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Evaluation of soil moisture retention characteristics using pedo-transfer functions for soils of dry semi-arid region

M. Lalitha[1,*], S. Dharumarajan[1], K.S. Anil Kumar[1], Shivanand[1], S. Parvathy[1], Arti Koyal[1], B. Kalaiselvi[1], Rajendra Hegde[1] and S.K. Singh[2]

[1]ICAR-National Bureau of Soil Survey and Land Use Planning, Regional Centre, Bangalore ; [2]ICAR-National Bureau of Soil Survey and Land Use Planning, Nagpur.

**Corresponding author:*
E-mail: mslalit@yahoo.co.in (M. Lalitha)

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ABSTRACT

Soil moisture assessment is crucial factor for crop growth and development in arid and semi-arid regions of India where the impact of climate change is predominant. Soil moisture prediction models using pedo-transfer functions are helpful for predicting soil moisture using soil variables since direct estimation is expensive and time-consuming. In the present study, three different models- Gupta and Larson, Rawls and Brakensiek, and Walczak models were employed to predict soil moisture of dry semi-arid region of Tamil Nadu, India. The results revealed that Gupta and Larson, and Rawls and Brakensiek models (R^2: θ_{FC}: 0.790 and θ_{PWP}: 0.899) performed better than Walczak model for predicting soil moisture, both at θ_{FC} and θ_{PWP}. However, an exclusive pedo-transfer function for predicting soil moisture was developed for semi arid region using variables selected through principal component analysis (PCA) and variable importance plot. Soil variables such as sand, silt, cation exchange capacity (CEC), exchangeable magnesium and soil electrical conductivity (EC) contributed significantly (P>0.05) to the soil moisture retention. Nevertheless, the model developed in the study resulted in more accurate estimation at 33 kPa (R^2 = 0.887) and 1500 kPa (R^2 = 0.932) matric suction compared to existing models. The developed models can be helpful for predicting soil hydraulic properties in dry semi-arid region with similar agro-ecological conditions.

Key words:
Dry semi-arid region
Matric suction
Pedo-transfer function
Soil moisture retention
Soil variables

1. INTRODUCTION

Plant available water is the amount of water stored in soil which is readily available to plants. It is important for crop growth and development, and depends mainly on soil properties. Plant available water in soil is measured by soil moisture retention, which is a hydro-physical characteristic of soil expressed as the dependence between soil water content and soil water potential. It is defined as water content of the soil at matric potential between 33 kPa (Field Capacity) and 1500 kPa (Permanent Wilting Point). The measurement of these soil water constants is both time and labour consuming and requires expensive special equipment. Mathematical models based on soil properties, otherwise known as pedo-transfer functions or equations have been proposed by many researchers to overcome these difficulties (Saxton and Rawls, 2006). Pedo-transfer functions are typically regression equations derived from soil profile data sets. Among the soil properties, proportions of sand, silt, and clay in soil, soil organic matter, bulk density (BD), porosity, soil mineralogy, pH of soil solution, soil structure and surface area of soil particles are important factors which influence the soil moisture retention characteristics. Of these, soil structure highly correlates with water retained at lower tension, and that retained at higher tension is related to particle size distribution and soil mineralogy (Rawls *et al.*, 1991). While the soil texture determines the matric pore systems, soil structure referred by aggregation led macro-pores control the water retention at lower tensions (Lipsius, 2002). Many models were developed by researchers throughout world and in India for estimating soil moisture at different suctions (Gupta and Larson, 1979; Rawls and Brakensiek, 1982; Kaur *et al.*, 2002, Patil *et al*., 2013; Dharumarajan *et al*., 2019). But the pedo-transfer models are region specific and the models developed for temperate regions may not be suitable for tropical region, where the edapho-climatic properties are different. Hence their application in tropical regions may not be feasible (Santra and Das, 2008). The same was confirmed by Botula *et al*. (2012) who found that the temperate climate pedo-transfer functions of Gupta and Larson (1979) and Rawls and Brakensiek (1982) largely overestimated water retention of soils in humid tropics, because the accumulation of Fe and Al in tropics and secondary calcium carbonate in arid and semi-arid condition tends to create soil mineralogy and soil structure, which are less common in temperate regions (Hodnett and Tomasella, 2002). Hence, there is always a need to validate the established models before estimating soil water potential for other regions. Similarly, there are no comprehensive pedo-transfer functions available for dry semi-arid region. In this context, the present study was aimed to develop pedo-transfer functions for field capacity and permanent wilting point for dry semi-arid regions of south India.

2. MATERIALS AND METHODS

Study Area

The study area, Kangayam grasslands, comes under the physiographic region of Tamil Nadu uplands and is one of the driest region of southern India. It lies between 77°43'19" and 77°27'06"E longitudes and 10°54'55" and 11°07'39"N latitudes characterised by ustic soil moisture and hyperthermic soil temperature regimes (Soil Survey Staff, 2003). The climate is semi-arid (dry) with mean annual rainfall (523 mm) ranging from 90 mm to 788 mm. The satellite imagery IRS Resourcesat-2 LISS IV (5.8 m resolution) in conjunction with Survey of India toposheets (1:50,000 scale) was used for the preparation of base maps showing land use and landform. Rainfed agriculture is predominant, and about 10% of the cultivated areas are irrigated with canal water. Major land use is agroforestry system in which field crops *viz.,* maize (*Zea mays*), horse gram (*Macrotyloma uniflorum*) and groundnut (*Arachis hypogaea*) are inter-cropped with tree spp. (predominantly *Acacia nilotica*). The length of the growing period (LGP) is 90–120 days.

