J. Earth Syst. Sci. (2018) 127:35
https://doi.org/10.1007/s12040-018-0937-0

Pedotransfer functions to estimate soil water content at field capacity and permanent wilting point in hot Arid Western India

Priyabrata Santra[1,*], Mahesh Kumar[1], R N Kumawat[1], D K Painuli[1], K M Hati[2], G B M Heuvelink[3] and N H Batjes[3]

[1] *ICAR-Central Arid Zone Research Institute (CAZRI), Jodhpur 342 003, India.*
[2] *ICAR-Indian Institute of Soil Science (ISSS), Bhopal 462 001, India.*
[3] *ISRIC-World Soil Information, Wageningen, The Netherlands.*
**Corresponding author. e-mail: Priyabrata.Santra@icar.gov.in*

MS received 17 August 2016; revised 10 August 2017; accepted 22 August 2017; published online 27 March 2018

Characterization of soil water retention, e.g., water content at field capacity (FC) and permanent wilting point (PWP) over a landscape plays a key role in efficient utilization of available scarce water resources in dry land agriculture; however, direct measurement thereof for multiple locations in the field is not always feasible. Therefore, pedotransfer functions (PTFs) were developed to estimate soil water retention at FC and PWP for dryland soils of India. A soil database available for Arid Western India (N=370) was used to develop PTFs. The developed PTFs were tested in two independent datasets from arid regions of India (N=36) and an arid region of USA (N=1789). While testing these PTFs using independent data from India, root mean square error (RMSE) was found to be 2.65 and 1.08 for FC and PWP, respectively, whereas for most of the tested 'established' PTFs, the RMSE was >3.41 and >1.15, respectively. Performance of the developed PTFs from the independent dataset from USA was comparable with estimates derived from 'established' PTFs. For wide applicability of the developed PTFs, a user-friendly soil moisture calculator was developed. The PTFs developed in this study may be quite useful to farmers for scheduling irrigation water as per soil type.

Keywords. Soil water retention; dry lands; western India; pedotransfer functions; soil moisture calculator.

1. Introduction

Fresh water is a precious natural resource that has become scarce over the last few decades (Rijsberman 2006; Schewe *et al.* 2013). It is projected that rapid population growth, urbanization, and economic prosperity in the next 25 years will make water-related challenges more pressing than the present situation (Vörösmarty *et al.* 2000). The scarcity of water is more prominent in the dry lands of the world, where the gap between availability and demand of water is large. In spite of acute scarcity of water in dry lands, there is a continuous increase in vegetation coverage and agricultural area in dry lands to support a great share of the global population (Millennium Ecosystem Assessment 2005). Likewise, there is a continuous increase in irrigated area and vegetation coverage in Indian dry lands, which has been exerting a severe pressure on the scarce, available water resources (CAZRI 2008). In the arid region of western India, water for irrigation is mainly available from groundwater and through the Indira Gandhi Nahar Project (IGNP). Indiscriminate use of this precious resource has led to multifaceted problems in the region, evidenced by a high rate of groundwater depletion, deterioration of soil quality through accumulation of salt at the surface especially in the canal command areas, and disputes among local communities for the use of scarce water for daily life consumption. In the context of global climate change, water scarcity in the dry lands may exacerbate the desertification process (D'Odorico *et al.* 2013). Therefore, urgent attention is required for judicious use of available water resources in dry land areas. This may be achieved through proper assessment of the soil water regime in the field.

Characterization of the soil water regime in the field depends mainly on two soil hydraulic properties: water retention $[\theta(h)]$ as a function of soil water potential (h) and hydraulic conductivity $[K(h)]$ as a function of h. These two soil hydraulic properties are key inputs for most models dealing with budgeting of water for various purposes (Balland *et al.* 2008; Wösten *et al.* 2013).

Soil water content at field capacity occurs in the field after 2–3 days of free drainage from saturation. As the soil continues to dry out and reaches a soil water potential of 15 bar (1500 kPa), most plants will start to wilt; therefore, soil water content at this potential is generally accepted as permanent wilting point (PWP). The potential amount of soil water that can be held between FC and PWP is a widely used measure for the plant available water capacity of a soil.

