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Pedotransfer functions for predicting points on the moisture retention curve of Indian soils

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ABSTRACT

Limited numbers of pedotransfer functions (PTFs) for predicting the soil moisture transmission parameters are available for the Indian soils. These PTFs have been developed from limited datasets and are area specific, limiting their applicability elsewhere. Secondary data from various sources often have non-systematic errors and lacking in uniformity. The present study makes an attempt to explore the possibility of developing PTFs from wide textural range of Indian soils for four points on the moisture retention curve, –33, –100, –500 and –1 500 kPa. Moisture content at these four matric potentials was significantly related to clay and sand but little or no correlation was observed with bulk density and organic C content in soils. For each potential, six sets of regression equations were used to predict the moisture content from textural composition, bulk density and organic C content. The predictive potential is better by considering only clay and silt at –33 and –500 kPa while clay, silt and bulk density gave good moisture predictability at –100 and –1 500 kPa potential values. The developed PTFs for moisture contents at –33 and –1 500 kPa were evaluated with existing PTFs and were found to perform satisfactorily.

Key words: Bulk density, Matric potential, Pedo-transfer function, Soil moisture, Texture

The process-based simulation models require input-parameters often difficult to measure directly; consumes large time and resource; and the spatial variability associated with the measured values. Efforts have been made to relate this difficultly measurable parameters, viz soil moisture retention and transmission characteristics with easily measurable and routinely available parameters like soil textural separates (mainly sand, silt and clay) through development of several functions, commonly known as pedotransfer functions or PTFs. The application of these PTFs has now become an important part for discipline of soil science and its associated database management (Singh 2004).

Attempts have been made to evaluate the general applicability and prediction accuracy of PTFs developed to predict soil moisture retention curve (SMRC) with particle size distribution, organic matter content and dry bulk density in India and abroad (Cornelis *et al*. 2001, Kaur *et al*. 2002, Singh 2004) with mixed results. The point-based approach, based on the prediction of moisture contents at specific matric potential values usually perform better than the parametric approach (Tomasella *et al*. 2003), because of lesser complexities and limited factors for specific points than the whole range of moisture content-potential relations. Few PTFs have been developed for Indian soils, but with limited or area-specific datasets, and mostly predicting the end points only, like moisture content at field capacity or wilting point, and therefore, not depicting the trends in SMRC. So far no secondary datasets in India have been developed and compiled using a standard and uniform protocol. Thus, an attempt was made to explore the possibility of developing PTFs from a wide textural range of Indian soils (based on primary data generated by following similar protocol), which may predict some more points on the MRC, other than FC and WP.

MATERIALS AND METHODS

One hundred and eighty seven soil samples were collected from three or more horizons at various locations in India (Table 1). Soil cores for determination of bulk density (BD)

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and for particle size distribution were taken using a core sampler with a volume of 196.5 cm^3. Sand, silt and clay content, BD and organic C of the soil were determined following standard procedures. The pressure chamber method was used to determine the gravimetric moisture content at field capacity (–33 kPa), wilting point (–1 500 kPa), and two in-between points on MRC, i e –100 and –500 kPa. All the analyses were performed during 2006–08. Different combinations of soil parameters and moisture contents at these four matric potentials were determined by regression analysis using SPSS, 2004 statistical package version 13.2. The 1st combination included clay and silt, while 2nd, 3rd, 4th, 5th and 6th combinations used sand and BD; clay, silt and BD; clay, silt and sand; clay, silt, sand and BD; and clay, silt, sand, organic C and BD, respectively to derive the moisture content at different matric potentials. The multiple regression analysis was performed on the predictor variables and response hydraulic parameters by using 107 data points in SPSS platform. As the predictor variables are mostly of independent and non-correlated in nature, principal component analysis was not performed. The equations were validated using the remaining 80 independent data points.