Soil Sampling and Analysis

Profile locations were identified based on landform, land use and slope characteristics for the detailed characterization of soil resources (Natarajan and Sarkar, 2010). Soil profiles in the cultivated fields were studied in catenary sequence for their morphological characteristics (Fig. 1). A total of 110 soil profiles were studied, and horizon-wise soil samples (138) from 32 soil profiles representing twelve identified soil series were collected. The morphological properties of one representative pedon from each soil series are presented in Table 1. The samples were air-dried, grounded, sieved (<2 mm) and analysed for soil physical and chemical properties. Particle size analysis was carried out by international pipette method (Piper, 1966); soil pH and EC were measured in 1:2.5 soil : water suspension (Whitney, 1998). Gravimetric water contents at −33 kPa and −1500 kPa were estimated by pressure plate apparatus (Klute, 1986), and BD by core method (Blake and Hartge, 1986). Organic carbon (OC) was determined by Walkley and Black (1934) method. Calcium carbonate ($CaCO_3$) equivalent (%) was determined by Piper (1966) method. CEC was determined by neutral normal ammonium acetate method. The ESP was calculated using the formula given by USDA (Richards, 1954). The soils were classified according to soil taxonomy (Soil Survey Staff, 2003). The soil series identified are *Aridic Lithic Ustorthents, Typic Haplustepts, Typic Rhodustalfs, Aridic Haplustepts, Calcic Haplustalfs* and *Typic Haplustalfs*.

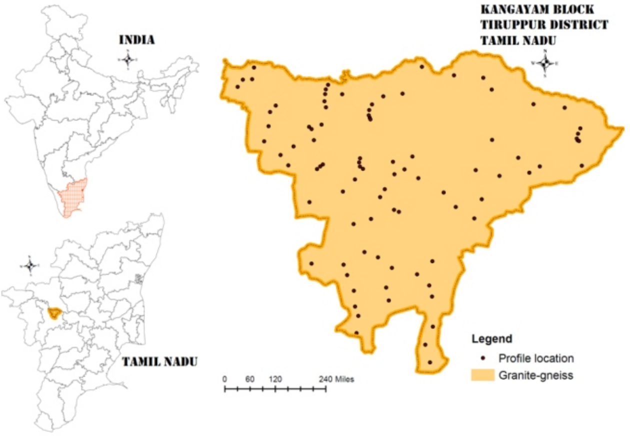


Fig. 1. Geological formation and profile location in Kangayam block

Model Developed

The soil properties analysed in laboratory were evaluated through PCA to select the most important variables or predictors for constructing new algorithm using XLSTAT program. Principal components (PCs) with eigen values more than one were selected (Kaiser, 1960) and further in each PC, the highly weighted variables were selected for further analysis of variable importance by classification and regression random forests method in XLSTAT program (ntree = 500, mtry = 3). The same were correlated using SPSS software (Waswa *et al*., 2013). Mean increase error and multivariate correlation coefficients were used to verify the degree of redundancy and variable selection (Andrews and Carroll, 2001). The most important variables selected were used to develop algorithms for estimating field capacity at –33 kPa and permanent wilting point at -1500 kPa. The results were validated using cross-validation techniques.

Models Investigated

Three popular models *viz.,* Gupta and Larson (1979), Rawls and Brakensiek (1982) which is the modification of

Table: 1
Morphological properties and taxonomy of typifying pedon of soil series used in the study