The difference between moisture content at FC and PWP provides a measure for the maximum amount of water held in soil that may be available for plant growth (depending on actual rainfall amount and distribution, or irrigation). FC and PWP thus are very important parameters for irrigation scheduling. One major problem of these hydraulic properties is that their direct measurement at multiple locations, even within an agricultural field, is time-consuming and expensive (Romano and Palladino 2002). Alternatively, soil hydraulic properties can be estimated using pedotransfer functions (PTFs), which relate hydraulic properties with easily measurable soil properties, such as soil particle size distribution (PSD) and soil organic carbon (OC) content (Rawls *et al.* 1982; Vereecken *et al.* 1989; Tomasella and Hodnett 1998; Wösten *et al.* 1999; Schaap *et al.* 2001; Minsany *et al.* 2002; Balland *et al.* 2008; Botula *et al.* 2013; Mohanty *et al.* 2015; Haghverdi *et al.* 2015; Khlosi *et al.* 2016; Zhao *et al.* 2016).

Concerted efforts in many countries over the last decades have led to the development of several 'established' PTFs for estimating soil water retention (Gupta and Larson 1979; Rawls *et al.* 1982; Wösten and van Genuchten 1988; Tomasella and Hodnett 1998; Wösten *et al.* 1999; Schaap *et al.* 2001; Minasny and McBratney 2002). Typically, PTFs are not portable with acceptable accuracy, not even when they are developed from large soil databases (Tietje and Tapkenhenrichs 1993; Wagner *et al.* 2001; Nemes *et al.* 2003; Santra and Das 2008). Cornelis *et al.* (2001) showed that a PTF yields more accurate estimates when it is applied to the geographical region for which it was developed. Similarly, Hodnett and Tomasella (2002) showed that the PTFs developed for temperate conditions performed poorly when applied to deeply weathered soils from tropical humid Brazil. Therefore, PTFs specifically developed and tested for soils of 'Arid Western India' (AWI), which is the geographical region delineated in figure 1 (hereafter referred to as 'arid soils' of India or abbreviated as SAWI) are required for characterization of the soil water regime and land use planning in these dry lands.

There are several PTFs for estimating soil water content at 1/3 bar (FC) and 15 bar (PWP) for other agro-ecological zones of India as well as for use at national scale (Singh 2000; Santra and Das 2008; Adhikary *et al.* 2008; Chakraborty *et al.* 2011; Patil *et al.* 2012; Shwetha *et al.* 2013). Therefore, the main objective of this study was to develop PTFs for arid soils of India to estimate soil water content at FC and PWP. These PTFs were evaluated and compared with several 'established' (i.e., widely cited) PTFs, using an independent dataset, to assess their reliability for wider application in arid regions. As use of a case example, the applicability of the developed PTF was demonstrated through development of a user-friendly soil moisture calculator in support of agricultural planning.

2. Materials and methods

2.1 *Arid Western India*

Arid Western India (AWI) mainly comprises the western part of Rajasthan and north-western part of Gujarat with some parts of Haryana and Punjab at its northeast and east, respectively