The degree of accuracy of a certain test-PTF was determined by four complementary indices: The mean error (ME, g/g), absolute mean relative error (AMRE, g/g), root of the mean squared error (RMSE, g/g) and the Pearson's correlation coefficient, r. The ME measures the bias of the estimate, while AMRE gives the absolute ratio of the difference to the measured value. The prediction improves with lowering the values of ME and AMRE. The RMSE estimates the overall error of the PTF, and as this approaches close to zero, prediction performance of the PTF increases. Pearson's correlation coefficient (r, dimensionless) indicates the linearity between measurements and predictions. Under perfect linearity, measured and predicted data points are located around the line of perfect agreement (1:1line), and the shape of the predicted curve becomes comparable with as the measured one. The developed PTFs at -33 kPa and -1500 kPa moisture contents were evaluated with some of the existing PTFs, which predicts the gravimetric moisture content (and not volumetric moisture) at these potentials.

RESULTS AND DISCUSSION

Sand and clay contents of the development (prediction) and validation (evaluation) data sets are presented in Fig 1. Dry bulk density ranged from 1.17 to 1.98 Mg/m while the range of organic C was 0.2 to 11.8 g/kg of soil. The gravimetric moisture content of the 187 soil samples varied between 2.9 and 38.9% (mean=23.2%, coefficient of variation, Cv. =0.43) at –33 kPa, 1.5 and 38.6% (mean=19.4%, Cv. =0.47) at -100 kPa, 1.3 and 31.1% (mean=15.1%, Cv. =0.44) at -500 kPa, and 1.0 and 26.7% (mean=12.9%, Cv. =0.46) at -1500 kPa. The regression equations developed between the moisture content and clay, sand, bulk density and organic C in soils are given with their corresponding coefficient of determination (R^2) values.

Table 1 Soil samples used in the study

Location	No. of samples	Climate	Slope	Geographic setting	Soil classification	Dominating soil texture
Chinsurah, Hooghly, West Bengal	16	Sub-humid sub-tropical	Leveled land	Alluvium	Typic Endoaquept	Silty clay, silt loam
Kalyani, West Bengal	23	Humid sub-tropical	Leveled to gentle slope	Alluvium	Aeric Haplaquept	Clay loam
Indore, Madhya Pradesh	12	Sub-humid tropical	Leveled to gentle slope	Basaltic alluvium	Typic Paleustalf	Loam
Barddhaman, West Bengal	29	Sub-humid sub-tropical	Leveled	Alluvium	Typic Endoaqualf	Silty clay
IARI, New Delhi	12	Semi-arid	Leveled	Alluvium	Typic Haplustept	Sandy loam
Alipur, Delhi		Semi-arid sub-tropical	Leveled to gently slope	Alluvium	Typic Haplustept	Fine loamy
Pali, Rajasthan	10	Semi-arid sub-tropical	Leveled to undulation	Weathered shale	Typic Camborthids	Clay loam
Nagaur, Rajasthan	17	Arid sub-tropical	Leveled	Coarse textured alluvium	Typic Torripsamments	Loamy fine sand
Gurgaon, Haryana	14	Semi-arid sub-tropical	Leveled to gentle slope	Mixed alluvium	Typic Haplustept	Loamy sand, sandy loam
Modipuram, Meerut	28	Semi-arid sub-tropical	Leveled	Alluvium	Typic Haplustept	Silty loam, sandy loam
Jodhpur, Rajasthan	13	Arid sub-tropical	Leveled to undulation	Old alluvium	Typic Camborthids	Sandy clay, sandy clay loam and clay loam

