Journal of the Indian Society of Soil Science, Vol. 57, No. 3, pp 273-279 (2009)

Estimation of Water Retention Characteristics of Shrink-Swell Soils using Pedotransfer Functions

N.G. Patil[1], Jagdish Prasad, Rajeev Srivastava and S.A. Dhale
National Bureau of Soil Survey and Land use Planning, Amravati Road, Nagpur, 440 010, Maharashtra

The shrink-swell soils under orchards (irrigated) over a long period develop unique hydraulic characteristics. As a case study, water retention characteristics of sweet orange growing soils were analyzed to define their analytical behaviour so that simulations can be made for projecting changes. Soil water retained (θ) at seven varied matric potentials (h) namely 33, 50, 75, 100, 400, 800, 1500 kPa was measured in the laboratory and seven water retention functions proposed by different researchers were fitted to the laboratory measured data. It was also observed that the h-θ relationship proposed by van Genuchten (VG) fitted better for these soils. Pedotransfer function (PTF) 'Rosetta' (computer code) was used to predict VG parameters from basic soil data. The parameters estimate suggested that the soils were unique in hydraulic behaviour. It was observed that the residual soil-water content Θ_r and saturated soil-water content Θ_s were lower in magnitude as compared to the class values. The estimates of VG parameters were used to predict soil-water retention at varied suction pressure(s). Observed and predicted values of soil-water retention were compared to evaluate the performance of Rosetta. The coefficient of determination (R^2 0.88) values suggested that it could predict soil-water retention in lower suction range with relatively greater accuracy. Comparatively better predictions were obtained with basic data on texture, bulk density and field capacity as an input.

Key words: Soil water retention, pedotransfer functions, VG parameters, Rosetta

India has nearly 62,000 ha area under sweet orange (Anonymous 2003) of which Maharashtra shares 15000 ha which is mainly confined to Nanded, Parbhani, Aurangabad and Jalna districts. Most of the area under sweet orange is along the drain-lines dominated clay texture. The soils under orchards for more than a decade are postulated to have a different hydraulic behavoiur as against the regularly tilled soils. Hydraulic conductivity and water retention properties of soils can influence the efficient use of water and, in turn productivity of crop. Changes in the continuity, size and extent of pores caused by consistent similar land use will strongly influence the surface hydraulic properties of the soil. Soil hydraulic properties are also needed as input data to describe and simulate transport of water and solutes in the soil profile. Water retention curve (WRC) or soil moisture retention curve (SMRC) represents the amount of water (θ) present in the soil under equilibrium conditions and is unique for each soil.

However, laboratory measurement of soil-water retention is time-consuming, capital-intensive and laborious process. It has prompted researchers to use pedotransfer functions (PTFs) that convert available soil information/properties to unknown soil properties. Soil-water retention has been widely researched and numerous PTFs have been developed for spatial applications (Rawls 1998; Schaap *et al.* 2001; Romano and Palladino 2002). Different PTFs developed for soils in different geo-climatic environments are mostly confined for use in the conditions they were developed. This study was aimed at understanding water retention behavoiur of the soils growing sweet orange and explore the possible use of a well accepted PTF 'Rosetta' in predicting water retention.

*Corresponding author (Email: nitpat03@yahoo.co.uk)

Material and Methods

Jalna district in Maharashtra is known for sweet orange. Profile sites were exposed in Baraswada, Belgaon, Bathan, Lalwadi, Awa, Sadesawangi and Gothan villages and horizon-wise sampling was done for laboratory analysis. Standard methods for laboratory analysis were used. Soil water retained (θ) at seven varied matric potentials (h) namely 33, 50, 75, 100, 400, 800, 1500 kPa was determined in the laboratory using pressure plate apparatus.

Soil moisture retention curve (SMRC) or water retention curve (WRC) is the relationship between the water content (θ), and the water potential of the soil (h). The SMRC serves as an input for quantifying the hydraulic functions, which in turn can be used to simulate water dynamics in the soil profile. The shape of water retention curves can be characterized by several functions proposed by different researchers. The variation in soils across time and space has necessitated different retention functions for different conditions. Selected water retention functions proposed by researchers were evaluated for their efficacy in describing θ-h relationship. A power law equation suggested by Brooks and Corey (1966) describes this relationship as

$$S= (h_b/h)^{\lambda} \quad \ldots(1)$$

where, S is the saturation degree,

$$S= (\theta-\theta r)/(\theta s-\theta r) \quad \ldots(2)$$

where, θ is the water content at pressure h, θs is the maximum water content, θr is the residual water content, h_b air entry pressure head, λ pore distribution index

