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STUDY ON SOIL MOISTURE RETENTION FUNCTION FOR THE INDIAN FORESTED HILLSLOPE SOILS

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ABSTRACT

Pedotransfer functions (PTFs) are one of the widely used tools to predict the soil water retention curves (SWRC). The objective of this study was to develop and validate point and parametric PTF models based on nonlinear regression technique using the different set of predictors such as particle-size distribution, bulk density, porosity and organic matter content. Soil samples were collected from different elevations at different depths in forested hillslope area of Pavanje river basin that lies in coastal area of Karnataka, India. The point PTF models estimated retention points at 33, 100, 300, 500, 1000, and 1500 kPa pressure heads and the parametric PTF models estimated the van Genuchten and Brooks-Corey retention parameters. The data were evaluated with the root mean square error (RMSE), mean error (ME), and coefficient of determination (R^2) between the measured and predicted water contents. The prediction of soil water retention curve using PTFs by point estimation method for the sampled soils was relatively successful (best case $R^2 = 0.862$). Further, a critical comparative analysis on the performances of point and parametric methods was done. It can be suggested to use the developed PTFs for the prediction of soil water retention curve for the loamy sand and sandy loam textured soils in this forest area of the coastal region in south western portion of India.

Key words: Matric potential, pedotransfer functions, regression, soil properties, validation.

1. INTRODUCTION

The use of measurements from agricultural soils for the hydraulic modeling of forest soils is quite inappropriate because forest soils show distinctively different physical and hydraulic properties. Forest soils differ significantly from the arable land in their particle size distribution, bulk density, porosity, organic matter content, and water retention parameters. Forest soils are less compacted, showing a greater aggregate stability and macroporosity and, therefore, a greater saturated hydraulic conductivity and air capacity (Fisher and Binkley 2000). The soil water retention curve $\theta(h)$ and the unsaturated hydraulic conductivity $k(h)$ are the two most frequently considered hydraulic properties of the soil. Of course, there are quite a few datasets on the hydraulic properties of forest soils. But relatively major portion of the research activities related to such measurements are restricted to agricultural land use (Mecke *et al*. 2000). For example, the databases such as UNSODA (Nemes *et al*. 2001) and HYPRES (Wçsten *et al*. 1999) contain large proportions of samples from nonforested areas. In the backdrop of this, it is quite expected to estimate the hydraulic properties for forest soils from the more easily measurable physical properties.

Soil water retention curve is a basic hydraulic property in soil and water management, and it is the relationship between soil water potential and its volumetric water content. The process of measurement and computation of soil water retention curve in field and laboratory is more expensive, laborious as well as time consuming. As an alternative to direct methods, a technique of indirect estimation of these properties from widely available or more easily measured basic soil properties, such as percentage of sand, silt, clay, organic matter or carbon content, bulk density, porosity using pedotransfer functions (PTFs) has emerged and received the attention (Wosten *et al*. (1995) and Minasny and McBratney (2002)) of researchers. PTF uses basic soil properties as input and yields hydraulic functions as output (Bouma 1989). Tietje and Tapkenhinrichs (1993) classified PTFs into three major types such as point estimation methods, parameter estimation methods and semi-physical methods.

Point pedotransfer functions predict the water content of the soil at certain matric potentials. A notable number of this type of PTFs can be seen in the literature. Gupta and Larson (1979) developed regression equations based on percentage of sand, silt, clay, organic matter and bulk density for 12 matric potentials considering laboratory measured water retention data for Eastern and Central American soils. Rawls and Brakensiek (1982) considered data of 500 American soils and developed three levels of regression equations for predicting water retention from soil texture, organic matter, bulk density and water retention at −33 kPa and −1500 kPa. Givi *et al*. (2004) evaluated the PTFs for predicting the soil water contents at field capacity and wilting point for 16 soil samples of fine clay or clay loam soil profiles in a semiarid region in Iran. Liu *et al*. (2007) applied pedo- transfer functions to simulate spatial heterogeneity of Cinnamon soil water retention characteristics in Western Liaoning Province. Mohammad *et al*. (2011) derived point pedotransfer functions for prediction of water retention of selected soil series in a semi-arid region of western Iran. They concluded that, considering soil saturated water content as a predictor significantly increased the

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accuracy of point PTFs, especially at low matric suctions.

Parametric pedotransfer functions estimate the parameters of a closed-form analytical equations, such as the model of Brooks and Corey (1964), Campbell (1974) and van Genuchten (1980) equations. Parametric PTFs have gained a considerable popularity with examples found in Rawls and Brakensiek (1985), Vereecken *et al*. (1989), Scheinost *et al*. (1997) and Minasny and McBratney (2002). Minasny *et al*. (1999) presented both parametric and point PTFs using different approaches, multiple linear regressions, extended nonlinear regression and artificial neural network for estimating soil water retention curve and found extended nonlinear regression and multiple linear regression to be the most appropriate tool for parametric and point PTFs respectively. Tomasella *et al*. (2003) compared two techniques, point based method and a parametric approach, to develop PTFs for water retention of Brazilian soils using the group method of data handling (GMDH) and concluded that the point-based method yields better results than the parametric method. Børgesen and Schaap (2005) developed a point and a parametric model using neural networks and Bootsrap method for a large database of Danish soils and observed that adding organic matter and bulk density as the input parameters of neural networks could improve the estimation of soil water retention curve.

