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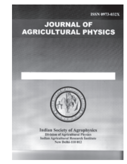

Research Article

Pedotransfer Functions for Estimating Water Content at Field Capacity and Wilting Point of Indian Soils using Particle Size Distribution and Bulk Density

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ABSTRACT

Pedotransfer functions (PTFs) for estimation of soil water retention at field capacity (θ_{FC}, -33 kPa) and permanent wilting point (θ_{PWP}, -1500 kPa) were developed under three soil categories (<20%, 20-40% and >40% clay) through linear, log-linear and stepwise-regression (SR) approach, using particle size distribution and bulk density data. Under <20% clay, the log-linear model was better than other models in predicting θ_{FC}, whereas SR model was better for predicting θ_{PWP}. Under 20-40% clay category, all the three approaches predicted θ_{FC} with equal efficiency, while SR was superior for θ_{PWP}. The log-linear models performed better in predicting both the θ_{FC} and θ_{PWP} with >40% soil clay.

Key words: Pedotransfer functions, Soil texture, Bulk density, Water retention characteristics

Introduction

The pedotransfer functions (PTFs) are defined as predictive functions of certain soil properties derived from other easily measured soil properties. The PTFs are important tool that can be effectively used to estimate the soil water characteristics from limited experimental data points assuming certain functional forms (Agyare *et al*., 2007). Various PTF have been developed to cater wide range of applications, but most of them have been derived empirically and using data from temperate soils. In many cases, textures of tropical soils fall outside the range of validity of these PTFs (Tomasella and Hodnet, 1998). As a result, the prediction is erroneous, or it fails totally. Generally, variability of estimates using textural data has been large and regressions are site specific. PTFs developed in one region or database has limited applicability in other conditions (Santra and Das, 2008). Functional evaluation of estimated soil hydraulic data helps to characterize the contribution of such data to the inaccuracy and uncertainty of simulations. A number of studies used soil water simulation models to evaluate the performance of estimated soil hydraulic characteristics through the simulation of different aspects of soil behavior (Van Alphen *et al*., 2001).

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In India, inter-relationships between soil texture, water retention and transmission characteristics have been worked out in the past (Kaur *et al*., 2002; Chakraborty *et al*., 2011; Das and Verma, 2011; Shwetha and Varija, 2012; Patil *et al*., 2013). However, these works relate to limited number of soil types or specific region, except a few (Adhikary *et al*., 2008). Simple and acceptable relationships for the entire range of soils of India are not available. The present study was, therefore, undertaken with data ranging nearly all the textural classes of Indian soils, for estimating the water retention characteristics. The main objective was to formulate broad-based PTFs, using a large number of available data across texture and bulk density of tropical and subtropical soils of India, to predict the soil water content under different potentials. The PTFs were also validated to find out their acceptability over the India soils.

Materials and Methods

Soil sampling and determination of physical parameters

We have collected samples from places covering a large variability of soil textures (Fig. 1). Pressure plate and membrane apparatus was used for soil water retention at –33 kPa (θ_{FC}) and -1500 kPa (θ_{PWP}) matric potentials. The soil bulk density (BD) was determined from undisturbed soil cores. For saturation moisture content, soil cores were thoroughly wetted by capillary action of water and the excess water drained by gravitational force. The gravimetric water content was determined after oven-drying at 105°C, and multiplied with corresponding BD to determine the volumetric water content in each case. The sand, silt and clay contents were determined using hydrometer method (Bouyoucos, 1962).

Fig. 1. Map of India showing the soil samples collected from different sites for the development and validation of PTFs (map is not up to the scale)

Development of pedotransfer functions

Water-holding capacity is primarily controlled by soil texture. We categorized the soils according to %clay (<20, 20-40 and >40) as outlined by Troeh and Thompson (2005). A soil with high silt and clay contents is likely to have higher water-holding capacity. In this study, we followed the point regression method of estimating the PTFs for θ_{FC} and θ_{PWP}. For development and cross validation, the data sets were separated into two groups. One group (60% data set, 491 data points) was used for development (regression) while rest 40% (302 data points) for validation (Table 1). Further, Pearson correlation was worked out to examine the relations among them (Table 2). Linear, log-linear and stepwise regression models were developed for estimating θ_{FC} and θ_{PWP} from basic sand, silt and clay content and BD. For stepwise multiple linear regression analysis, these data and also their derivatives (sand x silt, sand x clay, silt×clay, $clay^2$, $silt^2$, ln (clay), ln (silt) etc.) were used. Criteria of 1 and 5% level of significance were used for acceptance or rejection of a predictor variable in these models. The R^2 values associated with these models were used to select the most efficient PTF for different categories of clay. Further, t-test between the observed and predicted value was performed to assess the suitability of these selected PTFs.

