that the proposed PTFs predicted these soil hydraulic parameters adequately (Table 1). The GSDER, as an indicator of data scatter, is generally lowest for the PTFs predictions of K_ψ at higher applied tensions i.e., 0.2 and 0.15 m, while it can take quite large values indicating a larger scatter for the PTFs predictions of K_ψ at lower applied tensions especially 0.1 m.

In evaluation of PTFs predictions since the higher values of R^2, the lower values of NRMSE and GSDER, and the much closer value of GMER to one, correspond to the more accurate prediction, therefore, it can be concluded that $K_{0.15}$ was the most accurate predictions, whereas, $K_{0.1}$ and $K_{0.03}$ were the least accurate predictions (Table 1). Figure 1 confirms our judgment about the accuracy of PTFs predictions resulted from R^2, NRMSE, GMER, and GSDER values. Wagner et al. (2001) reported the GMER for predicted unsaturated hydraulic conductivity of 0.08 by Vereecken et al. (1990) model to 8.97 by Cambell (1974) model and GSDER of 11.31 by Wosten (1997) model to 131.21 by Vereecken et al. (1990) model among their eight well known tested models.

Comparison of PTFs accuracies for prediction of unsaturated soil hydraulic conductivity at different applied tensions

Based on the presented statistical parameters (Table 1) it can be concluded that the most accurate PTFs predictions were obtained for measured unsaturated soil hydraulic conductivity at applied tensions of 0.2 and 0.15 m ($K_{0.2}$ and $K_{0.15}$, respectively). Whereas, the least accurate ones were obtained at applied tensions of 0.1 and 0.03 m ($K_{0.1}$ and $K_{0.03}$, respectively). Generally, it seems that the high accurate PTFs predictions correspond to K_ψ at higher applied tensions than the lower ones.

Materials and methods

Study area and experimental design

The study was carried out at two separate neighbor study areas (with soil texture class of gravelly sandy clay loam to non gravelly silty clay loam) located in semi-arid region of Bajgah Agricultural Experimental Station, College of Agriculture, Shiraz University, I.R. of Iran (52° 32′ E, 29° 36′ N, 1810 m above the mean sea level). Measurements were conducted at 69 experimental locations in each study area that were schematically described in Fig. 2. It must be noted that such a nested scheme of sampling was used for studying the spatial variability of soil hydraulic properties (Moosavi and Sepaskhah, 2012) and not specifically for PTFs derivation.

Soil physical and chemical properties

Selected physico-chemical properties were measured in the vicinity or directly at each point immediately before and after the infiltration experiments. In order to determine the more real effect of soil physico-chemical properties on soil hydraulic attributes, the initial gravimetric soil water content was measured in the disturbed samples collected from the vicinity of each point immediately before the infiltration experiments. Undisturbed soil samples (diameter of 0.054 m and height of 0.03 m) were taken directly below the infiltration disc soon after infiltration experiments for determining gravimetric saturated water content. For preventing water losses via evaporation these samples were kept in plastic bags before taking them to laboratory. Gravimetric initial and saturated water contents were determined using oven-drying method in laboratory and multiplied to their corresponding BD to produce Θ_i and Θ_s, respectively. The other soil properties were measured directly underneath the infiltrometer disc at depth of 0-0.2 m in each experimental point soon after infiltration experiment using common methods as follows: sand, silt, and clay content by hydrometer method, gravel content by sieving, bulk density (BD) by core method, organic matter (OM) by wet oxidation method, electrical conductivity of soil saturated extract (EC_e) by EC- meter, pH of soil saturated paste by glass electrode pH-meter, cation exchange capacity (CEC), exchangeable sodium (Na_{ex}) and potassium (K_{ex}) by Chapman (1986) method, soluble Na and K (Na_{sol} and K_{sol}, respectively) by ammonium acetate extraction and flame photometry, Ca and magnesium (Ca_{sol} and Mg_{sol}, respectively) by titration, ESP determined using $[(Na_{ex}/CEC)\times100]$, EKP determined using $[(K_{ex}/CEC)\times100]$, and SAR determined using $[Na_{sol}/(Ca_{sol} + Mg_{sol})^{0.5}]$, in which Na_{sol}, Ca_{sol}, and Mg_{sol} are soluble Na, Ca, and Mg (mol L^{-1}), respectively.