Pedon No. and Depth (cm)	Horizon	Soil colour	Texture (M)	Structure	Effervescence
P1:Loamy-skeletal, mixed, isohyperthermic Typic Rhodustalfs					
0-14	Ap	Dark red (2.5YR 3/6)	Loamy sand	Sub-angular blocky	Nil
14-39	Bt1	Dark red (2.5YR 3/6)	Sandy loam	Sub-angular blocky	Nil
P2:Loamy-skeletal, mixed isohyperthermic Typic Rhodustalfs					
0-11	A	Dark brown (7.5YR 4/4)	Sand	Granular	Nil
11-19	Bw	Yellowish red (5YR 4/6)	Loamy sand	Granular	Nil
19-33	Bt1	Dark red (2.5Y 3/6)	Sandy loam	Sub-angular blocky	Nil
33-42	Bt2C	Dark red (2.5YR 3/3)	Sandy loam	Sub-angular blocky	Nil
42-56	CB	Red (2.5YR 4/8)	Sandy loam	Massive	Nil
P3:Loamy-skeletal, mixed, calcareous isohyperthermic Calcic Haplustalfs					
0-15	Ap	Reddish brown (5YR 3/4)	Sandy loam	Sub-angular blocky	Slight
15-47	Bt1	Reddish brown(5YR 4/4)	Sandy clay loam	Sub-angular blocky	Strong
47-52	Bt2	Yellowish red (5YR 4/6)	Sandy loam	Sub-angular blocky	Strong
P4:Loamy-skeletal, mixed, calcareous isohyperthermic Typic Haplustalfs					
0-13	Ap	Dark yellowish brown (10YR 3/4)	Clay loam	Sub-angular blocky	Slight
13-32	Bt1	Dark brown (7.5YR 3/4)	Clay loam	Sub-angular blocky	Slight
32-67	Bt2	Dark reddish brown (5YR 3/4)	Clay	Sub-angular blocky	Slight
67-90	Bt3	Dark reddish brown (5YR 3/4)	Clay	Sub-angular blocky	Strong
P5:Loamy, mixed, isohyperthermic Typic Haplustalfs					
0-22	Ap	Dark brown (10YR 4/4)	Loamy sand	Sub-angular blocky	Nil
22-49	Bt1	Yellowish red (5YR 4/6)	Sandy loam	Sub-angular blocky	Nil
49-78	Bt2	Yellowish red (5YR 4/6)	Sandy loam	Sub-angular blocky	Nil
78-105	Bt3	Yellowish red (5YR 4/6)	Sandy loam	Sub-angular blocky	Nil
105-140	Bt4	Yellowish red (5YR 4/6)	Sandy clay loam	Sub-angular blocky	Nil
P6:Loamy-skeletal, mixed, isohyperthermic Aridic Rhodustalfs					
0-10	Ap	Reddish brown (5YR 4/3)	Sandy loam	Sub-angular blocky	Nil
10-29	Bt1	Reddish brown (5YR 4/3)	Sandy loam	Sub-angular blocky	Slight
29-59	Bt2	Dark reddish brown (2.5YR 3/4)	Sandy clay loam	Sub-angular blocky	Nil
59-95	Bt3	Dark reddish brown (2.5YR 3/4)	Sandy clay loam	Sub-angular blocky	Nil
95-123	Bt4	Dark reddish brown (2.5YR 3/4)	Sandy clay loam	Sub-angular blocky	Nil
P7:Loamy-skeletal, mixed, calcareous isohyperthermic Aridic Lithic Ustorthents					
0-22	Ap	Dark brown (7.5YR 3/4)	Sandy loam	Sub-angular blocky	Nil
P8: Loamy, mixed, calcareous isohyperthermic Typic Haplustepts					
0-13	Ap	Dark brown (10YR 3/3)	Sandy loam	Sub-angular blocky	Strong
13-40	Bw	Dark yellowish brown (10YR 3/4)	Sandy clay loam	Sub-angular blocky	Violent
P9:Loamy-skeletal, mixed, calcareous isohyperthermic Typic Haplustepts					
0-12	0-12	Dark yellowish brown (10YR 4/4)	Sandy loam	Sub-angular blocky	Strong
12-40	12-40	Dark yellowish brown (10YR 3/4)	Sandy loam	Sub-angular blocky	Violent
40-63	40-63	Dark yellowish brown (10YR 3/4)	Sandy loam	Sub-angular blocky	Violent
P10: Loamy-skeletal, mixed, isohyperthermic Aridic Haplustepts					
0-13	Ap	Dark brown (10YR 3/3)	Loamy sand	Granular	Nil
13-26	Bw1	Reddish brown (5YR 4/4)	Sandy loam	Sub-angular blocky	Nil
26-43	Bw2	Dark reddish brown (5YR 3/3)	Loamy sand	Sub-angular blocky	Nil
P11: Coarse, loamy, mixed, calcareous isohyperthermic Typic Haplustepts					
0-12	Ap	Very dark grayish brown (10YR 3/2)	Sandy loam	Sub-angular blocky	Strong
12-46	AB	Very dark grayish brown (10YR 3/2)	Sandy loam	Sub-angular blocky	Strong
46-66	Bw1	Dark brown (7.5YR 3/4)	Sandy loam	Sub-angular blocky	Violent
66-85	Bw2	Dark brown (7.5YR 4/4)	Sandy loam	Granular	Violent
85-98	Bw3	Strong brown (7.5YR 4/6)	Loamy sand	Granular	Violent
98-106	Bw4	Strong brown (7.5YR 4/6)	Sandy loam	Granular	Violent
106+	CBk	Pale brown (10YR 6/3)	Loamy sand	Granular	Violent
P12: Coarse, loamy, mixed, calcareous isohyperthermic Fluventic Haplustepts					
0-10	Ap	Very dark gray (10YR 3/1)	Sandy loam	Sub-angular blocky	Nil
10-26	A2	Very dark gray (10YR 3/1)	Sandy loam	Sub-angular blocky	Nil
26-48	Bw1	Reddish brown (5YR 4/4)	Sandy loam	Sub-angular blocky	Nil
48-67	Bw2	Reddish brown (5YR 4/4)	Sandy loam	Sub-angular blocky	Nil
67-83	Bw3	Reddish brown (5YR 4/6)	Loamy sand	Granular	Nil
83-110	BC	Strong brown (7.5YR 5/6)	Loamy sand	Massive	Nil
110-118	CB	Brownish yellow (10YR 6/8)	Loamy sand	Massive	Nil

the Gupta and Larson model, and Walczak (1984) models were identified and soil moisture predictions were evaluated and compared. Gupta and Rawls model considered soil variables such as sand, silt, clay, OC and BD for predicting soil moisture, whereas Walczak model explained the variables of specific surface area (SSA), mean weight diameter of particles and BD (Table 2). The total SSA of soil with different amounts of sand, silt, and clay fractions was estimated as per Sepaskhah *et al*. (2010).