Models validation

The performance of the PTFs was evaluated through statistical indicators: the coefficient of determination (R^2), mean error, root mean square error (RMSE), modeling efficiency (ME), mean biased error (MBE) and graphically by the 1:1 ratio of predicted versus observed values.

$$\text{Mean error} = \frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)$$

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

$$\text{ME} = 1 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum\left(O_i - O_{mean}\right)^2}$$

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

Where: n is the number of observations, O_i the observed and Pi the predicted values. All the statistical analyses were carried out in *JMP 10* software.

Results and Discussion

Basic soil characteristics

The minimum, maximum and mean values of sand, silt, clay, BD, θ_{FC} and θ_{PWP} along with their standard deviations and standard errors are given in Table 1. Although there are differences in minimum and maximum values, the Student's *t*-test showed that both data sets were statistically similar.

There are wide variations in data, which is essential for the generation of PTFs. This also reflects different parent materials and soil formation processes. Santos and Curi (2013), Das and Verma (2011) have also argued the importance of heterogeneity of datasets in generating and validating PTFs. Increase in clay content resulted in higher water content at FC as well as PWP; whereas higher clay content decreased the value of BD in both datasets (Table 1). The clay increases the specific area of the soil matrix and as a consequence, favors the water absorption and retention processes. Higher clay content also tends to increase total porosity of soil which further reduces the BD (Reichert *et al.*, 2009).

Pearson correlation between θ_{FC} and θ_{PWP} with clay content was positive and significant, whereas sand fraction was negatively correlated. This indicated that soil water content is promoted by finer particles and discouraged by the coarse soil particle. Further, positive relation between BD and sand fraction and negative correlation with silt and clay fraction were observed. It reflects how the relative proportion of sand, silt and clay particle affects the BD of soil. Das and Verma (2011) and Ceddia *et al.* (2009) observed the similar trend and emphasized the role of soil

Table 1. Range of soil texture and other basic information used for pedotransfer function derivation and validation

	< 20% clay					20-40% clay					> 40% clay				
	Min	Max	Mean	SD	SE	Min	Max	Mean	SD	SE	Min	Max	Mean	SD	SE
Derivation of PTFs															
Clay (%)	1.3	19.3	12.9	5.2	0.42	18.6	40.0	29.4	5.7	0.4	40.1	69.8	49.4	7.6	0.7
Silt (%)	0.4	37.4	12.0	8.3	0.68	1.4	62.75	15.7	14.3	0.9	1.1	47.5	12.5	7.3	0.7
Sand (%)	49.50	97.8	75.2	11.7	0.95	9.5	79.4	54.9	15.3	1.0	10.4	58.0	38.0	9.9	0.9
Bulk density (Mg m^{-3})	1.41	1.94	1.61	0.12	0.01	1.11	1.91	1.54	0.13	0.01	1.06	1.68	1.44	0.12	0.01
Field capacity (%)	4.9	28.3	18.3	5.6	0.5	23.1	55.8	35.6	4.6	0.3	28.7	67.0	43.7	6.7	0.6
Permanent wilting point (%)	3.3	18.4	7.6	4.6	0.4	15.7	24.7	17.9	4.2	0.3	16.9	28.1	23.9	6.0	0.6
No. of samples	149	149	149	149	149	232	232	232	232	232	110	110	110	110	110
Validation of PTFs															
Clay (%)	3.0	16.6	12.3	4.5	0.5	20.0	40.0	31.7	5.6	0.6	40.1	76.8	49.5	7.4	0.7
Silt (%)	1.0	64.2	16.6	10.9	1.1	2.5	56.0	21.1	14.8	1.5	5.0	50.2	27.7	9.2	0.9
Sand (%)	19.6	92.0	71.1	13.9	1.4	9.0	72.5	46.1	17.2	1.7	4.4	58.0	22.9	9.9	1.0
Bulk density (Mg m^{-3})	1.41	1.81	1.61	0.10	0.01	1.02	1.83	1.54	0.14	0.01	1.15	1.74	1.51	0.10	0.01
Field capacity (%)	5.5	28.1	16.9	5.5	0.6	22.5	52.4	34.8	4.5	0.4	28.3	61.5	45.4	6.3	0.6
Permanent wilting point (%)	4.2	20.4	6.7	4.0	0.4	15.2	25.5	16.2	3.7	0.4	18.6	27.8	21.8	6.5	0.6
No. of samples	97	97	97	97	97	102	102	102	102	102	103	103	103	103	103