Unsaturated soil hydraulic conductivity measurements

Infiltration measurements were performed using a single-disc tension infiltrometer (Fig. 3) with diameter of 0.2 m (Soilmoisture Equipment Crop. P.O. Box 30025, Santa Barbara, CA 93105 U.S.A.) on the soil surface. At each location, after removing the grasses and leveling the soil surface, a thin contact layer of fine sand (particles with diameters of 0.0001 to 0.0025 m) with thickness of approximately 0.01 m was put on the soil surface between infiltrometer disc membrane and soil surface for an ensured good hydraulic contact. Infiltration measurements were made at successively applied tensions of 0.2, 0.15, 0.1, 0.06, 0.03, and 0 m. At each applied tension, water infiltration into the soil was manually recorded at time intervals of 15 s for about first 300 s after implementation of a new tension, and later on every 60 s until the steady state conditions were met. It must be pointed out that based on those reported in the manual of tension disc infiltrometer, when we have three to five consecutive similar infiltration data we can assume that the steady state conditions were established. Unsaturated soil hydraulic conductivities (K_ψ) at the mentioned applied

Table 2. Statistics for the entire data set along with the data set used for generating and testing of pedotransfer functions (PTFs).

Soil attribute**	Entire dataset					PTFs-generating dataset					PTFs- testing dataset				
	Min.*	Max.	Avr.	SD	CV	Min.	Max.	Avr.	SD	CV	Min.	Max.	Avr.	SD	CV
Sand (g kg^{-1})	74.00	449	217	74	34.16	74.00	411	219	73.81	33.65	94.00	449	213	75.67	35.51
Silt (g kg^{-1})	84.32	660	358	224	62.67	84.32	660	356	229	64.21	91.72	630	361	218	60.23
Clay (g kg^{-1})	93.15	316	215	54	25.32	109	316	214	52.59	24.57	93.15	316	216	58.32	27.00
Gravel (g kg^{-1})	0.01	629	210	224	107	0.01	629	211	224	106	0.01	629	210	228	109
MWD ($\times 10^{-3}$, m)	0.09	3.29	1.24	1.12	90.37	0.09	3.29	1.24	1.12	90.11	0.11	3.29	1.23	1.13	91.90
GMD	-1.97	1.65	0.08	0.48	569	-1.54	1.62	0.09	0.47	523	-1.97	1.65	0.07	0.51	686
BD (Mg m^{-3})	0.98	1.80	1.36	0.20	14.37	0.98	1.73	1.35	0.20	14.51	0.98	1.80	1.37	0.19	14.21
θ_i (m^3 m^{-3})	0.01	0.10	0.03	0.01	43.32	0.01	0.10	0.03	0.01	48.98	0.01	0.04	0.03	0.01	26.28
θ_s (m^3 m^{-3})	0.24	0.44	0.34	0.05	13.58	0.24	0.44	0.34	0.05	13.99	0.24	0.41	0.34	0.04	12.86
OM (g kg^{-1})	10.21	42.19	23.19	5.17	22.30	10.21	42.19	22.76	4.88	21.43	14.29	40.83	24.06	5.67	23.58
pH	7.06	8.23	7.84	0.15	1.91	7.06	8.23	7.85	0.15	1.93	7.06	8.03	7.84	0.15	1.88
EC_e (dS m^{-1})	0.46	0.91	0.67	0.08	11.45	0.47	0.91	0.67	0.07	10.99	0.46	0.91	0.68	0.08	12.41
CEC (cmol$_+$ kg^{-1})	36.17	51.78	46.46	3.59	7.73	36.17	51.78	46.38	3.62	7.80	37.23	50.72	46.62	3.58	7.68