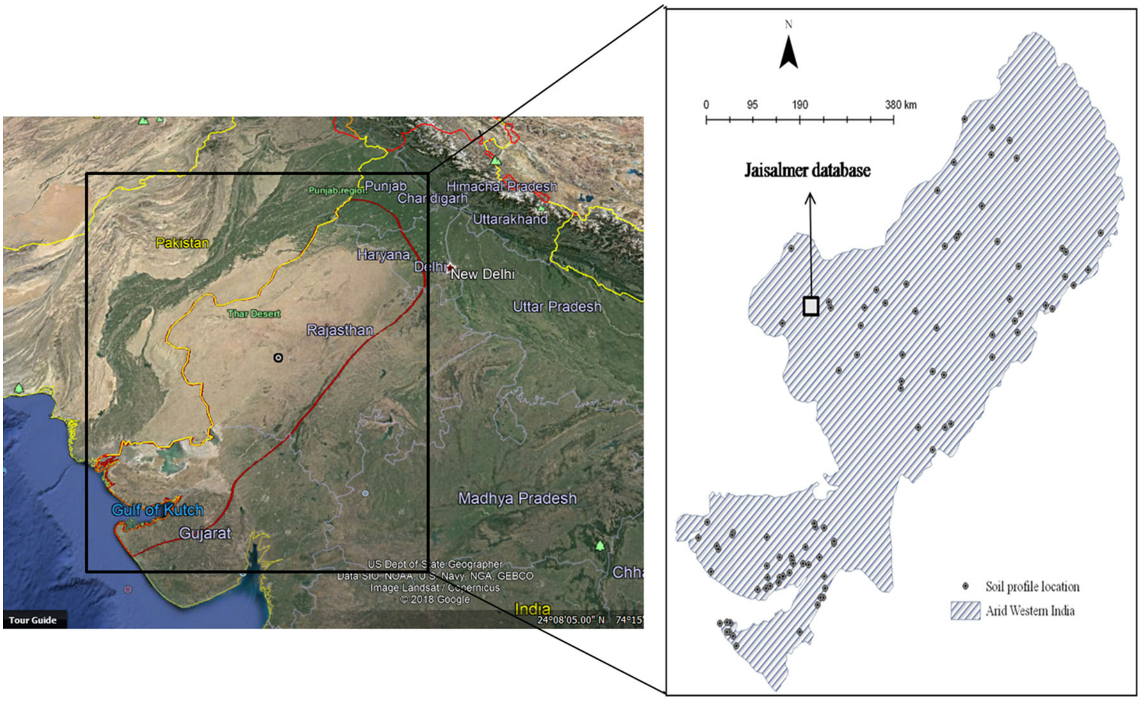

Figure 1. Hot arid ecosystem in India with soil profile locations.

(figure 1). It lies between 21°17′–31°12′N and 68°8′–76°20′E, covering an area of 32 million ha.

The southern, coastal part of the AWI is locally known as 'Kachch'. The central western and northwestern parts of the region are dominantly covered with high and low dunes with an average height of 10–15 m, which are locally known as 'Marusthali'. The mean annual rainfall in the AWI is 400 mm. The 'Marusthali' region receives less rainfall (200–300 mm/yr with 12–15 rainy days, mostly during July–September) than the 'Kachch' region (350–450 mm/yr with 16–18 rainy days during July–September). The mean summer temperature at the 'Marusthali' region is as high as 49°C during the day and decreases to less than 20°C during the night. The mean day temperature in the coastal part of 'Kachch' is 36–38°C, which is low compared to the western and northern plains with dune areas.

Main soil types of the SAWI region, defined according to USDA Soil Taxonomy (Soil Survey Staff 2010), include Aridisols (37.8%), Entisols (50.1%), and Inceptisols (13.1%) (figure 2 and table 1). Aridisols are mainly observed in buried pediments, interdunal plains and old alluvial plains. Average depth of such profiles is 106 cm with well-demarcated horizons; concretions of calcite below the soil profile are common. Psamments–Orthids are the major sub-order association under Aridisols. Average bulk density of these soils is 1.46 $\mathrm{Mg\,m^{-3}}$ and average sand, silt and clay content about 61%, 16% and 23%, respectively. Entisols are found in places where aeolian activity is dominant with Orthids–Psamments as major sub-order association. Average depth of Entisols is 105 cm and the bulk density 1.54 $\mathrm{Mg\,m^{-3}}$. Surface horizons are richer in sand content than subsurface horizons; the average sand, silt and clay content is 78%, 9% and 13%, respectively. Soils under Inceptisols are mainly observed at western and southern borders of Arid Western India with Ochrepts as the dominating soil sub-order. Average soil depth under Inceptisols is 83 cm, average sand, silt and clay content is 51%, 15% and 34%, respectively whereas average bulk density is 1.51 $\mathrm{Mg\,m^{-3}}$.