$$SSA = fc\, X\, SSAc + fsi\, X\, SSAs + fsa\, X\, SSAs$$

Where, SSA is the total specific surface area in m^2g^{-1}, and fc, fsi, and fsa are the clay, silt, and sand fractions of soil in percent, respectively. The mean weight diameter of particles (D) is calculated as:

$$D = \Sigma_{i=1}^{n} \left(\frac{\frac{(Di_{max} + Di_{min})}{2}}{100\%} \right) \text{ x } Pi$$

Where, n is number of fractions, Di_{max} and Di_{min} are the maximum and minimum diameters of i^{th} fraction (mm), respectively, and P_i is the percentage content of i^{th} fraction.

The soil moisture retention characteristics of the soils were predicted using the model by XLSTAT software. The measured and predicted soil moisture content values were correlated for evaluation and the best model was selected based on R^2 and RMSE value.

$$RMSE = \sqrt{\tfrac{1}{n}}\, \Sigma_{i=1}^{n} (\theta_p - \theta_m)^2$$

Where, n is the number of sample and θ_p and θ_m are predicted and measured water contents, respectively.

3. RESULTS AND DISCUSSION

Physical and Chemical Properties

The soil properties were interpreted using coefficient of variation (CV) and it was found that silt, clay, CEC, exchangeable cations (Ca, Mg, Na and K), $CaCO_3$ and EC were the most variable soil properties (>35). The moderately variable properties (CV 15–35) were sand and base saturation, and the least variable property was soil pH (<15) (Table 1). The intrinsic (weathering, erosion, deposition and soil-forming processes) and extrinsic (management practices) factors cause the variation in soil properties (Rao and Wagenet, 1985). The soils were mostly sandy, which has less SSA for water retention compared to clay (Hepper *et al*., 2006). Around 91% and 78% of the study samples had less than 20% clay and 20% silt content, respectively and belong to sandy loam, loamy sand and sand clay loam soil texture class. Both silt and clay tend to have more specific area and total porosity, which favour water absorption and retention (Reichert *et al*., 2009). The soils were non-saline (EC<2.5 dS m^{-1}) and had a low OC content (OC<0.5%). The soils were alkaline (pH>8) in range. Substantial amount of calcium carbonate nodules are present both in surface and subsurface layer, which favours soil particle aggregation (Pachepsky and Rawls, 2003). Exchangeable sodium, the property which imparts the property of dispersion was low in the samples (< 15 cmol (p+) kg^{-1}). The soil moisture retention at saturation, field capacity and permanent wilting point ranged from 13.1% to 48.67%, 3.24% to 36.49% and 0.98% to 26.74%, respectively (Table 3).

Principal Component Analysis (PCA)

The PCA showed that the first five PCs have eigen values >1 accounting for 83.5% of variance. Soil variables from each PC were considered for selection of variables. The grouping may provide better understanding of the relationship between soil properties (Siqueira *et al*., 2010). The first component (PC1) explained 48.5% of the variability mainly due to high variance of sand, silt and clay content, CEC, exchangeable magnesium, soil moisture retention at 1/3, 15 and 0 bar and, to a lesser extent, BD (>0.6). Among the parameters, except sum of cations, all other variables were selected for the study since it is a derived parameter which depends on sum of all exchangeable cations. However, among the factors, sand (-0.982) and silt (0.951) content have the highest factor loading followed by clay (0.926), CEC (0.822), exchangeable magnesium (0.796) and BD (-0.672). Other selected variables were exchangeable Ca/Mg ratio (0.969)

Table: 2
Pedotransfer model adopted for the prediction of water retention characteristics

Model equation	Parameters
Gupta and Larson (1979)	
Predicted water content θρ (m^3m^{-3}) = *a1X1+a2X2+a3X3+a4X4+a5X5*	X1 - Sand (%), X2 - Silt (%), X3 - Clay (%), X4 - Organic C (%), X5 - Bulk Density (Mg m^{-3}), a1, a2, a3, a4 and a5 - Regression Coefficients
Rawls and Brakensiek (1982)	
Predicted water content θρ (m^3m^{-3}) = *a0+a1X1+a2X2+a3X3+a4X4+a5X5*	X1 - Sand (%), X2 - Silt (%), X3 - Clay (%), X4 - Organic C (%), X5 - Bulk Density (Mg m^{-3}), a0,a1, a2, a3, a4 and a5 - Regression Coefficients
Walczak model (1984)	
Predicted water content θρ (m^3m^{-3}) = *b0+b1Y1+b2Y2+b3Y3*	Y1 - Specific Surface Area (m^2 g^{-1}), Y2 - Mean weight diameter of particles (mm), Y3 - Bulk density (Mg m^{-3}), b0,b1, b2, b3 - Regression Coefficients