Existing PTFs for estimating soil water retention curve in the literature are not always applicable in other regions with acceptable accuracy (Tietje and Tapkenhinrichs 1993; Kern 1995; Nemes *et al*. 2003). The research works carried out on an effective representation of soil water retention curves for the forest soils of coastal region of Karnataka, India are not available in the literature. This article is the first one on the topic from the region under consideration. It provides both types of pedotransfer functions describing the vast literature in this field, and explains how the value of soil data can be increased by using them in pedotransfer function. The main objectives of this study are: (a) to measure the soil water retention curves for the different types of forest soils by the laboratory methods using pressure plate apparatus; (b) to develop and validate point PTFs for the estimation of water retention points; (c) to develop and validate parametric PTFs for the estimation of van Genuchten (1980) and Brooks and Corey (1964) water retention parameters from basic soil properties namely, particle-size distribution, bulk density, porosity and organic matter content using multiple nonlinear regression methods; (d) to compare the performances of point and parametric methods using some evaluation criteria.

2. MATERIALS AND METHODS

2.1 Description of the Study Area and Soil Sampling

In the present study, the Pavanje river basin in Dakshina Kannada district of coastal Karnataka is considered. The Pavanje river originates in the foothills of Western Ghats and flows towards west to join the Arabian Sea and lies between North latitudes 12°57′30″ to 13°07′30″ and East longitudes 74°45′00″ to 75°02′30″. The basin lies within the Dakshina Kannada district of Karnataka State, India. It is planked on the east by the foothills of the Western Ghats and on the west by the Arabian Sea. The soils of the basin mainly consist of coastal alluvium and lateritic soils. Coastal alluvium is relatively rare and contains river sand and silt. Lateritic soils are formed on the crust of the lateritic hills. The soils are yellowish red to dark red, or reddish brown to brown in color. In texture, they vary from clay loam to gravelly sandy loam in the surface, and clay loam to gravelly sandy clay in the subsurface horizon. The study area has a hot humid climate. The climate of the region is marked by heavy rainfall (about 95%) during the southwest monsoon (June to September). The mean daily temperature from March to May is 35°C and from December to February is 23°C. Average values of evapotranspiration are about 5 mm/day during summer and 2.5 mm/day during winter. The area of catchment is 202.33 km^2. Soil sampling was carried out on a forested hillslopes of the Pavanje river basin. A total of fifty six soil samples were collected from eight different elevations distributed from the crest to the footslope. For the each elevation, physical properties and soil water retention data of seven soil layers with the thickness of 10, 20, 30, 40, 50, 60 and 75 cm were determined. During the last week of November 2011, the soil sampling was done from the forest land falling in the above said area.

2.2 Laboratory Measurements and Soil Sample Analysis

Cores were used for soil sampling and volume of the core was 1020 cm^3. All the undisturbed and disturbed soil samples collected were subjected to laboratory measurements to determine bulk density, particle-size distribution, specific gravity, porosity, organic carbon content and soil water retention characteristics.

Undisturbed soil samples were oven dried at 105°C to determine dry bulk density. Total porosity was calculated from the measured oven-dry bulk density and a soil particle density by using the relationship of (1-bulk density/particle density). Organic carbon content was determined with the Walkley and Black method (Nelson and Sommers 1982). Organic matter was then calculated by a factor of 1.724 (Van Bemmelen's Correction Factor). Particle-size distribution was determined using sieve analysis and hydrometer. Sand, silt and clay contents are expressed as a percentage by mass of the fine earth fraction and soil texture is identified according to the United States Department of Agriculture (USDA) system of particle-size classification.

Soil water retention data at 33, 100, 300, 500, 1000 and 1500 kPa matric potentials were measured using pressure plate apparatus. Soil samples were pressurized adequately and weighed at every potential. Point series of measured water retention data was fitted to an empirical closed form mathematical function. The most popular and widely used closed form water retention relations suggested by van Genuchten (vG), (1980) (Eq. (1)) and Brooks and Corey (B-C), (1964) (Eq. (2)) were used.

$$\theta(h) = \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^{(1-1/n)}} + \theta_r \quad \text{for} \quad h < 0 \tag{1}$$

$$\begin{aligned} \theta(h) &= \theta_r + (\theta_s - \theta_r)\left(\frac{h_b}{h}\right)^{\lambda} && \text{for } 0 < h < h_b \\ &= \theta_s && \text{for } h_b \le h \le 0 \end{aligned} \tag{2}$$

where θ, θ_s and θ_r are the volumetric water content, saturated water content and residual water contents (cm^3/cm^3) respectively, h is pressure potential, h_b is air entry pressure head, λ is pore size index, α, n and m are empirical shape parameters, where $m = 1 -$

$1/n$. Residual water content represents the soil moisture, when water in soil is immobile. The parameter α is approximately equal to the inverse of the pressure head at the point, where $d\theta/dh$ has maximum value. The dimensionless parameter n expresses the steepness of the curve. The parameters (θ_r, α, n, h_b and λ) of both the hydraulic models (Eqs. 1 and 2) were fitted to the water retention data using a nonlinear least squares optimization program, Retention Curve Program for Unsaturated Soils (*RETC*) (van Genuchten *et al*. 1991).