2.2 *Soil database from arid western India*

The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), India, carried out comprehensive soil surveys for different states, including Rajasthan (Shyampura *et al.* 2002) and Gujarat (Sharma *et al.* 2006), which lie in Arid Western India. The corresponding survey reports contain measured data on particle size distribution, organic carbon (OC) content ($\mathrm{g\,kg^{-1}}$), pH, electrical conductivity ($\mathrm{dS\,m^{-1}}$), free $CaCO_3$ content (%, g/g), FC and PWP (%, g/g) as well as data on exchangeable bases and major nutrient contents, and these

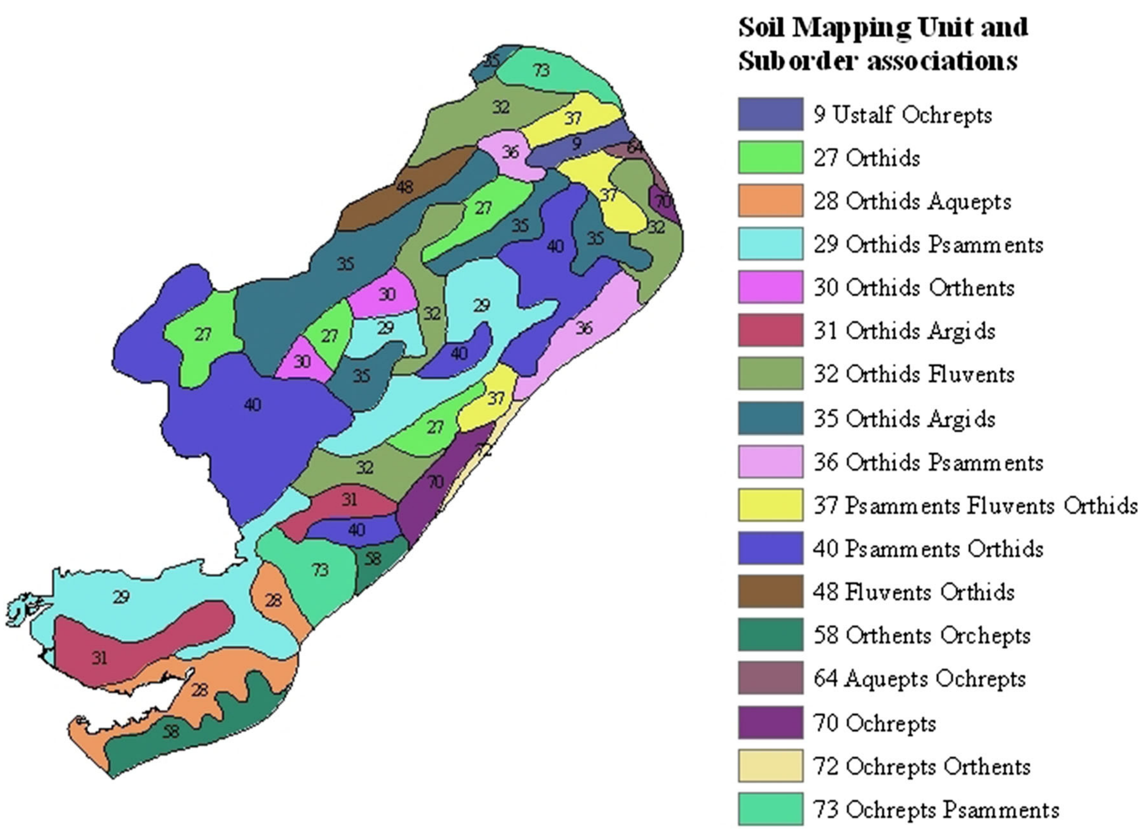

Figure 2. Soil suborder association map of hot Arid Western India. Numbers refer to mapping units as described in table 1.

were digitalized. The soil database for Arid Western India (SAWI) was collated from the state level databases for Rajasthan and Gujarat (Shyampura *et al.* 2002; Sharma *et al.* 2006) by extracting those soil profiles lying within the AWI region and having data on particle size distribution, OC content, FC and PWP. This yielded a total of 93 soil profiles, of which 50 were from western Rajasthan and 43 from northwestern Gujarat.