Another most widely used function suggested by van Genuchten (1980) describes the relationship as

$$S=1/\ [1+ (\alpha)^n]^{\ m} \quad \ldots(3)$$

This equation is mostly under the assumption of m=1-1/n.

where,

θ_s is saturated water content

θ_r is residual water content

α is related to the inverse of the air entry suction, α > 0 : and,

n is a measure of the pore-size distribution, *n* > 1

Campbell (1974) described water retention function as,

$$\Theta = \Theta_s (h/h_e)^{-1/b} \quad \text{for } h < h_e \quad \ldots(4)$$

$$\Theta = \Theta_s \quad \text{for h e" } h_e \quad \ldots(5)$$

Other functions evaluated in this study are enlisted below

Function	Analytic expression
Matric potential as dependent variable	
Exponential	$h= \alpha\ e^{-\beta\theta}$
Power	$h= \alpha\ \theta^{-\beta}$
Farrel and Larson (1972)	$h= h_{crit}\ e^{\ \alpha\ [1-(\theta-\theta r/\theta s-\theta r)]}$
Simmons *et al.* (1979)	$h= \alpha\ [^{e\beta(\theta-\Phi)}-1]$
Libardi *et al.* (1979)	$H= \alpha[e^{\beta(\theta-\ \theta s)}-1]$
Soil water content as dependent variable	
Driessen (1986)	$\theta = \theta_s h^{-rln(h)}$

Seven water retention functions proposed by different researchers were fitted to the laboratory measured soil-water retention data. A public domain computer code SWRC was used for fitting water retention functions. Hierarchical rules in generic PTF code 'Rosetta' (Schaap 2000; Schaap *et al* 2001) were executed to obtain estimates of WRC of all the 29 horizons in seven soil profiles. This code uses VG equation and fits/predicts VG parameters, with the restriction m=1-1/n. Parameter estimates of VG function can be used to predict water retention at chosen suction pressure (point of interest). The PTFs in Rosetta are based on artificial neural networks. A hierarchical set of models (increasing number of inputs) is available for use and depending on the availability of data, user can select appropriate model. Minimum input is texture class alone and maximum input is soil texture, bulk density (BD), field capacity (FC), and permanent wilting point (PWP). Four input levels were distinguished for estimating VG parameters:

1. Texture - silt, sand and clay (SSC)
2. Texture +bulk density (SSCBD)
3. Texture +BD+ field capacity (SSCBDFC)
4. Texture +BD+ FC+ permanent wilting point (SSCBDFCPWP)

Thus the input level increased with addition of one soil property in hierarchical manner.

The performance of water retention functions and PTF 'Rosetta' was evaluated by statistical indices namely coefficient of determination (R^2) and Akaike information criteria (AIC). The AIC (Webster and McBratney 1989) is a number associated with each model:

$$AIC=\ln (s_m^2) + 2m/T \quad \ldots(6)$$

where, m is the number of parameters in the model, and s_m^2 is the estimated residual variance [s_m^2 = (sum of squared residuals for model m)/T], that is, the average squared residual for model m. T is the number of observations.

The criterion may be minimized over choices of m to form a trade-off between the fit of the model (which lowers the sum of squared residuals) and the model's complexity, which is measured by m. Thus a water retention WR (m) model *versus* a WR (m+1) can be compared by this criterion for a given batch of data. The selection based on the AIC statistic usually provides more accurate results.

Results and Discussion

Pedons had their Munsell colour of 10YR/7.5YR/5YR) with value 3 to 4 and chroma 1 to 4 and were associated with pressureface (P1, P2, P3) and pressureface and slickenslides in others. Higher cation exchange capacity [38.8 to 67.8 cmol(p^+)kg^{-1}], smectite content [35.1 to 85.7%] in clay fractions in different horizons and linear extensibility more than 6 cm for all the pedons justified their mineralogy as smectite (dominant) and hence these soils possess shrink-swell properties. The details of these data have been referred elsewhere (Dhale and Jagdish Prasad 2009). Clay content of the soils ranged from 38.1 to 66.3% (Table 1) with relatively less variation than sand and silt fractions as indicated by the coefficient of variation. Though the sand content had greater variability, it mostly replaced the silt content which was also reflected by less variation in bulk density. The soils on an average had 4 g kg^{-1} organic carbon, but it varied greatly.