Table 2 Regression equations and R^2 values of different parameters

	Matric potential (kPa)	Regression equation	R^2 value
Clay	–33	y= 0.431x+8.812	0.484
	–100	y= 0.385x+6.344	0.459
	–500	y= 0.320x+4.214	0.565
	–1500	y= 0.246x+4.483	0.422
Sand	–33	y= –0.403x+42.690	0.801
	–100	y= –0.354x+36.318	0.722
	–500	y= –0.261x+27.642	0.727
	–1500	y= –0.207x+22.725	0.566
Bulk density	–33	y= –23.443x+59.960	0.090
	–100	y= –19.127x+49.160	0.070
	–500	y= –16.263x+40.395	0.092
	–1500	y= –11.587x+30.861	0.059
Organic carbon	–33	y= 10.888x+19.187	0.048
	–100	y= 11.179x+15.107	0.059
	–500	y= 6.595x+12.431	0.037
	–1500	y= 5.558x+10.631	0.034

Soil moisture content was positively correlated with clay content and negatively with sand contents of soils at all the four suctions (Fig 2, Table 2). Relationship of moisture contents at –33, –100 and –500 kPa potentials with per cent sand content is quite strong, but with clay, moderate association was noticed. No variation in trend in moisture content at various potentials could be explained with bulk density and organic C content in soils. As the soil moisture content at various potentials was expressed on per cent oven-dry basis, no relation between moisture content and bulk density was obtained. Soils with high organic C are expected to retain more moisture; however, in the present study the organic C was very low and also had short range of variation. This possibly explains why we could not get significant relation, as found in some other studies (Mugabe 2004).

Six multiple linear regression equations with different combinations of the soil parameters and moisture content at four matric potentials (–33, –100, –500 and –1 500 kPa) are presented with their coefficient of determination (R^2) and standard error of estimation (SEE) in Table 3. Maximum R^2 values were obtained at –33 kPa potential with average SEE of 4. The validation indices of the regression equations developed, given in Table 2 indicates mixed trend (Table 4). The validation indices described here helped us to rank the equations. A final ranking was based on the mean of rankings given to the equations for each validation index separately. Ranking was introduced since the evaluation of equations should not be based on one validation index only, but should take into account of different indices simultaneously.

At –33 kPa, prediction did not improve much with the inclusion of more parameters. Clay and silt together resulted R^2 0.820, which improved slightly to a value of 0.844 with inclusion of sand and 0.847 and 0.849 with inclusion of sand+BD and sand+BD+OC together. Pore size distribution contributes maximum in determining the moisture retention at this potential, which fundamentally depends on soil structure and bulk density; thus, inclusion of bulk density could slightly improve the predictability. However, in our study, moisture retention characteristics were determined using sieved and air-dry soil samples and hence, bulk density effect might be ignored. Linearity between the prediction and measurement is maximum (r=0.906) for eq. 2, though the bias in prediction is minimum (mean error, ME=0.57 g/g) for eq. 3 (Table 3). Absolute mean relative error (AMRE) was similar with the equations. Although in overall ranking, eq. 5 came first but by considering ME and RMSE of eq.1 close to eq. 3, we can choose eq. 1 as the best prediction of moisture content at –33 kPa potential, as this function contains minimum predictor parameters. Clay and silt content of soils can be easily determined by simply removing the sand fraction with 0.5 mm sieve, and does not require particle size analysis in the laboratory, its usability in obtaining moisture content at –33 kPa could be the most simple and quick option in practical application like scheduling irrigation.

In case of predication of moisture at –100 kPa, R^2 improved with addition of more parameters. Equations 4 and