CCE (g kg^{-1})	313	490	408	23.33	5.71	338	490	412	22.46	5.45	313	439	402	23.88	5.94
Na_{sol} (mmol L^{-1})	0.09	3.42	0.64	0.38	60.29	0.09	1.75	0.61	0.30	49.72	0.29	3.42	0.70	0.51	72.70
K_{sol} (mmol L^{-1})	0.03	0.12	0.06	0.02	32.57	0.03	0.12	0.06	0.02	33.69	0.03	0.12	0.06	0.02	30.61
Ca_{sol} (mmol L^{-1})	6.40	24.00	11.50	3.43	29.79	6.40	24.00	11.50	3.63	31.55	7.20	19.20	11.50	3.02	26.23
Mg_{sol} (mmol L^{-1})	0.40	36.40	8.07	5.17	64.09	0.80	36.40	8.24	5.57	67.60	0.40	26.40	7.72	4.29	55.61
Na_{exch} (cmol$_+$ kg^{-1})	0.17	2.69	1.49	0.43	28.93	0.17	2.69	1.50	0.45	29.75	0.21	2.23	1.47	0.40	27.43
K_{exch} (cmol$_+$ kg^{-1})	0.13	0.23	0.16	0.02	9.57	0.13	0.23	0.16	0.02	10.41	0.13	0.19	0.16	0.01	7.59
ESP	0.39	5.40	3.20	0.89	27.79	0.39	5.40	3.22	0.92	28.44	0.44	4.44	3.16	0.84	26.64
EKP	0.28	0.52	0.35	0.04	12.40	0.30	0.52	0.36	0.05	12.94	0.28	0.45	0.35	0.04	11.23
SAR (mol$^{0.5}$ L$^{-0.5}$)	0.04	1.50	0.29	0.16	54.29	0.04	0.71	0.27	0.12	42.13	0.14	1.50	0.32	0.22	67.70
$K_{0.2}$ ($\times 10^6$, m s^{-1})	0.03	0.48	0.15	0.07	44.94	0.03	0.32	0.15	0.06	40.87	0.03	0.48	0.16	0.08	51.96
$K_{0.15}$ ($\times 10^6$, m s^{-1})	0.04	0.67	0.22	0.10	46.45	0.04	0.46	0.22	0.10	44.40	0.05	0.67	0.23	0.11	50.64
$K_{0.1}$ ($\times 10^6$, m s^{-1})	0.05	0.94	0.36	0.18	50.90	0.05	0.84	0.36	0.18	49.40	0.07	0.94	0.36	0.20	54.40
$K_{0.06}$ ($\times 10^6$, m s^{-1})	0.08	1.42	0.57	0.29	50.99	0.09	1.32	0.56	0.27	48.61	0.08	1.42	0.58	0.32	55.61
$K_{0.03}$ ($\times 10^6$, m s^{-1})	0.10	2.39	0.90	0.48	53.53	0.11	2.39	0.90	0.47	52.53	0.10	2.22	0.91	0.51	56.01
K_0 ($\times 10^6$, m s^{-1})	0.12	6.97	1.57	1.04	66.32	0.12	6.97	1.56	1.05	67.43	0.12	4.47	1.60	1.03	64.81

*. Min., Max., Avg., SD, CV, and W are the minimum, maximum, average, standard deviation, coefficient of variation (%), and Shapiro- Wilk's W statistic for normality test, respectively.

**. Sand, silt, clay, gravel, MWD, GMD, BD, θ_i, θ_s, OM, pH, EC_e, CEC, CCE, Na_{sol}, K_{sol}, Ca_{sol}, Mg_{sol}, Na_{exch}, K_{exch}, ESP, EKP, and SAR are the sand, silt, clay, and gravel contents, mean weight diameter and geometric mean diameter of primary particles, bulk density, initial and saturated volumetric water contents, organic matter content, pH of saturated paste, electrical conductivity of saturated extract, cation exchange capacity, calcium carbonate equivalent, soluble sodium, potassium, calcium and magnesium, exchangeable Na and K, exchangeable sodium percentage, exchangeable potassium percentage, and sodium adsorption ratio in the given units, respectively. *.$K_{0.2}$, $K_{0.15}$, $K_{0.1}$, $K_{0.06}$, $K_{0.03}$ and K_0 are near saturated hydraulic conductivity of soil measured at applied tensions of 0.2, 0.15, 0.1, 0.06, 0.03 and 0 m.