SD= Standard deviation, SE= Standard error

Table 2. Pearson correlation coefficient among the soil data set

	Field capacity (%)	Permanent wilting point (%)	Bulk density (Mg m^{-3})	Clay (%)	Silt (%)	Sand (%)
Field capacity (%)	1.00					
Permanent wilting point (%)	0.93**	1.00				
Bulk density (Mg m^{-3})	-0.38**	-0.34**	1.00			
Clay (%)	0.88**	0.82**	-0.55**	1.00		
Silt (%)	0.06	0.03	-0.40**	0.04	1.00	
Sand (%)	-0.71**	-0.61**	0.66**	-0.80**	-0.64**	1.00

**indicates significant at 1% level of significance

separates in water retention characteristics and variability in BD.

Derivation of PTFs

For predicting the soil water retention at FC under <20% clay content category the linear model (PTF 1) accounted for 85% variation in the observed value followed by stepwise regression model (PTF 5, R^2 = 0.77**) and log-linear model (PTF 3, R^2 = 0.75**) (Table 3). While, for prediction of soil water content at PWP, the proposed stepwise regression model (PTF 6) accounted for 55% variability in the observed value followed by log-linear model (PTF 4, R^2= 0.53**) and linear model (PTF 2, R^2 = 0.40**) (Table 3). On the basis of coefficient of determination presented in Table 3, which indicate the range of dependent variables that were explained by independent variables, PTF 1 and PTF 6 were qualified for determination of water content at FC and PWP under <20 % clay content.

Under the category of 20-40% clay, log-linear model (PTF 9) appears better for predicting θ_{FC} which is accounted for 57% variation in observed values, whereas both linear (PTF 7) and the stepwise regression model (PTF 11) accounted for 55% variation (Table 4). For θ_{PWP}, the stepwise regression model (PTF 12) could account for 53% variation as compared to linear (PTF 8) and log-linear model (PTF 10) accounted only 23% (Table 4). Similarly, under >40% clay content, PTF 15 and 16 can be selected for predicting θ_{FC} and θ_{PWP} (Table 5). Sand content was not included in these selected PDFs. Das and Verma (2011) opined that increase of sand increases macro-porosity, BD and therefore, decreases total porosity of soil. Soil water retention is related to the porosity, but with meso- and macro-porosity at high suction levels.

Evaluation of derived PTFs

Out of 18 PTFs, PTF 1, 6, 9, 12, 15 and 16 were selected on basis of higher R^2 (Table 6). The t-test was performed for comparing predicted vs observed soil water content. The t-statistics was non-significant for all, which indicates good agreement between observed and predicted values. Lower absolute value of RMSE, mean error, MBE and higher value of R^2 and ME also indicate good prediction (Table 7). Significant R^2 in all three categories indicated that the PTFs could successfully predict the water contents. Negative mean error indicated that PTFs underestimated the moisture contents. Mean error ranged from 0.10 to 1.77%, which are low and acceptable. Similar results were also reported by Nemes *et al*. (2009) and Reichert *et al*. (2009). Model efficiency used to quantify the accuracy of model outputs. An efficiency of 1 corresponds to a perfect fit between predicted and observed values. The ME values are close to 1 except PTF 6, which indicated reliability of suggested PTFs. Further, figure 2 revealed that the predicted water contents q_{FC} and q_{PWP} were close to the measured values. All model evaluation statistics indicated the practical utility of the suggested PTFs (Table 7).

Table 3. Coefficient of regression equations developed for prediction of soil water content at FC & PWP and available water capacity of the soil (< 20% clay)

PTF No.	Matric potential	Intercept	Clay (%)	Silt (%)	Sand (%)	BD (Mg m^{-3})	ln (Silt)	ln (BD)	Clay ^{2}	R^2
					a) Linear model					
1	33 kPa	-23.02	1.268	-1.22 × 10^{-2}		15.57				0.85**
2	1500 kPa	-23.52	0.783	-2.17 × 10^{-2}		13.17				0.40**
					b) Log-linear model					
3	33 kPa	6.714	0.163				0.479	4.837	0.0357	0.75**
4	1500 kPa	-5.969	-0.202				0.500	17.333	0.0376	0.53**
					c) Stepwise regression model					
	Matric potential	Intercept	Clay (%)	BD (Mg m^{-3})	Clay^2	BD^2	Clay × Silt	Clay × BD	Sand × BD	R^2
5	33 kPa	-18.77			1.826 × 10^{-2}		1.216 × 10^{-2}	0.661	0.146	0.77**
6	1500 kPa	-189.10		203.69	4.36 × 10^{-2}	-53.734				0.55**