Water retention characteristics (Table 2) of the soils were described by fitting different empirical relationships enlisted earlier. Table 3 shows AIC values and R^2 values for the water retention functions fitted. It was noted that van Genuchten and Campbell functions were fitted better than others for describing moisture characteristics of these soils, with a criterion of coefficient of determination. Change of criteria to AIC also indicated that VG function was best suited. For a second best choice Farrel and Larson function had a marginal advantage over Campbell function. The average values of empirical fitting parameters of different functions are shown in table 3. Since numerical solution to the above relationships could vary, the values of parameters could also vary making it pertinent to find a set that could be subsequently used for further applications like estimating saturated hydraulic conductivity (Rawls *et al*. 1998). For instance VG parameters estimated by PTF ‘Rosetta’ can be employed in different relationships to estimate saturated hydraulic conductivity.

The estimates of VG parameters (Table 4) were used to predict soil-water retention at varied suction pressure. The observed and predicted values of soil-water retention were compared to evaluate the performance of ‘Rosetta’. The R^2 values (Table 5) suggested that this PTF could predict soil-water retention in lower suction range with relatively greater accuracy as compared to higher suction range when SSC and SSCBDFCPWP data were used as an input. The predictions made with intermediate inputs exhibited a mixed trend. Accuracy of ‘Rosetta’ improved with inclusion of data on field capacity, and further improvement with inclusion of data on permanent wilting point. However, inclusion of bulk density did not improve the prediction as compared to textural composition alone. Though the best predictions were obtained with inclusion of field capacity and permanent wilting point, there was a marked improvement in predictions with field capacity alone in higher suction range as indicated by higher R^2 values. Further inclusion of field capacity as an input (predictor variable) led to the best prediction in higher suction range and in general, predictions were relatively better than with other input levels. However, for the best predictions data related to texture, bulk density and field capacity were required. Data on permanent wilting point was thus not necessary for best estimates (Figures 1, 2). Average R^2 value of 0.88 suggested (Table 3) that the code could be used to predict soil-water retention in swelling clay soils of the study area.

VG parameters estimated by ‘Rosetta’ are shown below:

Texture Class	θr	θs	α	n	m
Rosetta class values	0.0980	0.4590	0.0150	1.2531	0.2020
Fitted values	0.0853	0.4288	0.0169	1.3296	0.2273

It was observed that the residual soil-water content (Θ_r) and saturated soil-water content (Θ_s) were lower in magnitude as compared to the class values. On the other hand empirical parameters defining shape of the retention curve were higher in magnitude. The value of α equals to the inverse of potential at the point where curve is steepest. Higher value of α implies far more large pores and better structure. Conversely, lower values obtained here implied less large pores and blocky structure (intrinsic character-

Table 1. Soil properties of the study area

Statistical index	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg m^{-3})	pH	EC (dS m^{-1})	OC (g kg^{-1})	CEC [cmol(p^+)kg^{-1}]
Mean	28.63	19.40	51.95	1.60	8.31	0.28	4.02	53.53
SEm±	1.77	0.79	1.48	0.03	0.05	0.02	0.38	1.45
Standard deviation	9.51	4.27	7.95	0.17	0.28	0.10	2.06	7.68
Variance	90.42	18.19	63.25	0.03	0.08	0.01	4.23	59.04
Coefficient of variation	0.33	0.22	0.15	0.11	0.03	0.34	0.51	0.14
Minimum	14.40	8.10	38.10	1.29	7.90	0.15	0.43	38.82
Maximum	46.90	27.30	66.30	1.96	8.87	0.54	9.15	67.79