A pedotransfer function acts as a tool for generating the soil hydraulic characteristics by using a more or less complicated algorithm with combinations of the soil physical and chemical properties, primarily texture, bulk density and organic matter content. Two types of PTFs were developed to estimate the soil water retention curve. Each of the water contents at selected water potentials (33, 100, 300, 500, 1000 and 1500 kPa) and fitted parameters of both models were related to basic soil properties sand (*S*), silt (*Si*), clay (*C*), bulk density (*BD*), Porosity (*P*) and organic matter content (*OM*) using multiple nonlinear regression techniques in order to develop PTFs. The most significant input variables were determined using backwards stepwise method, and then linear, quadratic, and possible interaction terms of these basic soil properties were investigated using the statistical analysis system.

The general form of the resulted regression equations can be expressed as:

$$\begin{aligned} Y = b_0 &+ b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 \\ &+ b_6X_1^2 + b_7X_2^2 + b_8X_3^2 + b_9X_4^2 + b_{10}X_5^2 \\ &+ b_{11}X_1X_2 + b_{12}X_2X_3 + b_{13}X_3X_4 + b_{14}X_4X_5 + b_{15}X_5X_1 \end{aligned} \tag{3}$$

where Y represents the dependent variable such as water content at selected water potential or one of the parameters of the retention models, b_0 is the intercept, b_1, b_2, …, b_{15} are the regression coefficients and X_1, X_2, X_3, X_4, X_5 are the independent variables representing the basic soil properties.

Forty two soil samples were used in the derivation and the remaining fourteen soil samples were used in the validation of PTFs. The performances of point and parametric PTFs in predicting the water retention were evaluated using coefficient of determination (R^2), root mean square error (RMSE) and mean error (*ME*). Under and over prediction of PTFs for given parameter are represented by positive and negative values of *ME* respectively. *ME* is a measure of prediction bias. RMSE defines the expected magnitude of the prediction error. Smaller value of RMSE indicates smaller deviation, or higher agreement between the predicted and measured values. The best condition will give a smaller RMSE and *ME* and greater R^2.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y}_i)^2} \tag{4}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{N}} \tag{5}$$

$$ME = \frac{\sum_{i=1}^{N} (y_i - \hat{y}_i)}{N} \tag{6}$$

where y_i denotes the measured value, $\hat{y}_i$ refers to the predicted value, $\bar{y}_i$ represents the average of the measured values of y, and N is the total number of observations.

3. RESULTS AND DISCUSSION

Some basic statistics (minimum, maximum, mean, and standard deviation) of soil physical and hydraulic properties used in the derivation and validation of PTFs is summarized in Table 1. Soils used in this study had wide ranges of physical properties. These soil samples were taken from the different soil profiles from the surface layer down to 75 cm. The most of the soils (about 55%) were sandy loam textured and remaining was loamy sand (47%) and sandy textured (3%). In present study, all the soil layers had high sand contents, ranging from 43 to 74%, silt contents ranging from 24 to 54% and clay contents of around 0 to 6%, bulk density increased with soil depth, ranging from 1.22 to 1.69 g/cm^3 and organic matter content ranges from 0.65 to 5.96% for the derivation data set. The amount of the organic matter was decreasing towards the bottom layer. The data used in the validation set also have the similar physical properties. The lab measurements showed that the sampled soils were more or less homogeneous and assumed as coarse-textured based on the mean sand fraction, bulk density and organic matter content. Soils were classified as loamy sand, sandy loam, and sand based on USDA system of particle-size classification.

Table 2 shows the water retention data obtained from the laboratory experiments by using pressure plate apparatus and fitted parameters of van Genuchten and Brooks-Corey model (θ_r, α, n, h_b and λ). Present study considered six pressure heads (33, 100, 300, 500, 1000 and 1500 kPa) and measured the moisture retention data for the forty two soil samples. Afterwards water retention data of each soil samples were fitted to van Genuchten and Brooks and Corey model by using a nonlinear least squares curve fitting procedure based on the Marquardt method as developed in the RETC software package (van Genuchten *et al*. 1991). For the loamy sands, water contents were varying from 0.17 to 0.20 (cm^3/cm^3) at 33 kPa and from 0.06 to 0.09 (cm^3/cm^3) at 1500 kPa. In sandy soils water contents varied from 0.18 to 0.19 (cm^3/cm^3) at 33 kPa and 0.06 (cm^3/cm^3) at 1500 kPa. However, in sandy loam textured soils, water content drastically increased from 0.18 to 0.28 (cm^3/cm^3) at 33 kPa and from 0.07 to 0.13 (cm^3/cm^3) at 1500 kPa. As the matric potential increased, the water content decreased. This was mainly because the water retained at lower tensions had a greater relation to soil structure, while at higher tensions it was related to particle size distribution and soil mineralogy. Figure 1 shows the moisture retention curves for different types of soil textural group in Pavanje river basin.