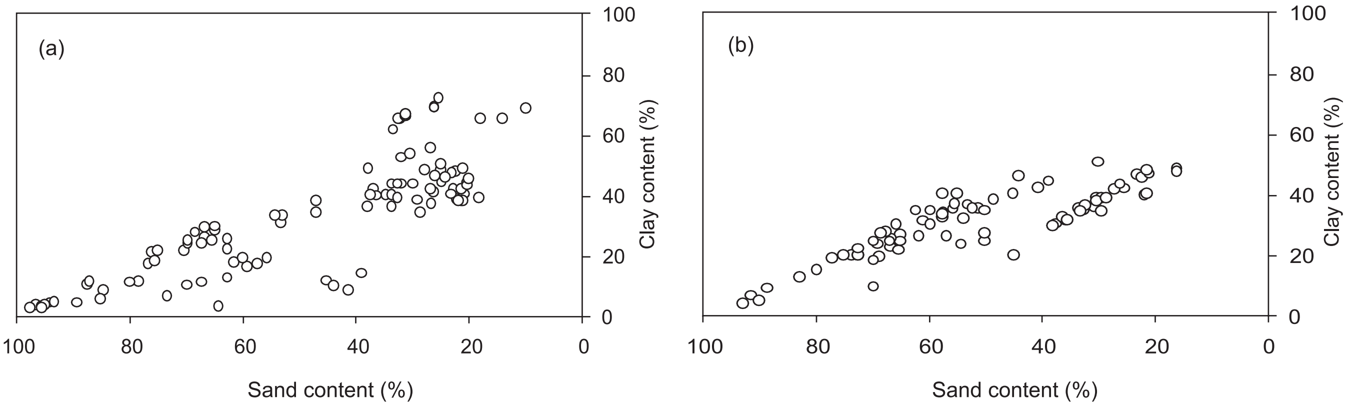

Fig 1 Clay (0–2 μm) and sand (50–200 μm) content of the (*a*) development and (*b*) validation data sets