2.3 *Development datasets*

The data on soil particle size distribution in the SAWI database were available for five size fractions: very coarse sand (1–2 mm), coarse sand (0.5–1 mm), fine sand (0.05–0.5 mm), silt (0.002–0.05 mm) and clay ($<$0.002 mm). However, other soil survey reports from India mostly contain data on only three fractions: sand (0.05–2 mm), silt (0.002–0.05 mm) and clay ($<$0.002 mm). Keeping in mind the future applications of the developed PTFs in India, the most commonly available particle size fractions (sand, silt and clay) and OC content were selected as predictor variables in the PTFs. In total, the SAWI database contained data for 380 soil horizons having data for sand, silt and clay content as well as OC content, FC and PWP. Further, to develop robust PTFs for dryland soils in the world, the SAWI database was merged with a database representing major soils types from arid USA (see below).

2.4 *Testing datasets*

To test the developed PTFs, two independent datasets were prepared, which are also different from the development dataset. The first was generated for the Jaisalmer district within AWI (see figure 1). Seventeen profiles were excavated representing different land-use situations in the Thar desert to collect 78 soil samples. All collected soil samples were analyzed in the laboratory to determine bulk density by core method, particle size distribution by pipette method, OC content by Walkley and Black method (Walkley and Black 1934), and water retention at 1/3 bar and 15 bar by pressure plate apparatus method (Klute 1986). The

Table 1. *Area under different mapping units and suborder associations in Arid Western India.*

Map unit	Suborder associations	FAO name	Area (%)	Major suborder	Area (%)	Major order	Area (%)
27	Orthids	Solonchaks/Yermosols	6.4	Orthids	31.5	Aridisols	36.8
37	Psamments–Fluvents–Orthids	Arenosols–Fluvisols	4.2				
40	Psamments–Orthids	Arenosols–Yermosols	18.9				
48	Fluvents–Orthids	Fluvisols–Yermosols	2.0				
31	Orthids–Argids	Yermosols–Yermosols	5.3	Argids	5.3		
35	Psamments	Arenosols	12.7	Psamments	33.5	Entisols	50.1
29	Orthids–Psamments	Solonchak/Yermosols–Arenosols	16.0				
73	Ochrepts–Psamments	Cambisols–Arenosols	4.8				
30	Orthids–Orthents	Yermosols–Regosols	2.0	Orthents	2.6		
72	Ochrepts–Orthents	Cambisols–Regosols	0.6				
32	Orthids–Fluvents	Yermosols–Fluvisols	10.5	Fluvents	14.0		
36	Psamments–Fluvents	Arenosols–Fluvisols	3.5				
70	Ochrepts	Cambisols	2.3	Ochrepts	7.6	Inceptisols	13.1
9	Ustalf–Ochrepts	Planosols/Luvisols/Nitosols–Cambisols	1.2				
64	Aquepts–Ochrepts	Gleysols–Cambisols	0.3				
58	Orthents–Ochrepts	Regosols–Cambisols	3.8				
28	Orthids–Aquepts	Solonchak–Solonchaks	5.5	Aquepts	5.5		

Table 2. *Detail composition of soil database from arid region of USA used in this study.*

County	No. of samples
Arizona state ($N = 93$)	
Cochise	93
California state ($N = 521$)	
Inyo	80
Kern	235
Los Angeles	9
Orange	38
Riverside	15
San Bernardino	113
San Diego	10
Santa Barbara	21
Nevada state ($N = 1175$)	
Churchill	75
Clark	81
Douglas	10
Elko	201
Esmeralda	50
Eureka	22
Humboldt	68
Lander	115
Lincoln	51
Lyon	27
Mineral	26
Nye	134
Pershing	106
Washoe	127
White Pine	82

Source: NCCS Soil Characterization Database (http://ncsslabdatamart.sc.egov.usda.gov/).

resulting dataset is hereafter referred to as 'Jsm' database.