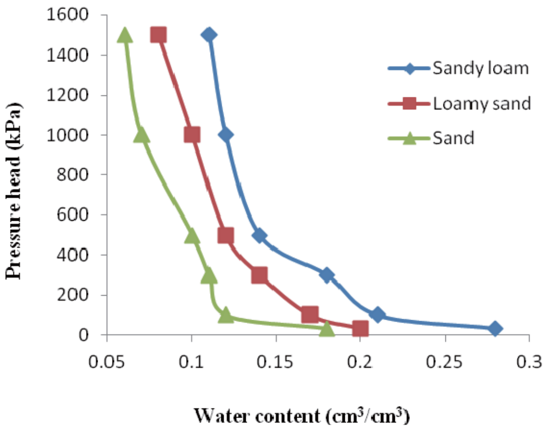

Fig. 1 Soil moisture retention curves for different types of soils

Pedotransfer functions can be generated when some of the basic soil properties like particle size distribution, soil mineralogy, bulk density, porosity and organic matter content are known. Each of the water contents at selected water potentials of 33, 100, 300, 500, 1000, and 1500 kPa and parameters of both models (van Genuchten model and Brooks and Corey model) were related to basic soil properties (*S*, *Si*, *C*, *BD*, *P* and *OM*) using multiple nonlinear regression techniques in order to develop PTFs. For the initial estimate of the θ_r, we considered the value at permanent wilting point. The saturated water content is often considered to be identical to the porosity, but, in practice, it can be smaller than the porosity because, in the field saturated condition, the pores are entrapped with air. Therefore in our study we considered θ_s as 0.93 times of soil porosity and it was considered same for both the van Genuchten and Brooks-Corey model. PTFs developed for the estimation of water contents at selected water potentials and parameters of water retention models are summarized in Table 2.

Firstly, multiple linear regression equations were used for the development of PTFs by considering the basic soil properties (mentioned in the Table 1) as an input to the equation. In terms of coefficient of determination (R^2), multiple linear regressions had high representative values for θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000}, θ_{1500} and θ_s and but low values for the parameters of θ_r, α, n, h_b and λ. The poor prediction of θ_r, α, n, h_b and λ may be due to several reasons. Measurement errors might also cause the poor prediction of the parameters (Tomasella *et al*. 2003). Minasny *et al*. (1999) stated that regression could not be used to predict van Genuchten model parameters because there was no linear relationship between the parameters and soil properties. This problem can be solved by using nonlinear regression (Minasny *et al*. 1999). Therefore in order to improve the R^2 values, nonlinear regression equations were later considered. These equations increased the efficiency of the models effectively by increasing the R^2 values. Overall, PTFs performed better in estimation of water contents at selected water potentials than in estimation of parameters of both water retention models based on the R^2 and RMSE values.

Secondly, nonlinear regression equations were developed with different combinations of input variables to improve the efficiency of the models. For both the PTFs (point and parametric), we used the different combinations of input variables such as sand, silt, bulk density, porosity and organic matter content and observed that water contents at selected pressure heads (point PTFs) have good relationship with the basic soil properties. In van Genuchten and Brooks-Corey model, the saturated water content (θ_s) had the better efficiency than the other parameters. But overall the R^2 values for the B-C model parameters were relatively less when compared to van Genuchten model parameters.

Table 1 Descriptive statistics for physical and hydraulic properties of soils used in derivation and validation of PTFs

Variables	Derivation data set				Validation data set			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Physical properties								
S (%)	43	74	62.08	7.32	58	73	64.34	4.65
Si (%)	24	54	35.90	7.07	27	41	35.08	4.24
C (%)	0	6	2.02	1.62	0	2	0.58	0.82
BD (g /cm^3)	1.22	1.69	1.47	0.13	1.31	1.49	1.39	0.06
OM (%)	0.65	5.96	2.29	1.45	0.91	7.50	2.60	2.09
P (cm^3/cm^3)	0.32	0.52	0.42	0.06	0.41	0.48	0.45	0.02
Soil moisture retention data								
θ_{33}	0.17	0.28	0.22	0.03	0.18	0.26	0.22	0.03
θ_{100}	0.12	0.22	0.17	0.03	0.15	0.23	0.18	0.02
θ_{300}	0.11	0.20	0.15	0.02	0.13	0.19	0.15	0.02
θ_{500}	0.10	0.17	0.13	0.02	0.11	0.16	0.13	0.01
θ_{1000}	0.07	0.15	0.10	0.02	0.10	0.13	0.11	0.01
θ_{1500}	0.06	0.13	0.09	0.02	0.08	0.11	0.09	0.01
van Genuchten parameters								
θ_r	0.00	0.08	0.02	0.03	0.00	0.05	0.01	0.01
θ_s	0.3	0.47	0.39	0.05	0.38	0.45	0.42	0.02
α	0.01	0.21	0.06	0.06	0.01	0.27	0.09	0.09
n	1.17	1.31	1.24	0.03	1.18	1.31	1.23	0.03
Brooks-Corey parameters								
θ_r	0	0.07	0.01	0.02	0.00	0.02	0.01	0.01
θ_s	0.3	0.47	0.39	0.05	0.38	0.45	0.42	0.02
h_b	2.44	79.37	30.17	20.78	3.48	71.43	23.18	20.40
λ	0.13	0.29	0.22	0.04	0.18	0.24	0.21	0.02

Note: *S*, *Si*, *C* are sand, silt, clay fractions (%), respectively, *BD* is bulk density (g /cm^3), *OM* is organic matter content (%), *P* is porosity (cm^3/cm^3), θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of 33, 100, 300, 500, 1000 and 1500 kPa, respectively, θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3) respectively, α is the inverse of air entry pressure head (cm^{-1}), h_b is air entry pressure head, λ is pore size index and *n* is the empirical shape parameters, *SD* is standard deviation.