Table: 3
Descriptive statistics of soil properties

Soil parameters	Descriptive statistics					
	Max	Min	Mean	Std. dev	CV	Shapiro-Wilk test *(P=0.05)*
Sand [%]	88.23	11.24	70.36	15.44	21.95	< 0.0001
Silt [%]	49.39	2.31	15.82	9.04	57.17	< 0.0001
Clay [%]	39.37	6.72	13.82	7.09	51.28	< 0.0001
pH [1:2.5]	8.92	6.23	8.29	0.70	8.50	< 0.0001
EC [1:2.5][dS m^{-1}]	0.85	0.03	0.22	0.15	66.86	< 0.0001
Calcium Carbonate Equivalent [%]	38.54	0.00	6.00	6.91	115.24	< 0.0001
Bulk Density (Mg m^{-3})	1.941	1.342	1.688	0.128	7.58	0.012
OC [%]	0.86	0.00	0.32	0.22	66.49	0.001
CEC [cmol (p+) kg^{-1}]	58.83	2.49	13.87	9.67	69.73	< 0.0001
Exch. Ca	52.04	1.74	15.68	10.36	66.03	0.000
Exch. Mg	23.36	1.37	7.87	4.99	63.50	0.001
Exch. Na	1.37	0.01	0.29	0.29	101.05	< 0.0001
Exch. K	1.16	0.07	0.36	0.28	77.27	< 0.0001
Sum of Ex. Cations [cmol (p+) kg^{-1}]	75.12	5.65	24.20	13.18	54.45	0.005
Ca/Mg	12.19	0.45	2.81	2.64	93.85	< 0.0001
ESP [%]	12.95	0.06	2.57	2.72	106.08	< 0.0001
EMP [%]	18.61	0.52	3.30	3.07	93.08	< 0.0001
BS [%]	304.54	84.86	186.76	48.96	26.22	0.534
Soil moisture retention ~ 1/3 bar [%]	36.49	3.24	14.58	7.30	50.07	0.053
Soil moisture retention ~ 15 bar [%]	26.74	0.98	7.02	4.78	68.05	< 0.0001
Soil moisture retention ~ 0 bar [%]	48.67	13.61	27.46	8.43	30.69	0.196

from PC2, exchangeable sodium (0.824) and exchangeable sodium percent (0.946) from PC3, electrical conductivity (0.957) and exchangeable K (0.688) from PC4, and calcium carbonate equivalent (CCE) (0.963) from PC5. All these variables had highest loading in their respective PCs and were chosen for variable importance plot as well as correlation for further selection of variables (Table 4). Interestingly, OC variable was not a part of any of the PCs, which may be due to very low value (mean-0.32%) and uncertainty in most soil profile databases due to dry semi-arid situation (Reynolds *et al.*, 2000).

Table: 4
Principal components, eigen values and component matrix variables

	F1	F2	F3	F4	F5
Eigen value	9.70	2.36	1.82	1.62	1.21
% variance	48.5	11.8	9.1	8.1	6.0
% cumulative variance	48.5	60.3	69.4	77.5	83.5
Factor loadings					
Sand	**-0.982**	0.028	0.001	-0.055	-0.007
Silt	**0.951**	-0.032	-0.025	0.152	-0.069
Clay	**0.926**	-0.020	0.029	-0.075	0.104
OC	0.224	0.053	-0.030	0.045	0.027
CEC	**0.822**	0.286	-0.023	0.141	0.027
PH	0.278	0.047	0.011	0.237	0.100
EC	0.184	0.010	0.044	**0.957**	0.014
CCE	0.214	-0.107	-0.027	0.004	**0.963**
Ca	0.633	0.641	-0.026	0.133	0.000
Mg	**0.796**	-0.342	0.198	0.264	0.192
Na	0.410	0.120	**0.824**	0.078	-0.069
K	0.334	-0.158	-0.123	**0.688**	-0.017
Sum of cations	0.815	0.374	0.070	0.221	0.071
SMR ~ 1/3 bar [%]	**0.873**	-0.028	-0.011	0.213	0.222
SMR ~ 15 bar [%]	**0.932**	-0.082	0.042	0.103	0.166
SMR ~ 0 bar [%]	**0.812**	0.021	0.050	0.239	0.195
Ca/Mg	-0.142	**0.969**	-0.059	-0.088	-0.114
ESP	-0.190	-0.154	**0.946**	-0.051	0.016
EMP	-0.138	-0.144	-0.080	0.164	-0.010
BD	**-0.672**	0.033	0.033	0.039	-0.197

Selection of Soil Variables

Classification and regression random forest was applied to the variables selected through PCs to identify the most important variables which have significant influence on soil moisture retention based on mean increase in error value. The variables in descending order of sand (7.342), silt (4.713), exchangeable magnesium (ex. Mg: 3.657), clay (2.978), cations sum (1.235), CEC (1.097), EC (0.591), CCE (0.218) and BD (0.209) were found to be the most important variables for predicting moisture retention at 0.3 bar matric potential (Fig. 2). Similarly, variables such as sand (12.030), ex. Mg (9.329), clay (8.836), silt (3.905), cations sum (3.511), EC (3.279), CEC (3.270), ex. K (1.129) and BD (0.153) were found important for predicting moisture retention at 15 bar matric potential. Variables with higher values of percentage increase in mean square error (MSE) contribute more to the predictive accuracy (Mcinerney *et al.*, 2010). Pearson correlation was worked out for the parameters selected through PCA for further confirmation. Correlation between the properties revealed that θ_S, θ_{FC} and θ_{PWP} were positively correlated with silt, clay, CEC, exchangeable calcium, and magnesium, and