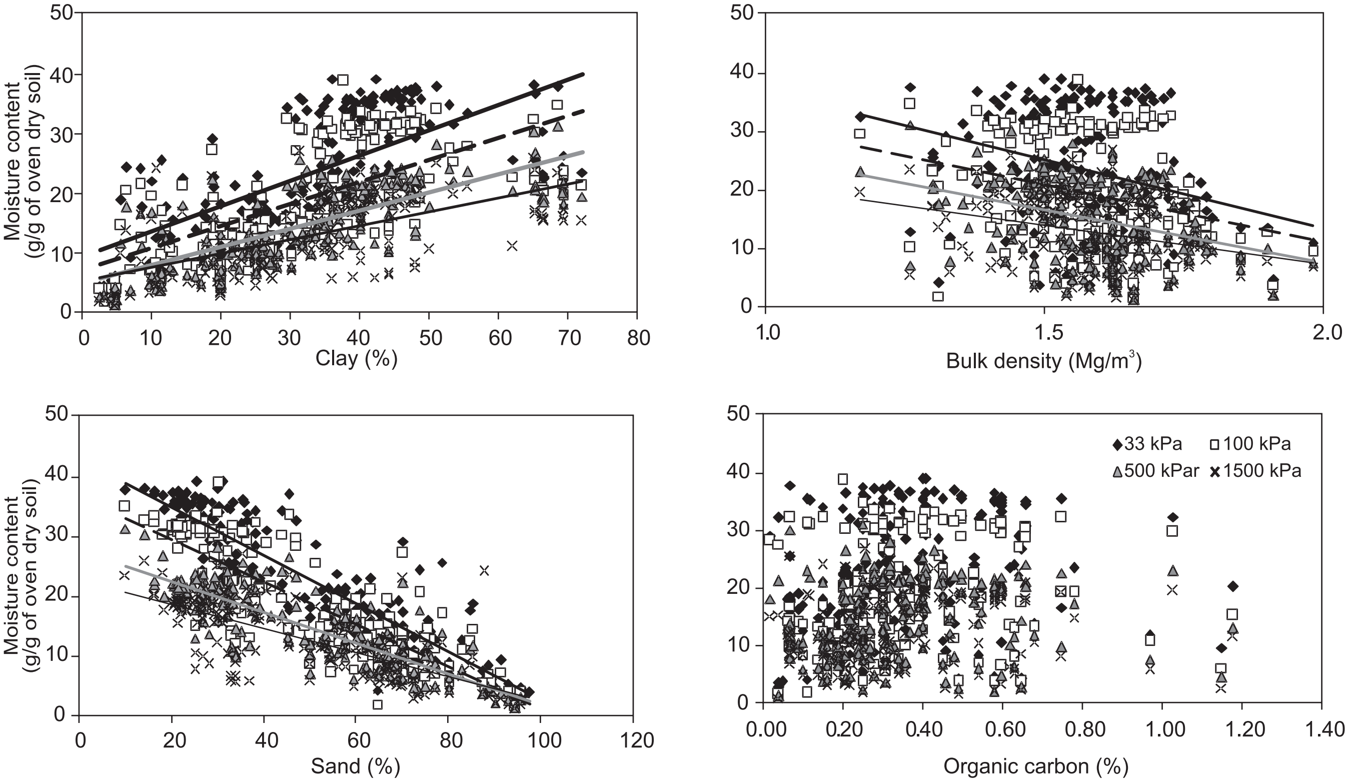

Fig 2 Relations between moisture content (g/g of oven dry soil) at –33, –100, –500 and –1 500 kPa and % clay, % sand, bulk density (Mg/m) and % organic C

5 performed equally well with same R^2 (0.737) and comparable SEE (4.820 and 4.855 for equations 4 and 5, respectively). However, the predictive potential is better for eq. 3 (ME=1.255 g/g, RMSE=5.157 g/g and r=0.872) considering the comparable validation indices. This function also has less number of parameters as compared to eq. 4 and 5.

At –500 kPa potential, soil moisture content could be predicted most satisfactorily by using eq. 4 (R^2=0.734, SEE=3.618); inclusion of BD or BD and OC could not improve the prediction with eq. 5 (R^2=0.734, SEE=3.637) or 6 (R^2=0.736, SEE=3.645). However, the ME was the least in eq. 1, and was also quite close to zero as compared with other models. The linearity in case of eq. 1 is also quite satisfactory (r=0.878) and the RMSE was second lowest (3.748 g/g only after eq. 2, i e 3.730 g/g). Considering the regression coefficient close to 0.7 (only 0.003 less than eq. 3), and with only clay and silt involved in the prediction, eq. 1 may be ranked first.

As indicated by R^2 values, moisture content at –1 500 kPa could not be predicted well by either of the equations. However, eq. 4, 5 and 6 performed similarly considering both R^2 and SEE values. Linearity was the best with eq. 3 and did not improve with inclusion of other parameters, neither RMSE improved. Again the bias was less in eq. 3 (ME=0.73 g/g). Based on these observations, eq. 3 may best be used for prediction of moisture content at –1 500 kPa. At lower potential, i e towards the dry end of the moisture curve, moisture is retained mainly through the adsorptive forces, and thus related to the specific surface area and more of texture controlled. So moisture at this point could be best predicted by clay+silt content of soils. In either of the case, eq. 6, which included all the five parameters (% clay, silt and sand, per cent organic C and bulk density), could be chosen as the best PTF. This function accounted for 85, 75, 74 and 53% of the variation in moisture content at –33, –100, –500 and –1 500 kPa, respectively.

Performance evaluation of the developed PTFs at –33 kPa and –1 500 kPa moisture contents

The developed PTFs underestimated the moisture content at –33 (field capacity, FC) and –1 500 kPa (wilting point, WP) as compared to De Jong *et al.* (1983) and Gupta (1992) methods (positive ME values); and overestimated in comparison to Rao *et al.* (1988), Bhavanarayana *et al.* (1986) and Aina and Periaswamy (1985) methods (negative ME values) (Table 4).