Table 2 PTFs developed for estimation of water contents at selected water potentials and parameters of water retention models

Pedotransfer functions developed	R^2
Water contents at specific matric potentials	
$\theta_{33} = 0.394 - 0.00446 \times Si - 0.705 \times P - 0.05302 \times OM + 0.00009 \times Si^2 + 0.0047 \times Si \times P - 0.00036 \times Si \times OM + 0.438 \times P^2 + 0.194 \times P \times OM - 0.00138 \times OM^2$	0.82
$\theta_{100} = 0.913 - 0.0045 \times Si - 0.978 \times BD + 0.04762 \times OM + 0.00011 \times Si^2 + 0.00143 \times Si \times BD - 0.00081 \times Si \times OM + 0.300 \times BD^2 - 0.0109 \times BD \times OM + 0.00013 \times OM^2$	0.84
$\theta_{300} = 0.456 - 0.00313 \times Si - 0.42 \times BD + 0.03818 \times OM + 0.00008 \times Si^2 + 0.00101 \times Si \times BD - 0.00043 \times Si \times OM + 0.128 \times BD^2 - 0.0150 \times BD \times OM + 0.00042 \times OM^2$	0.86
$\theta_{500} = -0.0783 + 0.0049 \times Si + 0.264 \times BD - 0.04769 \times OM + 0.000009 \times S^2 - 0.0046 \times S \times BD + 0.000435 \times S \times OM - 0.06784 \times BD^2 + 0.0328 \times BD \times OM - 0.00168 \times OM^2$	0.80
$\theta_{1000} = 0.044 + 0.01199 \times Si + 0.0187 \times BD - 0.0577 \times OM - 0.00007 \times Si^2 - 0.00565 \times Si \times BD + 0.0006 \times Si \times OM - 0.01989 \times BD^2 + 0.0413 \times BD \times OM - 0.0016 \times OM^2$	0.86
$\theta_{1500} = -0.111 - 0.0027 \times S + 0.637 \times P + 0.06313 \times OM - 0.000008 \times S^2 + 0.0089 \times S \times P + 0.00004 \times S \times OM - 0.652 \times P^2 - 0.132 \times P \times OM - 0.00027 \times OM^2$	0.82
van Genuchten model Parameters	
$\theta_r = -0.318 - 0.00402 \times S + 1.501 \times P + 0.07159 \times OM - 0.000018 \times S^2 + 0.01964 \times S \times P - 0.000752 \times S \times OM - 2.498 \times P^2 - 0.09407 \times P \times OM + 0.000032 \times OM^2$	0.68
$\theta_s = 0.501 + 0.0074 \times Si + 0.06746 \times BD + 0.02488 \times OM - 0.000004 \times Si^2 - 0.00461 \times S \times BD - 0.000295 \times Si \times OM - 0.110 \times BD^2 - 0.00820 \times BD \times OM - 0.000408 \times OM^2$	0.98
$\alpha = 0.662 - 0.02181 \times S - 1.709 \times P + 0.09568 \times OM + 0.000134 \times S^2 + 0.03547 \times S \times P - 0.000982 \times S \times OM + 1.011 \times P^2 - 0.194 \times P \times OM + 0.0038 \times OM^2$	0.91
$n = 0.04352 + 0.00883 \times S + 1.146 \times BD + 0.192 \times OM - 0.000125 \times S^2 + 0.00304 \times S \times BD - 0.00121 \times S \times OM - 0.362 \times BD^2 - 0.105 \times BD \times OM + 0.000365 \times OM^2$	0.62
Brooks-Corey model Parameters	
$\theta_r = -0.01045 - 0.00121 \times S - 0.00174 \times Si + 0.22762 \times P - 0.00005 \times S^2 - 0.000043 \times Si \times S \times Si + 0.01675 \times S \times P - 0.00004 \times Si^2 + 0.01543 \times Si \times P - 1.60115 \times P^2$	0.62
$h_b = 117.57 + 12.64 \times S - 3.291 \times Si - 1461.8 \times P - 0.07759 \times S^2 + 0.120 \times S \times Si \times BD - 23.60 \times S \times P + 0.07552 \times Si^2 - 11.39 \times Si \times P + 3251.2 \times P^2$	0.74
$\lambda = 0.32345 + 0.01437 \times S - 0.980 \times P - 0.1545 \times OM - 0.00009 \times S^2 - 0.01908 \times S \times BD \times P + 0.000002 \times S \times OM + 1.29507 \times P^2 + 0.34940 \times P \times OM - 0.00067 \times OM^2$	0.70

Note: θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of 33, 100, 300, 500, 1000 and 1500 kPa, respectively, S, Si are sand and silt fractions (%), BD is bulk density (g/cm^3), OM is organic matter content, P is porosity (cm^3/cm^3), θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3), respectively, α and n are vG model parameters, h_b and λ are B-C model parameters. R^2 is coefficient of determination.