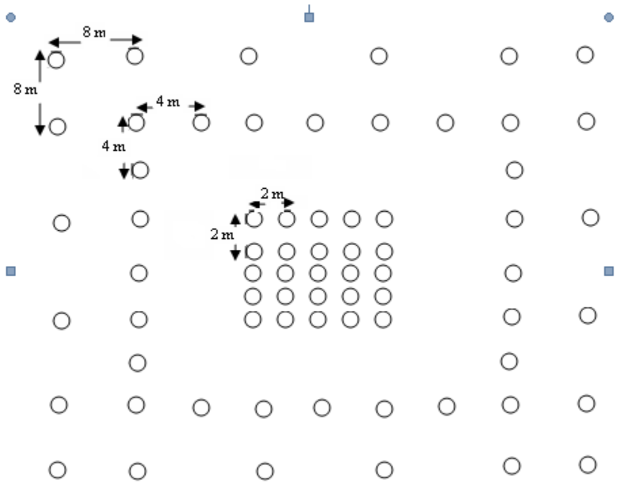

Fig 2. Schematic description of 69 sampling point in each study area.

Fig 3. Single-disc tension infiltrometer (Soilmoisture Equipment Crop. P.O. Box 30025, Santa Barbara, CA 93105 U.S.A.) was used to determine unsaturated soil hydraulic conductivities at different applied tensions.

tensions were determined using the collected infiltration data by applying the approaches proposed by *Wooding* (1968, After Ankeny et al. 1991).

Statistical analysis

Measured soil properties were analyzed in terms of statistical moments of the empirical distribution functions. General statistic parameters such as minimum, maximum, mean, variance, coefficient of variation, skewness and kurtosis coefficients were calculated for each measured soil properties. The normal distribution of each soil parameter was checked using Shapiro-Wilk (1965) test by calculation of W parameter as follow:

$$W = \frac{\sum_{i=1}^{n} (\varepsilon_i X_i)^2}{\sum_{i=1}^{n} \left(X_i - \bar{X} \right)^2} \qquad i = 1, \ldots, n \qquad (1)$$

In which X_i is the *i*th order statistic, i.e., the *i*th-smallest number in the sample; $\bar{X}$ is the sample mean, and ε_i is a constant obtained based on those published by Shapiro and Wilk (1965).

Derivation of pedotransfer functions (PTFs) for prediction of unsaturated soil hydraulic conductivity

Prediction of less readily available soil properties such as hydraulic properties can be possible from easily collected soil parameters, such as soil texture, bulk density and organic matter contents, by forming mathematical relationships (Schaap and Leij, 1998). These mathematical relationships for estimation of soil water characteristics and soil hydraulic conductivity function that indeed are regression equations, are often called pedotransfer functions, PTFs (Rawls et al., 2004). In present study, the continuous PTFs were derived using nonlinear regression methods by applying SPSS software package (SPSS, Version 16, 2007). Since the more data we use the more accurate PTFs will generate, therefore, we used all of measured soil attributes together from 138 sampling locations of both studied soil series. The W statistics were close to 0.9 for almost all of measured soil attributes; therefore, there was no need to transform the original data into normal ones. In generation of PTFs based on our measured data, we divided the entire dataset into two subsets, randomly. The first that consisted of 70 % of our data (92 data) was used to generate PTFs, and the second subset that consisted of 30 % of our data (46 data) was used to test (calibration procedure) the generated PTFs. (Table 2 shows the statistics for the entire data set along with the data set used for generating and testing of PTFs). In generation of PTFs for prediction of each hydraulic attribute, we considered it as dependent variable and the other measured physical and chemical properties, their squares, their logarithms and some of their products as independent variables in stepwise regression modeling (using SPSS, version 16, 2007). In this study, dependent data consisted of unsaturated soil hydraulic conductivity (K_ψ) at applied tensions of 0.2, 0.15, 0.1, 0.06, 0.03, and 0 m. The independent data consisted of soil particle fractions (% sand, silt, clay, and gravel contents), mean weight diameter (MWD), geometric mean diameter (GMD), bulk density (BD), total soil porosity (F), initial and near saturated volumetric soil warter content (θ_i and θ_s, respectively), organic matter content (OM), electrical conductivity of soil saturated extract (EC_e), pH of soil saturated paste, soluble sodium, potassium, calcium, and magnesium (Na_{sol}, K_{sol}, Ca_{sol}, and Mg_{sol}, respectively), exchangeable sodium and potassium (Na_{ex} and K_{ex}, respectively), cation exchange capacity (CEC), calcium carbonate equivalent (CCE), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), exchangeable potassium percentage (EKP), the squared and natural logarithm value of these independent soil variables, and some of their product combinations. The parameters of regression models were adjusted so that the software enters each independent soil variable into regression equation automatically if its influence was statistically significant at probability level of 0.05. Consequently, each soil hydraulic attributes at different applied tensions were modeled as a significant function of some independent soil variables, named PTFs. Independent measured values of soil testing dataset were put into the generated PTFs to produce the PTFs predictions. In order to make comparisons between measured and PTFs-predicted soil hydraulic attributes, the measured soil hydraulic attributes of testing dataset were plotted against the PTFs predictions and their determination coefficients (R^2) were determined. The higher values of determination coefficient indicate the higher performance of PTFs in prediction of soil hydraulic attributes and the lower ones exhibit the poor performance of PTFs. The closeness of measured-predicted pairs of data values to 1:1 line was another criterion which we used for checking the performance of generated PTFs. The more closeness of measured–predicted pairs of data to 1:1 line correspond to high performance of PTFs in prediction of soil hydraulic attributes, whereas the less clossness correspond to poor performance of PTFs. Furthermore, normalized root mean squared error (NRMSE) were calculated [using Eq. (2)] for each PTFs-prediction of soil hydraulic attributes and were considered as the other criteria in checking the performance of PTFs (Schaap and Leij, 1998).