Rao *et al.* (1988), Aina and Periaswamy (1985) and De Jong *et al.* (1983) showed relatively higher AMRE (0.36 g/g) as well as higher RMSE (7.53 , 8.39 and 7.53 g/g, respectively), indicating their better predictive accuracies. Our study suggests that PTF by Bhavanarayana *et al.* (1986) resulted to minimum AMRE and RMSE values. The ME was

Table 3 Six equations used to predict the soil moisture content at matric potentials of –33, –100, –500 and –1 500 kPa

Matric potential (kPa)	Eq	Coefficients associated with					Intercept	R^2	SEE
		Clay (%)	Silt (%)	Sand (%)	Org C (%)	BD (Mg/m^3)			
–33	1	0.297	0.478				4.600	0.820	4.351
	2			–0.377		–0.215	41.114	0.812	4.454
	3	0.280	0.481			–7.566	17.095	0.830	4.253
	4	0.078	0.248	–0.241			27.447	0.844	4.078
	5	0.093	0.276	–0.213		–4.481	32.210	0.847	4.045
	6	0.095	0.268	–0.206	2.420	–4.402	30.960	0.849	4.060
–100	1	0.270	0.379				2.988	0.709	5.051
	2			–0.330		2.611	30.160	0.726	4.875
	3	0.262	0.380			–3.167	8.219	0.711	5.059
	4	0.049	0.147	–0.242			25.945	0.737	4.820
	5	0.048	0.145	–0.245		0.370	25.551	0.737	4.855
	6	0.053	0.113	–0.230	6.434	1.528	21.236	0.750	5.682
–500	1	0.251	0.185				2.958	0.698	3.837
	2			–0.244		–0.795	27.495	0.721	3.691
	3	0.244	0.187			–3.079	8.046	0.701	3.843
	4	0.067	–0.008	–0.204			22.216	0.734	3.618
	5	0.067	–0.008	–0.203		–0.135	22.359	0.734	3.637
	6	0.069	–0.017	–0.195	2.461	0.079	20.895	0.736	3.645
–1 500	1	0.184	0.144				3.702	0.489	4.488
	2			–0.187		1.241	19.320	0.519	4.352
	3	0.183	0.144			–0.689	4.840	0.490	4.509
	4	0.021	–0.028	–0.179			20.695	0.524	4.365
	5	0.014	–0.041	–0.192		2.093	18.47	0.526	4.370
	6	0.017	–0.053	–0.184	2.950	2.327	16.802	0.529	4.369

Org C, Organic carbon; BD, bulk density; SEE, standard error of estimation

also less compared to other methods. Even at –1 500 kPa, the AMRE and RMSE of Bhavanarayana *et al*. (1986) PTF was less compared to other PTFs. The negative values of ME associated with PTFs of Gupta, Rao *et al.* (1988) and Bhavanarayana *et al*. (1986) and positive values with Aina & Periaswamy (1985) indicate underestimation and overestimation, respectively, of moisture content at –1 500 kPa by the presently developed PTF. Prediction accuracies are more in Bhavanarayana's PTF for both FC and WP moisture contents. For FC moisture content, the AMRE and RMSE values ranged between 0.22 to 0.36 g/g and 4.67 to 8.39 g/g. The linearity between the predicted (present PTF) and observed (existing PTFs) are almost conserved (except for De Jong *et al.* 1983). The RMSE slightly improved in the prediction of WP moisture, but the linearity reduced. The lower prediction potential of the PTFs at FC moisture compared to soil moisture content at WP soil moisture content might be due to the role of structure in influencing the moisture retention at higher matric potential. Considering all the evaluation indices, the present PTFs are most distantly related to De Jong *et al.* (1983). Relatively high sand (16.4–92.7%) and silt (2.5–38.4%) content in the evaluation data set resulted in better agreement with Bhavanarayana *et al.* (1986) (data with high sand and silt content) and poor agreement with De Jong *et al.* (1983) (data with high sand but low silt content). The prediction of WP moisture using Aina & Periaswamy (1985), PTF remarkably improved (ME from –5.40 to 0.92 g/g and RMSE 8.39 to 4.28 g/g), probably due to inclusion of only clay at WP moisture (Kaur *et al.* 2002).