The performances of point and parametric PTFs in predicting the measured or fitted data were evaluated using R^2, RMSE and *ME*. Derivation and validation accuracies of PTFs between measured or fitted and predicted water contents and model parameters are tabulated in Table 3.

All the three statistical measures were used to compare the water contents at several suction points and parameters of van Genuchten and Brooks-Corey model parameters. Accuracy of each method with derivation data set was slightly better than validation accuracies. Ahuja *et al.* (1985) applied the point based estimation to the Southern plain database and obtained the accuracy of RMSE is about 0.05(m^3/m^3). Schaap and Leij (1998) applied the parametric estimation method to three databases and obtained overall RMSE of about 0.1(m^3/m^3). In this study the obtained RMSE value for point based estimation was about 0.01(m^3/m^3) for both derivation and validation sets (Table 3).

Pachepsky *et al.* (1996) reported relatively high prediction accuracies, $R^2 = 0.738 - 0.984$, between measured and predicted water contents at 8 selected water potentials. Similarly, Batjes (1996) developed PTFs for water contents at 10 different water potential with the equation accuracies between $R^2 = 0.880 - 0.940$. Vereecken *et al.* (1992) found that estimation accuracies of PTFs for van Genuchten parameters ranged between 0.560 – 0.848 (R^2). Wösten *et al.* (1995) derived PTFs for estimation of these parameters in sandy soils with the accuracy of $R^2 = 0.71$, 0.53 and 0.63 for θ_r, α and n respectively. Tomasella *et al.* (2000) also developed regression PTFs for Brazilian soils with the equation accuracy of 0.83, 0.84, 0.41and 0.37 for θ_r, θ_s, α and n respectively. In our study we reported relatively high prediction

Table 3 Derivation and validation accuracies of PTFs between measured (fitted) and predicted water contents and model parameters

Variables	Derivation			Validation		
	R^2	RMSE	*ME*	R^2	RMSE	*ME*
θ_{33}	0.812	0.0122	0.0000	0.631	0.0153	–0.0020
θ_{100}	0.844	0.0114	0.0000	0.652	0.0128	–0.0005
θ_{300}	0.862	0.0085	0.0000	0.617	0.0137	0.0053
θ_{500}	0.804	0.0082	0.0000	0.718	0.0094	–0.0062
θ_{1000}	0.861	0.0082	0.0000	0.613	0.0178	0.0015
θ_{1500}	0.819	0.0086	0.0000	0.672	0.0137	–0.0108
vG parameters						
θ_r	0.681	0.0159	0.0008	0.632	0.0098	–0.0035
θ_s	0.977	0.0074	0.0000	0.747	0.0105	0.0022
α	0.913	0.0168	0.0000	0.855	0.0344	–0.0083
n	0.623	0.0178	–0.0005	0.587	0.0172	–0.0033
B-C parameters						
θ_r	0.621	0.0107	–0.0009	0.587	0.0039	–0.0011
h_b	0.743	0.0231	–0.0062	0.566	0.0336	–0.0036
λ	0.704	0.0205	0.0000	0.667	0.0124	0.0001

Note: θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of 33, 100, 300, 500, 1000 and 1500 kPa respectively, θ_r and θ_s are residual and saturated soil water contents (cm^3/cm^3) respectively, α and n are vG model parameters, h_b and λ are B-C model parameters. R^2 is coefficient of determination, RMSE is root mean square error, *ME* is mean error.

accuracies of R^2 = (0.804 – 0.862) and (0.613 – 0.718) for derivation and validation sets respectively between measured and predicted water contents at 6 selected water potentials. The accuracy of vG model parameters was 0.681, 0.977, 0.913 and 0.623 for θ_r, θ_s, α and n respectively and for B-C model it was 0.621, 0.743 and 0.667 for θ_r, h_b and λ respectively for the derivation sets. Thus the present study concludes that the prediction accuracies of point PTFs were slightly better than parametric PTFs.

Accuracies of point and parametric (by van Genuchten and Brooks-Corey models) predictions of water contents at selected water potentials on water retention curves are presented in Table IV for both derivation and validation sets. The corresponding graphs are plotted and given in Figs. 2, 3, 4 for easier understanding of the comparative accuracies of the developed models. Application of two methods (point and parametric) to estimate soil water retention curve gave strictly different results, even though the equation to fit water retention curves and soil properties used as predictors were the same for both methods. Point estimation method needs less input variables in predicting water retention curve with relatively high accuracy (high R^2 and low RMSE), but parametric estimation of water retention curve (van Genuchten or Brooks-Corey model) with better accuracy is preferred especially for producing continuous functions of water retention used in water and solute transport modeling studies.