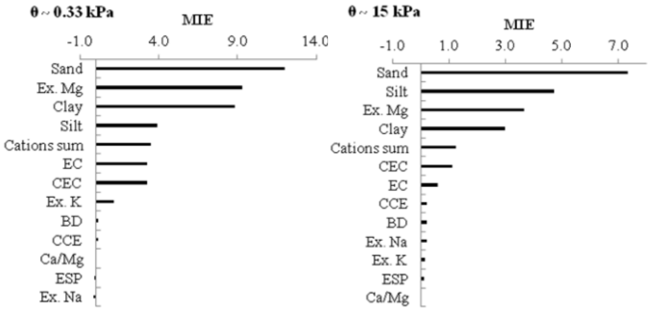


Fig. 2. Relative variable importance of soil variables for predicting soil moisture retention at field capacity (0.33 kPa) and permanent wilting point (15 kPa)

negatively correlated with sand, BD and exchangeable sodium percent (Das and Verma, 2011; Ceddia *et al*., 2009) (Table 5). The significant positive correlation with silt (θ_S: 0.782**, θ_{FC}: 0.832**and θ_{PWP}: 0.896**) and clay (θ_S: 0.822**, θ_{FC}: 0.858**and θ_{PWP}: 0.908**) is an indication of greater water holding capacity in micro-pores of clay and silt-sized particles (Iqbal *et al*., 2005). The effect of BD on moisture retention increased with increasing pressure (θ_S: -0.630**, θ_{FC}: -0.653**and θ_{PWP}: -0.668**). The calcium carbonate equivalent (θ_S: 0.396**, θ_{FC}: 0.436**and θ_{PWP}: 0.382**) and exchangeable magnesium (θ_S: 0.819**, θ_{FC}: 0.836**and θ_{PWP}: 0.866**) were highly correlated with moisture retention at θ_S, θ_{FC} and θ_{PWP} due to their positive impacts on soil aggregation and flocculation. In addition, CEC, a measure of number of negatively-charged binding sites in soil, and explains the SSA of soil (Rashidi and Seilsepour, 2008), correlates positively with soil moisture at different matric suctions (θ_S: 0.649**, θ_{FC}: 0.737**and θ_{PWP}: 0.807**). Finally, the moisture content of the soil corresponding to a particular tension is influenced by soil texture (Patil *et al*., 2013), structure (Esmaeelnejad *et al*., 2015), soil electrolyte concentration (Mamedov, 2014) and temperature (Joseph, 2010). Accordingly, the new model considered sand, and silt to explain the influence of texture, CEC and exchangeable magnesium to represent soil structure, electrical conductivity signifying electrolyte concentration in soil solution, and BD to represent soil porosity. The variables were selected based on RMSE and R^2 value, which indicate the extent to which the dependent variable is explained by the independent variables.

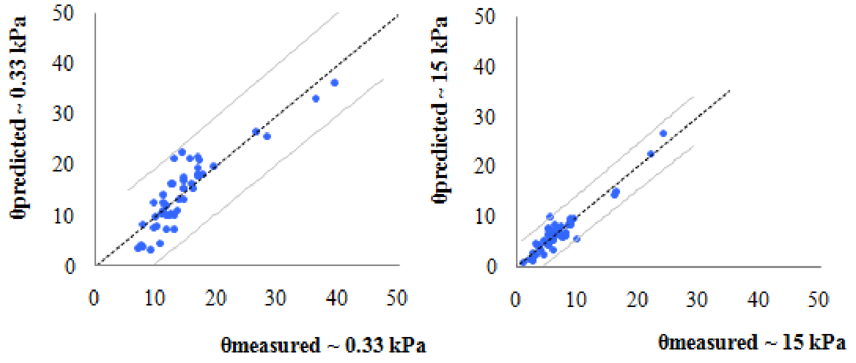
Soil Moisture Retention Prediction

The comparison of different models in predicting moisture retention revealed that the established models were on par except the model developed in the study. The developed model showed comparatively higher prediction value at θ_{FC} and θ_{PWP} matric suction, and its prediction is close to the estimated value (θ_{FC} R^2 = 0.887 and θ_{PWP} R^2 = 0.939) (Table 6). The plot of residuals versus predicted value of new algorithm showed that the residuals are equally spread