Table 2. Soil water retention measured at varied potentials/ suctions

Horizon	Depth (cm)	Soil-water suction (kPa) [100 kPa = 1 bar]						
		33	50	75	100	400	800	1500
Pedon 1 BARASWADA : Clayey, smectitic (calcareous) isohyperthermic Vertic Haplustepts								
Ap	0-12	36.9	34.7	31.4	30.9	27.4	25.3	16.4
Bw	12-32	43.8	37.5	34.6	33.7	30.8	27.5	21.8
2Ck	32-60	22.2	21.2	20.4	18.2	10.0	17.6	11.9
Pedon 2 BELGAON : Clayey, smectitic (calcareous) isohyperthermic Vertic Haplustepts								
Ap	0-15	39.1	36.6	33.7	32.1	28.3	27.4	19.9
Bw	15-30	42.7	37.9	35.9	34.0	31.7	25.3	20.5
2Cr	30-56	18.9	16.5	15.1	14.3	14.0	11.9	9.3
Pedon 3 BATHAN : Clayey-skeletal, smectitic (calcareous) isohyperthermic Typic Haplustepts								
Ap	0-12	36.6	33.9	31.7	29.2	27.7	24.2	17.8
Bw	12-30	40.3	37.4	34.0	31.7	29.2	28.3	19.2
Ck	30-52	32.1	28.9	26.8	24.1	22.4	19.9	15.1
Pedon 4 LALWADI : Very-fine, smectitic (calcareous) isohyperthermic Leptic Haplusterts								
Ap	0-15	45.3	39.5	37.4	34.0	33.9	31.7	28.3
Bw1	15-30	47.1	42.6	40.3	37.4	36.3	29.8	21.6
Bss1	30-53	40.1	36.3	34.0	31.5	29.8	25.5	18.5
2Bss2	53-75	47.8	44.9	41.5	37.7	32.1	29.3	21.6
3Cr	75-100	24.9	22.4	21.0	18.2	16.1	13.2	11.9
Pedon 5 AWA : Fine, smectitic (calcareous) isohyperthermic Typic Haplusterts								
Ap	0-18	16.2	15.1	14.3	13.1	10.9	11.9	9.3
Bw1	18-49	29.2	26.8	24.1	21.2	19.8	16.5	13.9
Bss1	49-77	31.7	29.9	26.8	25.3	21.2	18.2	14.3
2Bss2	77-114	32.1	31.5	29.9	24.9	21.8	20.4	16.8
3Bss3	114-138	42.7	39.5	38.8	34.8	28.3	23.9	19.4
3Bss4	138-170	43.8	42.6	37.4	32.1	29.9	27.4	21.6
Pedon 6 SADESAWANGI : Fine, smectitic (calcareous) isohyperthermic Leptic Haplusterts								
Ap	0-12	23.5	22.2	20.4	18.1	17.6	16.5	11.0
Bw1	12-36	36.6	34.8	32.8	29.4	25.5	21.2	17.2
2Bss1	36-60	33.7	31.7	28.3	27.4	25.9	22.2	16.9
3Ck	60-150	22.4	20.4	18.2	16.5	16.1	11.9	9.5
Pedon 7 GOTHAN : Fine, smectitic (calcareous) hyperthermic Typic Haplusterts								
Ap	0-18	34.0	31.7	29.6	24.2	21.0	22.5	17.6
Bw1	18-48	34.0	31.7	28.3	26.8	23.7	22.1	16.9
Bss1	48-81	37.4	35.8	34.7	29.8	27.2	24.7	17.0
Bss2	81-120	38.7	35.9	32.5	29.3	24.0	22.2	17.4
2Bss3	120-157	47.7	44.9	37.6	32.8	31.4	28.2	20.6

istics of swelling clay soils). It also indicates that the parameter estimates were likely to be useful for further applications. The parameter θ_s was relatively lower entailing relatively higher bulk density. Here value of 'n' was relatively high. Apparently retention characteristics of the sample soils have relatively more decline in retention with increase in suction as compared to the retention data used for developing PTFs. Similar observation was also made by Patil (2006) for clay soils of Jabalpur (Madhya Pradesh). He further observed that inclusion of bulk density as a predictor variable for estimation of water retention did not improve the results obtained with textural composition as prediction input. Reasoning that the relatively higher value of parameter 'n' could be due to lower bulk density was not considered appropriate. Hodnett and Tomasella (2002) reported significant differences in van Genuchten parameters derived for tropical and temperate soils. For clay class, differences showed that both soil texture and mineralogy were important factors to be considered. The mean values of fitted θ_s for tropical dataset were higher than for the temperate data for all classes. Similarly, mean θ_r values in the tropical dataset were shown to be higher than for the temperate soils. Thus the marked differences between water release curves were explained. They opined that specific soil hydraulic behaviour in semi-arid region needs to be better understood. Wösten *et al.* (2001) emphasized on the specificity of semi-arid region soils behaviour.