** Significant at P<0.01

Table 4. Coefficient of regression equations developed for prediction of soil water content at FC & PWP and available water capacity of the soil (20-40 % clay)

PTF No.	Matric potential	Intercept	Clay (%)	Silt (%)	Sand (%)	BD (Mg m^{-3})	ln (Silt)	ln (BD)	Clay ^{2}	R^2
					a) Linear model					
7	33 kPa	27.093	0.262	-0.284	-0.287	13.670				0.55**
8	1500 kPa	33.888	-5.86×10^{-2}	-0.373	-0.292	4.958				0.23*
					b) Log-linear model					
9	33 k Pa	-0.065	1.150				0.377	23.116	-0.0099	0.57**
10	1500 k Pa	-2.6727	1.115				-1.186	8.459	-0.0144	0.23*
					c) Stepwise regression model					
Equations	Matric potential	Intercept	Silt (%)	Clay × Silt	Clay × BD	Silt × BD	Silt × Sand			R^2
11	33 kPa	18.989			0.368					0.55**
12	1500 kPa	15.459	-0.316	7.81×10^{-3}	8.501×10^{-2}					0.53**

** Significant at P<0.01 * significant at P<0.05

Table 5. Coefficient of regression equations developed for prediction of soil water content at FC & PWP and available water capacity of the soil (>40 % clay)

PTF No.	Matric potential	Intercept	Clay (%)	Silt (%)	Sand (%)	BD (Mg m^{-3})	ln (Silt)	ln (BD)	Clay ^{2}	R^2
					a) Linear model					
13	33 k Pa	77.128	-0.517	-0.832	-1.058	29.715				0.41**
14	1500 k Pa	-63.169	0.771	0.627	0.432	18.542				0.31**
					b) Log-linear model					
15	33 k Pa	-5.039	0.5954				2.7252	41.752	-0.0007	0.53**
16	1500 k Pa	17.681	-0.517				2.051	25.090	0.0079	0.43**
					c) Stepwise regression model					
Equations	Matric potential	Intercept	Clay (%)	(Clay)^2	BD	Clay x BD	Silt x Sand			R^2
17	33 kPa	-4.89			8.306	0.454	1.034x10^{-2}			0.43**
18	1500 kPa	-0.83				0.319	9.572x10^{-3}			0.39**

** Significant at P<0.01

Table 6. T-statistic of selected PTFs

Matric Potential	PTF No.	t-statistics	Expression	R^2	P-value	Level of significance
			< 20% clay			
-33 kPa	1	1.180	-23.02+1.264(Clay %)-0.0122 (Silt %) + 15.37 (BD)	0.85	0.239	Non-significant
-1500 kPa	6	0.691	-189.10 + 203.69 (BD) + 0.0436 (Clay^2) - 53.734 (BD^2)	0.55	0.490	Non-significant
			20-40 % clay			
-33 kPa	9	0.045	-0.065+ 1.150(Clay)+0.377(ln Silt)+23.116(ln BD)- 0.0099 (clay^2)	0.57	0.964	Non-significant
-1500 kPa	12	0.001	15.459 -0.316 (Silt) + 0.00781 (Clay*Silt) + 0.08501(Clay*BD)	0.53	0.999	Non-significant
			>40% clay			
-33 kPa	15	0.496	-5.039+ 0.5954 (Clay)+ 2.7252 (ln Silt) +41.752 (ln BD)-0.0007 (Clay^2)	0.53	0.620	Non-significant
-1500 kPa	16	0.272	17.681-0.517(Clay)+ 2.051 (ln Silt) +25.090 (ln BD)+0.0079 (Clay^2)	0.43	0.786	Non-significant

Table 7. Validation indices of the derived PTFs for the independent datasets.

	PTF No.	RMSE (%)	Mean error (%)	R^2	ME	MBE (%)
			<20%			
-33 k Pa	1	2.42	-0.59	0.87**	0.98	-0.17
-1500 k Pa	6	3.32	-0.10	0.54**	0.78	0.23
			20-40%			
-33 k Pa	9	2.14	-0.85	0.67**	0.99	-1.82
-1500 k Pa	12	4.20	-1.77	0.41**	0.93	-2.02
			>40%			
-33 k Pa	15	6.13	-0.48	0.33**	0.98	-1.69
-1500 k Pa	16	6.50	-0.87	0.46**	0.94	-1.05

RMSE= Root meat square error, ME= Model efficiency, MBE= Model biased error

** Significant at $P<0.01$

Conclusions

We proposed some PTFs to estimate of water retention at FC and PWP, which gave realistic estimates under three categories of clay contents. These PTF could be useful for converting basic information from soil survey data to soil water retention, which could be difficult to obtain.

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