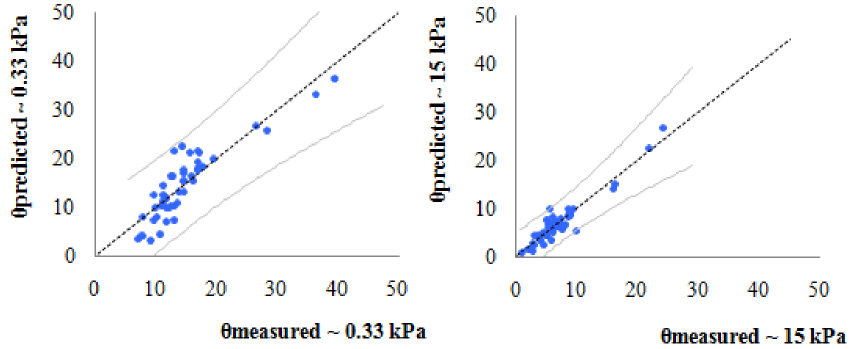
Table: 5
Correlation coefficient of highly loaded parameters in Principal Components 1 to 5

	Sand	Silt	Clay	CEC	EC	CCE	Ex. Mg	Ex. Na	Ex. K	Cations sum	~ 1/3 bar	~ 15 bar	~ 0 bar	Ca/Mg	ESP	BD
Sand	1															
Silt	-.967**	1														
Clay	-.945**	.831**	1													
CEC	-.804**	.800**	.731**	1												
EC	-.228	.303*	.109	.294*	1											
CCE	-.235	.145	.327*	.178	.065	1										
Ex. Mg	-.816**	.784**	.779**	.633**	.440**	.408**	1									
Ex. Na	-.405**	.393**	.382**	.413**	.218	-.005	.495**	1								
Ex. K	-.406**	.426**	.342*	.286	.722**	.100	.530**	.021	1							
Cations sum	-.814**	.803**	.750**	.925**	.394**	.224	.670**	.475**	.360*	1						
~ 1/3 bar	-.881**	.832**	.858**	.737**	.408**	.436**	.836**	.377**	.465**	.817**	1					
~ 15 bar	-.942**	.896**	.908**	.807**	.299*	.382**	.866**	.453**	.392**	.804**	.895**	1				
~ 0 bar _0	-.835**	.782**	.822**	.649**	.431**	.396**	.819**	.388**	.532**	.781**	.925**	.817**	1			
Ca/Mg	.168	-.165	-.155	.153	-.109	-.242	-.499**	.029	-.299*	.214	-.192	-.228	-.143	1		
ESP	.189	-.212	-.143	-.252	-.066	-.040	.051	.613**	-.205	-.165	-.192	-.156	-.133	-.177	1	
BD	.751**	-.675**	-.775**	-.551**	-.042	-.390**	-.597**	-.194	-.340*	-.559**	-.653**	-.668**	-.630**	.161	.150	1

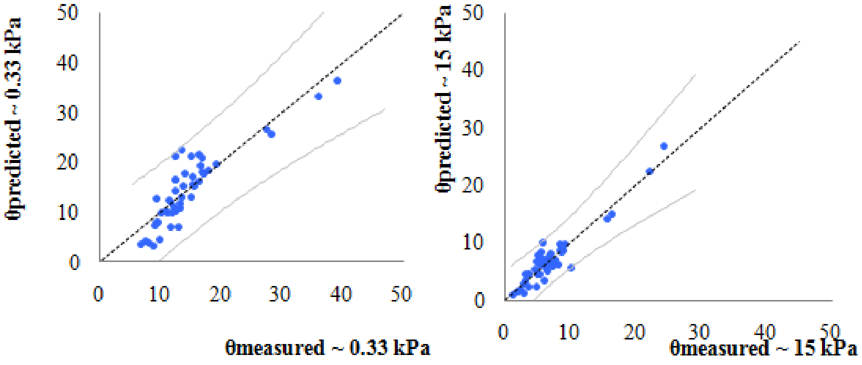
**Correlation is significant at the 0.05 level (2-tailed) ; **Correlation is significant at the 0.01 level (2-tailed)*



Gupta model



Rawls model



Walczak model

Fig. 3. Comparison between measured to predicted soil moisture retention at field capacity (0.33 kPa) and permanent wilting point (15 kPa) by different models

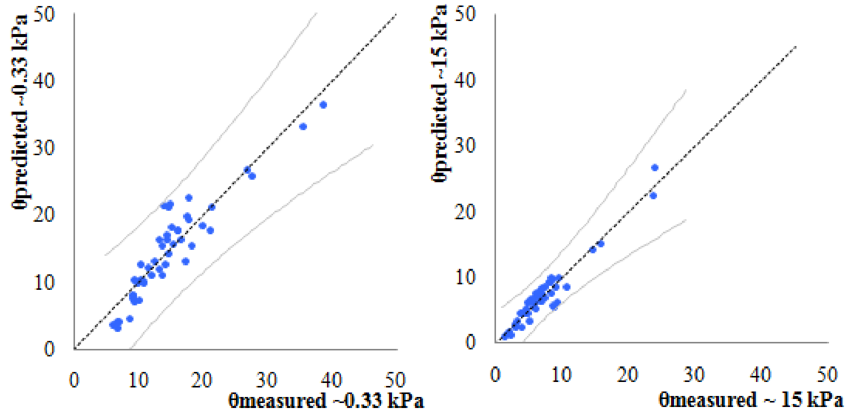


Fig. 4. Comparison between measured to predicted soil moisture retention at field capacity (0.33 kPa) and permanent wilting point (15 kPa) by developed model