Table 3. Soil water retention function parameters of h-θ relationships proposed by different researchers and their evaluation

Function	Parameter	Parameter value	R^2	AIC
Brooks and Corey	alpha (α)	0.0026	0.9101	-9.51679
	lambda (λ)	0.5118		
	theta r (θr)	0.1690		
	theta s (θs)	0.3508		
Campbell	Lambda (λ)	6.2451	0.9175	-10.1396
	PSIe	309.96		
	theta s (θs)	0.3508		
Driessen	gama (γ)	0.0051	0.6600	-6.7098
	theta S (θs)	0.3508		
Exponential	alpha (α)	1926909	0.8969	-9.2282
	beta (β)	27.996		
Farrel and Larson	alpha (α)	4.3675	0.9163	-10.1638
	PSI crit	257.4669		
	theta r (θr)	0.1690		
	theta s (θs)	0.3508		
Libardi, Reichardt andNascimento	alpha (α)	241.0784	0.8673	-8.1892
	beta (β)	-28.3084		
	theta s (θs)	0.3508		
Power	alpha (α)	1.1245	0.9174	-10.1135
	beta (β)	6.2982		
Simmons NielsenBiggar	alpha (α)	0.8242	0.9164	-8.4884
	beta (β)	-26.6358		
	theta r (θr)	0		
	theta s (θs)	0.6077		
van Genuchten	theta r (θr)	0.0861	0.9248	-10.1754
	theta s (θs)	0.4317		
	alpha (α)	0.0165		
	n	1.3194		

Table 4. Mean VG parameters estimated by Rosetta

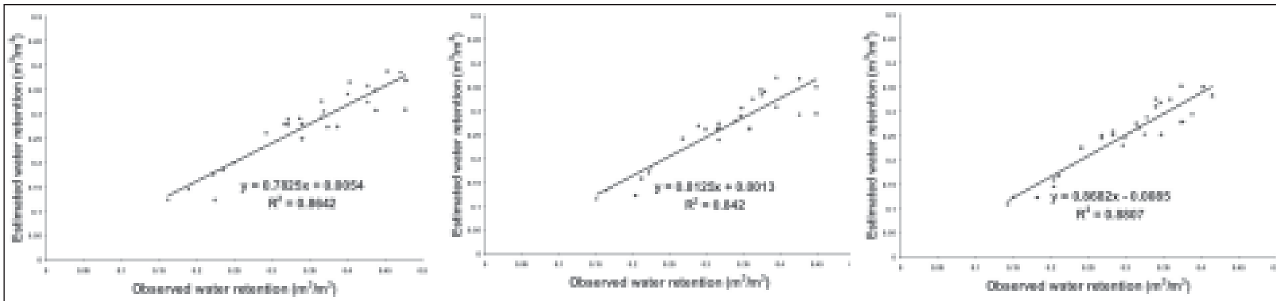
Input	θr	θs	α	n	m
Texture (Sand, silt, clay %)	0.09232	0.4600	0.0222	1.2283	0.1854
Texture and bulk density	0.08804	0.4115	0.0208	1.2219	0.1807
Texture +bulk density+ field capacity	0.09177	0.4084	0.0226	1.3463	0.2206
Texture +bulk density+ field capacity+ permanent wilting point	0.06414	0.4218	0.0068	1.5560	0.3462

Table 5. Coefficient of determination (R^2) values for observed and estimated data on water retention using hierarchical inputs in 'Rosetta'

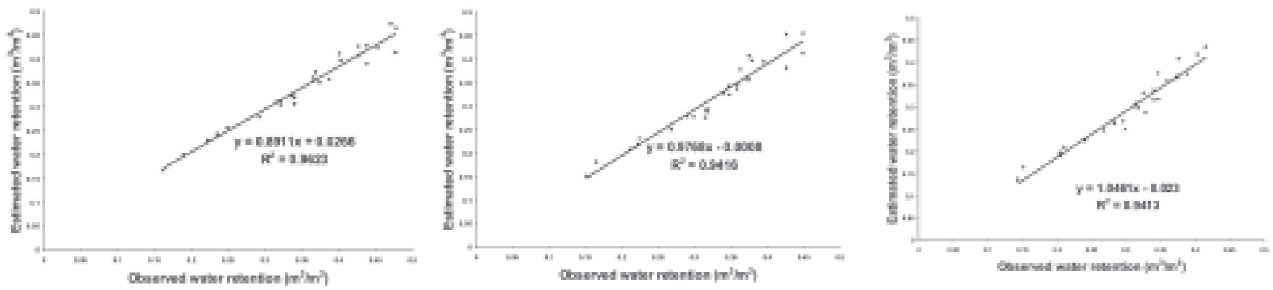
Potential (kPa)	Coefficient of determination (R^2)			
Input	SSC	SSCBD	SSCBDFC	SSCBDFCWP
33	0.71	0.14	0.86	0.96
50	0.63	0.13	0.84	0.94
75	0.63	0.22	0.88	0.94
100	0.66	0.33	0.92	0.90
400	0.65	0.51	0.93	0.74
800	0.56	0.42	0.87	0.75
1500	0.5	0.42	0.86	0.75
Mean	0.62	0.31	0.88	0.85