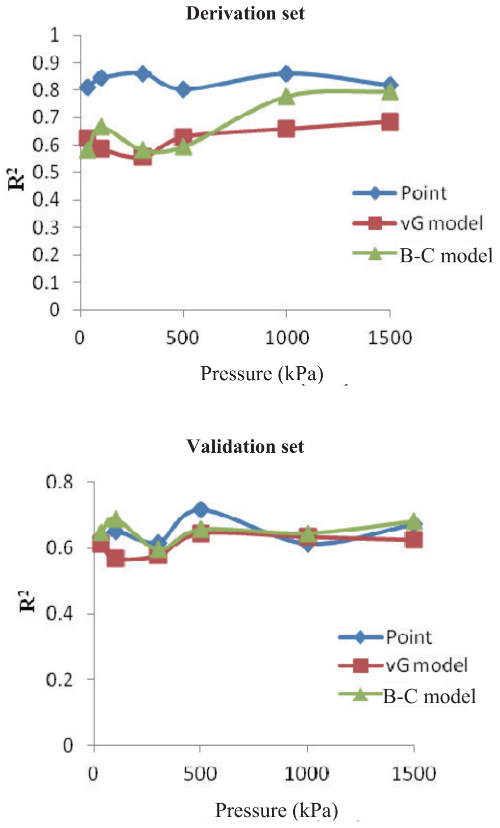

Fig. 2 Comparison graphs of error analysis in terms of R^2 values

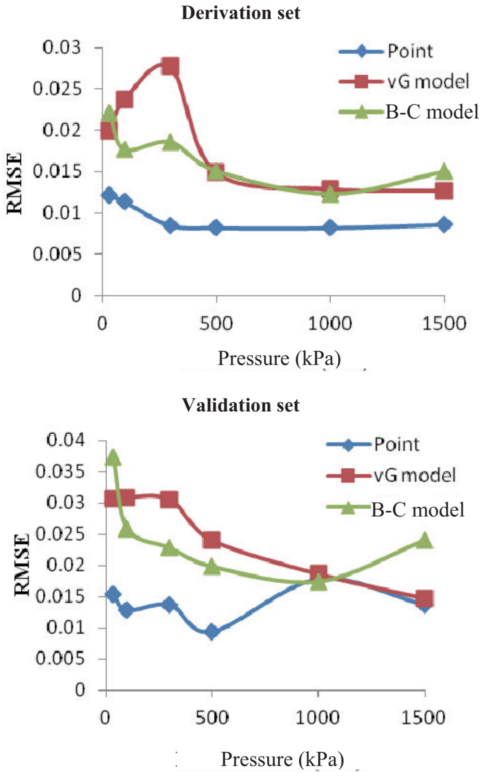

Fig. 3 Comparison graphs of error analysis in terms of RMSE values

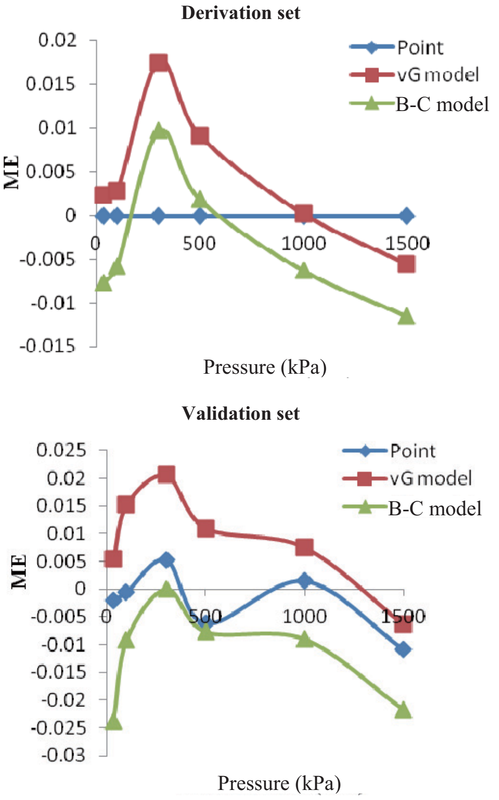

Fig. 4 Comparison graphs of error analysis in terms of ME values

Several factors could contribute in the superiority of the point method over the parametric method in this work. The difference in data used could not contribute since the same dataset has been used to calibrate and validate both methods, and both point and parametric data were optimized using sum of squared differences between measured and simulated water contents. It is therefore theoretically possible that regression based method would perform better on point data than on parametric data. It is well known that a group of basic soil properties are more important in the wet range of the water retention curve, while other properties control the variability on the dry range. Shape parameters of the analytical water retention curve, on the other hand, describe its behavior both in the dry and wet range. Therefore, the most probable explanation for a better performance of the point over the parametric method is that relationship between water retention parameters and basic soil properties is highly complex and cannot be accurately described by the parametric method. Figure 5 shows the soil water retention curve for three different types of soils of Pavanje river basin by using four different methods explained earlier.