$$NRMSE = (\sqrt{1/N\left[\sum_{i=1}^{N}(\hat{y}_i - y_i)^2\right]}) / \bar{y} \qquad i = 1,..., N \qquad (2)$$

where N is the number of measured or predicted value and $\bar{y}$ is the mean value of measured , y .

The $NRMSE$ is always a positive value, with low and high $NRMSE$ -values indicating good and poor performance of PTFs, respectively.

In addition to R^2 and NRMSE, the geometric mean error ratio (GMER) and geometric standard deviation of the error ratio (GSDER) were calculated for evaluation of PTFs predictions from the error ratio, ε , of N measured hydraulic attribute, y_m , vs. the corresponding predicted, y_p , values using the following equations (Wagner et al., 2001):

$$\varepsilon = \frac{y_m}{y_p} \qquad (3)$$

$$GMER = \exp\left(\frac{1}{N}\sum_{i=1}^{N}\ln(\varepsilon_i)\right) \qquad (4)$$

$$GSDER = \exp\left[\left(\frac{1}{N-1}\sum_{i=1}^{N}\left[\ln(\varepsilon_i) - \ln(GMER)\right]^2\right)^{0.5}\right] \qquad (5)$$

The GMER equal to 1 corresponds to an exact matching between measured and predicted values; the GMER < 1 indicates that predicted values are generally under-estimated; GMER >1 points to a general over-prediction. The GSDER equal to 1 corresponds to a perfect matching and it grows with deviation from measured data. The best model will, therefore, give a GMER close to 1 and a small GSDER (Wagner et al., 2001).

Conclusions

Based on the values of R^2, NRMSE, GMER, and GSDER for PTFs predictions, it can be concluded that the PTFs predictions of K_ψ were most accurate at applied tensions of 0.2 and 0.15 m, whereas, were the least accurate at applied tensions of 0.1 and 0.03 m. In another word, the proposed PTFs could predict K_ψ with much more confidence at higher applied tensions than the other applied tensions. Because all models were calibrated with data from one database the predictions among models and input data levels are consistent. Additionally, the availability of uncertainty estimates provided information about the reliability of the predictions. These characteristics can be very useful to generate uncertainty estimates of water and solute transport processes, even when limited information about the soil is available. Although prediction errors were often large, estimation of soil hydraulic properties with PTFs may be accurate enough for most applications, and hence will rectify a need where hydraulic properties are not available.

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