Evaluation results show reliable estimation of the four points on the MRC by using the PTFs as developed in the present study. Results also indicate the possibility of getting satisfactory prediction of hydraulic functions for various field levels by using a very limited number of easily and rapidly measurable parameters. However, more number of data points need to be incorporated to tune into the functions for further improving the predictability and applicability of these PTFs in the field conditions. This requires a network programme on generating the primary datasets, where a

Table 4 Validation indices and final ranking of the pedotransfer functions as computed on the complete evaluation of the data set. (figures in parentheses indicate comparative ranking)

Matric potential (kPa)	Model number	ME (g/g)	AMRE (g/g)	RMSE (g/g)	Pearson's number (r)	Final ranking
–33	1	0.67 (2)	0.20(3)	4.770 (5)	0.890 (4)	4
	2	1.45 (6)	0.18(1)	4.849 (6)	0.906 (1)	4
	3	0.57 (1)	0.20(3)	4.754 (4)	0.890 (4)	3
	4	1.03 (5)	0.19(2)	4.742 (2)	0.894 (3)	3
	5	0.94 (4)	0.19(2)	4.712 (1)	0.894 (3)	1
	6	0.92 (3)	0.20(3)	4.746 (3)	0.895 (2)	2
–100	1	1.26 (2)	0.26(3)	5.183 (2)	0.872 (3)	2
	2	1.95 (6)	0.25(2)	5.370 (5)	0.877 (1)	4
	3	1.25 (1)	0.26(3)	5.157 (1)	0.872 (3)	1
	4	1.66 (4)	0.24(1)	5.190 (3)	0.873 (2)	2
	5	1.69 (5)	0.24(1)	5.198 (4)	0.873 (2)	3
	6	1.52 (3)	0.28(4)	5.423 (6)	0.871 (4)	5
–500	1	0.18 (1)	0.28(4)	3.748(2)	0.878 (3)	2
	2	1.04 (4)	0.22(1)	3.730(1)	0.871 (6)	3
	3	0.70 (2)	0.26(3)	3.753(3)	0.881 (1)	1
	4	1.07 (5)	0.23(2)	3.783(4)	0.876 (5)	5
	5	1.09 (6)	0.23(2)	3.792(5)	0.877 (4)	6
	6	1.02 (3)	0.26(3)	3.871(6)	0.880 (2)	4
–1500	1	0.75 (2)	0.35(3)	3.995(4)	0.838 (2)	3
	2	1.02 (3)	0.31(1)	3.993(3)	0.826 (6)	4
	3	0.73 (1)	0.35(3)	3.979(2)	0.839 (1)	1
	4	1.03 (4)	0.31(1)	3.963(1)	0.836 (3)	2
	5	1.07 (5)	0.32(2)	4.008(5)	0.830 (5)	6
	6	1.02 (3)	0.35(3)	4.117(6)	0.833 (4)	5

ME, Mean error; AMRE, absolute mean relative error; RMSE, root of the mean squared error

Table 5 Performance evaluation of the developed pedotransfer functions with some of the existing pedotransfer functions

Test PTFs	Soil matric potential at							
	–33 kPa				–1 500 kPa			
	ME (g/g)	AMRE (g/g)	RMSE (g/g)	r	ME (g/g)	AMRE (g/g)	RMSE (g/g)	r
Gupta (1992)	3.44	0.22	6.66	0.91	–1.30	0.37	4.14	0.78
Rao *et al.* (1988)	–5.92	0.36	7.53	0.90	–0.49	0.35	3.75	0.82
Bhavanarayana *et al.* (1986)	–1.08	0.23	4.67	0.91	–1.41	0.35	3.75	0.83
Aina and Periaswamy (1985)	–5.40	0.36	8.39	0.91	0.92	0.34	4.28	0.78
De Jong *et al.* (1983)	3.02	0.36	7.53	0.77	1.38	0.47	5.17	0.70

ME, Mean error; AMRE, absolute mean relative error; RMSE, root of the mean squared error

standard protocol of analysis procedure is maintained.

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