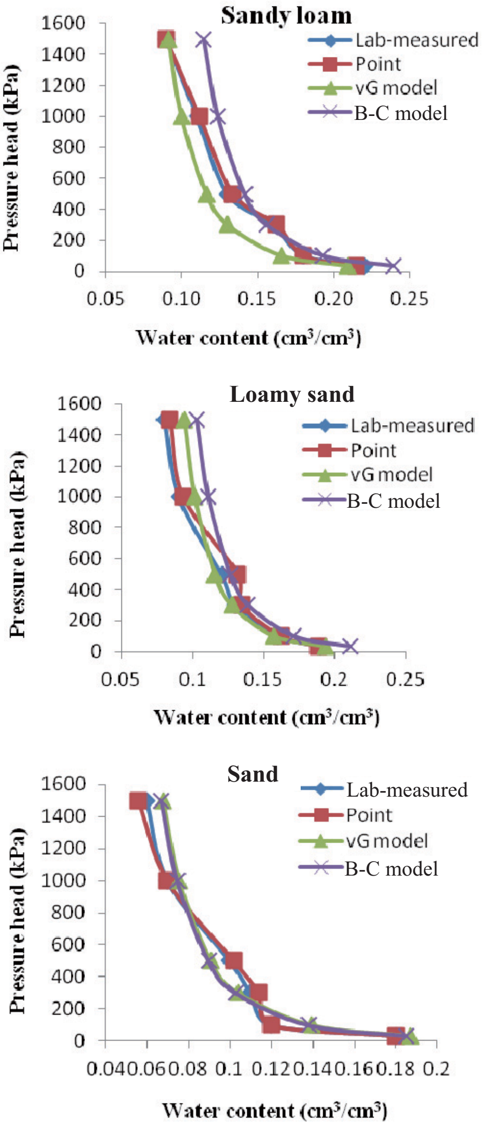

Fig. 5 **Comparative analysis graph of soil moisture retention values obtained by different methods**

Schaap and Bouten (1996) observed not much differences between the two methods (point and parametric). However, their database consisted mostly of coarse soils. The present study also came up with almost similar observations for the sandy textured soils. The analysis done here, suggests that more input variables are necessary to improve the prediction of water retention curve and the differences between the field and laboratory values of water retention data might be associated to the sample quality, spatial variation, hysteresis, scale effects, *etc*. The prediction of soil water retention curve using PTFs by point estimation method for soils lying in the coastal region of India is of relatively considerable accuracy (best case $R^2 = 0.862$), whereas parametric estimation method (van Genuchten and Brooks and Corey models) performs slightly lower in predicting the parameters.

4. CONCLUSIONS

Pedotransfer functions are widely used to estimate water retention characteristics from more easily measurable soil properties. The majority of pedotransfer functions developed were established based on the measurements in samples taken from arable land. However, the pedotransfer functions established in this paper are based exclusively on samples from forest soils. Here we presented the development and validation of point and parametric PTFs for the estimation of water retention curve from basic soil properties using multiple nonlinear regression technique and comparison of the performances of point and two parametric methods criteria. There was a slight difference among the two methods (point, vG and B-C model) in predicting water retention curves, but the point-based method was superior to the parametric method of PTFs development for Pavanje river basin soils (Table 4). This might be explained by the fact that moisture

Table 4 **Accuracies of point and parametric (by vG and B-C models) predictions of soil water retention curves for derivation and validation data set**

Variables	R^2			RMSE			*ME*		
	Point	vG	B-C	Point	vG	B-C	Point	vG	B-C
Derivation data set									
θ_{33}	0.812	0.626	0.585	0.0122	0.0199	0.0221	0.0000	0.0023	–0.007
θ_{100}	0.844	0.586	0.665	0.0114	0.0237	0.0177	0.0000	0.0028	–0.005
θ_{300}	0.862	0.556	0.582	0.0085	0.0277	0.0186	0.0000	0.0175	0.0097
θ_{500}	0.804	0.629	0.595	0.0082	0.0149	0.0151	0.0000	0.0091	0.0018
θ_{1000}	0.861	0.659	0.777	0.0082	0.0129	0.0123	0.0000	0.0002	–0.006
θ_{1500}	0.819	0.685	0.795	0.0086	0.0127	0.0150	0.0000	–0.005	–0.011
Validation data set									
θ_{33}	0.631	0.612	0.648	0.0153	0.0307	0.0373	–0.0020	0.0054	–0.0238
θ_{100}	0.652	0.568	0.689	0.0128	0.0309	0.0259	–0.000	0.0152	–0.0091
θ_{300}	0.617	0.578	0.596	0.0137	0.0305	0.0228	0.0053	0.0206	0.0000
θ_{500}	0.718	0.645	0.656	0.0094	0.0240	0.0198	–0.006	0.0110	–0.007
θ_{1000}	0.613	0.634	0.645	0.0178	0.0186	0.0174	0.0015	0.0075	–0.009
θ_{1500}	0.672	0.625	0.681	0.0137	0.0147	0.0240	–0.010	–0.006	–0.021

Note: θ_{33}, θ_{100}, θ_{300}, θ_{500}, θ_{1000} and θ_{1500} are soil water contents θ (cm^3/cm^3) at matric potentials of 33, 100, 300, 500, 1000 and 1500 kPa, respectively, point is point prediction, vG is van Genuchten model, B-C is Brooks-Corey model, R^2 is coefficient of determination, RMSE is root mean square error, *ME* is mean error.

content is controlled by different independent variables at different water potentials and PTFs developed for point-based method allows for a more appropriate combination of those independent variables. In point estimation, limited discrete points on water retention curves are estimated; otherwise, it is time-consuming and needs intensive efforts especially for large and spatially variable lands. However, parametric estimation methods yield continuous water retention functions in less time and effort.

Since the soils used in this study are relatively sandy-textured, PTFs developed in this study can be used for the estimation of soil water retention data for the soils in the region under consideration. Even though there are some prediction errors, the results may be accurate enough to predict soil water retention curve with PTFs, especially where the water retention data are not available.

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