Table: 6
Comparison of predicted and measured values

S.No.	Predicted vs Measured		R^2	Regression Model
1	$\theta_{Gupta} = 0.95864*\theta_{Measured}$	~ SMR ~ 0.3 bar (%)	0.790	$\theta_{prediction} = -0.02285*Sand+0.29046*Silt+0.59299*Clay-2.81349*OC\%+2.55353*BD$
	$\theta_{Gupta} = 0.96841*\theta_{Measured}$	~ SMR ~ 15 bar (%)	0.899	$\theta_{prediction} = -0.11592*Sand+0.13402*Silt+0.29046*Clay+1.27333*OC\%+5.11389*BD$
2	$\theta_{Rawls} = 3.06068+0.79006*\theta_{Measured}$	~ SMR ~ 0.3 bar (%)	0.790	$\theta_{prediction} = 59.29972-0.61585*Sand-0.30254*Silt-2.81349*OC\%+2.55353*BD$
	$\theta_{Rawls} = 0.71146+0.89869 *\theta_{Measured}$	~ SMR ~ 15 bar (%)	0.899	$\theta_{prediction} = 29.04594-0.40638*Sand-0.15644*Silt+1.27333*OC\%+5.11389*BD$
3	$\theta_{Walczak} = 3.14896+0.78401*\theta_{Measured}$	~ SMR ~ 0.3 bar (%)	0.784	$\theta_{prediction} = 26.19224+3.47336*BD-0.30022*MWD+0.38426*SSA$
	$\theta_{Walczak} = 0.73178+0.89580*\theta_{Measured}$	~ SMR ~ 15 bar (%)	0.896	$\theta_{prediction} = 13.91098+4.69759*BD-0.23906*MWD+0.22551*SSA$
4	$\theta_{New} = 1.95329+0.86602*\theta_{Measured}$	~ SMR ~ 0.3 bar (%)	0.887	$\theta_{prediction} = 56.24616-0.57392*Sand-0.47375*Silt+0.044657*CEC+0.70034*BD+0.26435*Mg+10.67007*EC$
	$\theta_{New} = 0.47514+0.93235*\theta_{Measured}$	~ SMR ~ 15 bar (%)	0.939	$\theta_{prediction} = 21.61717-0.30018*Sand-0.17762*Silt+0.081139*CEC+3.54735*BD+0.27389*Mg+0.31671*EC$

with defined shape along the horizontal line meeting the homoscedasticity of linear assumption (Mueller, 2003) (Fig. 3). The standardised residuals were between -2 to 2 (-1.393 to 1.673), which indicate that values are normally distributed and the standard deviation to mean (maximum-0.804) is less than 2 (Stephanie, 2017). The better prediction is because of the selected variable according to evaluation criteria which could better explain the moisture retention for the given agro-ecological situation. Hence the model may be applied in places with similar agro-ecological situation where rainfall is uncertain and evapotranspiration is high. In all the pedo-transfer functions, the R^2 value was low for θ_{FC} (0.784, 0.790, 0.790 and 0.866) compared to θ_{PWP} (0.896, 0.899, 0.899 and 0.939) (Tomasella and Hodnett, 2004) because water in the wet range of the retention curve is more allied to the soil structural properties whereas the dry range depends more on the soil texture (Vereecken *et al*., 2010). Once again, the R^2 value in predicting permanent wilting point was high in newly developed model compared to the existing model. The results are identical with Medina *et al*. (2002) who found that clay type rather than clay content range is crucial for soil moisture retention and transmission. The study soils have a mixed mineralogy with varying types and amount of clay minerals. Clay mineral identification and quantification on a routine basis is difficult, therefore CEC of soil is substituted to reflect the kind of clay minerals in soil (Lambooy, 1984). Hence the selection of CEC variable in the proposed model increased the R^2 value to 0.939 for the θ_{PWP} (Fig. 4). At the same time, the prediction error for the θ_{FC} is increased ($R^2 = 0.887$) and the accuracy is lower than $\theta_{PWP.}$ It might be because of soil structure attributes which is not adequately explained and predicted by soil BD in the present study. Hence a more representative variable such as aggregate stability index can be used for expanding the soil structure in future studies for higher accuracy.

4. CONCLUSIONS

Pedo-transfer function for predicting soil moisture retention characteristics using available data sets are one among the predominant cost effective tools for assessing its spatial variability. In this study, pedo-transfer functions were developed for the dry semi-arid agro region of south India considering variables that were identified through PCA and variable importance plot. The variables such as sand, silt, CEC, exchangeable magnesium, electrical conductivity and BD of the soil could better explain factors that influence soil moisture content, and significant better multiple correlation coefficients ($P > 0.05$) were also obtained. Hence, the developed model could be of great help in predicting soil moisture in places where agro-ecological conditions are similar. Besides, the study used disturbed soil sample for the measurement as well as prediction. Since the soil moisture retention at lower tension is dependent on soil structure, the developed algorithm can be evaluated in undisturbed soil to study the effect of structure on soil moisture retention at different suctions. Future studies in this line may also utilize independent variables such as aggregate stability to better explain the soil structural properties for greater results in the lower matric tension.

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