The differences in behaviour may be explained by some factors related to specificity on soil hydraulic functioning in these regions, accuracy level of relationships between soil properties and predicted parameters, among other factors. They argued that despite these limitations, calculated differences between parameters showed a reasonable agreement with the same trend. Results of this analysis also conform to their conclusion.

It was concluded that the swell-shrink soils under sweet orange cultivation differed in hydraulic behaviour and further investigations are necessary to explain the differences. Their water retention charac-

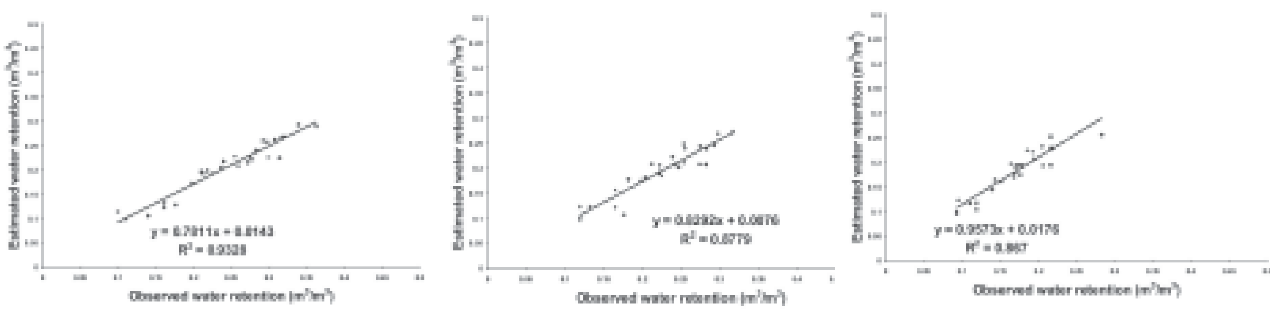


Observed and estimated water retention at varied potential (33, 50 and 75 kPa in order) using VG function with parameters derived from data on texture, bulk density and field capacity

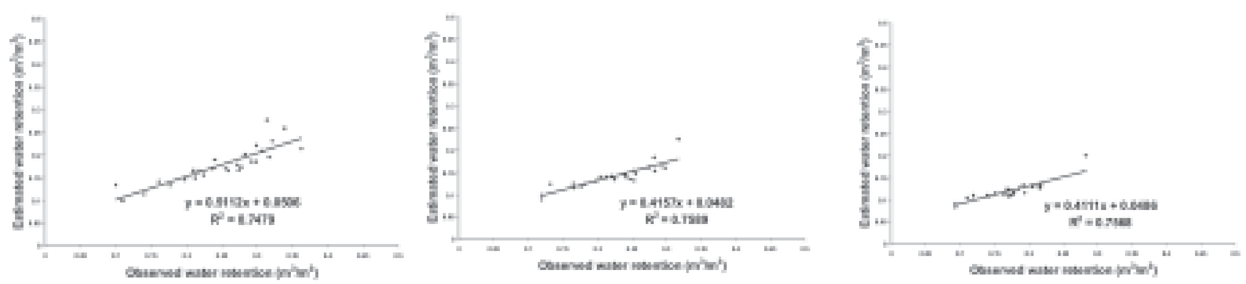


Observed and estimated water retention at varied potential (33, 50 and 75 kPa in order) using VG function with parameters derived from data on texture, bulk density, field capacity and permanent wilting point

Fig. 1



Observed and estimated water retention at varied potential (400, 800, 1500 kPa in order) using VG function with parameters derived from data on texture, bulk density and field capacity



Observed and estimated water retention at varied potential (400, 800, 1500 kPa in order) using VG function parameters derived from data on texture, bulk density, field capacity and permanent wilting point

Fig. 2

teristics could be predicted by generic pedotransfer code ‘Rosetta’ with accuracy.

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Received April 2007; Accepted June 2009