The second test dataset, with soil profiles from the arid parts of Arizona, California and Nevada states of USA ($N = 1789$, table 2), was prepared by downloading the relevant predictor data from the NCCS Soil Characterization Database (http://ncsslabdatamart.sc.egov.usda.gov/).

2.5 *Methods for measuring soil water retention*

The soil databases from Arid Western India (SAWI) and the arid region of USA (arid-USA) contain data on water retention measured using pressure plate extraction methods (Sarma *et al.* 1987; Sehgal *et al.* 1987; Soil Survey Staff 1996; Bhattacharya *et al.* 2009). In case of water retention data extracted from the NCCS Soil Characterization Database, only samples analyzed according to laboratory methods 4B1c and 4B2a were considered. Procedure 4B1c measures water retention, expressed on a <2 mm base, using clods at 0.33 bar and pressure-plate extraction, whereas procedure 4B2a measures water retention at 15 bar using <2 mm air dry soil samples and pressure-membrane extraction (Soil Survey Staff 1996). Alternatively, as commonly done in many, especially developing countries (Bell and Van Keulen 1996; Klute 1986), the FC data for SAWI were determined on disturbed samples although it is known that structure and macro-porosity of the sample affect water retention (Unger 1975; Young and Dixon 1966; van Reeuwijk 2002) and this especially in the lower suction range except for the coarser textured soils (Bell and Van Keulen 1996); the latter soils predominate in the study region (table 4 and section 3.1). In this study, we used 1/3 bar or 33 kPa as the soil water potential that best corresponds with FC.

2.6 *Data analysis*

2.6.1 *Descriptive statistics*

Mean, standard deviation and range of soil properties in the development database (SAWI) as well as in the testing databases ('jsm' and 'USA-arid') were calculated using R software (R Core Team 2013). The Spearman rank correlation coefficient between soil water retention and basic soil properties was calculated and the correlation matrix prepared. Significance of the correlation coefficient was tested using the t-statistic (Gupta and Kapoor 2000).

2.6.2 *PTF development*

Point PTFs for soil water content at FC and PWP were developed using a multiple linear regression (MLR) equation of the form

$$Y = a_0 + \sum_{k=1}^{K} a_k X_k \qquad (1)$$

where Y is the dependent variable, X_k is the kth independent variable (input), $a_0, \ldots, a_k$ are regression coefficients and k is the number of independent variables in the regression equation.

The MLR equations were developed using the linear model (lm) function of R software. Three major soil properties, namely sand content (%), clay content (%) and organic carbon content (g/kg), and their two-way interactions were used as an initial set of explanatory variables followed by a stepwise approach to remove statistically insignificant terms. Stepwise regression analysis was carried out for two major categories of input data: (i) PSD category containing information on sand and clay content along with their two-way interactions (e.g., sand×clay) and (ii) PSD+OC category data containing sand, clay and OC content along with their two-way interactions (i.e., sand×clay, sand×OC and clay×OC). Selected sets of inputs in the stepwise approach were further reduced to common sets separately for soil water content at FC and PWP under the two main categories of inputs. These common sets were further used to develop PTFs from the SAWI database and the merged SAWI and USA-arid database.

2.6.3 *Validation of PTFs*

Developed PTFs were first validated using 10-fold cross-validation using the cross-validation function in R. In this approach, the total dataset is randomly divided into 10 subsets. Next the model is developed 10 times, each time calibrating the model on data of nine subsets and testing it on the remaining subset. Bias and root mean square error (RMSE) of estimation were calculated from the predictions of the target variable using:

$$\mathrm{Bias} = \frac{1}{N} \sum_{i=1}^{N} \left(Y_i - \hat{Y}_i \right) \qquad (2)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2} \qquad (3)$$

where Y_i is an observed value of the target variable, which is either $\theta_{1/3\mathrm{bar}}$ or $\theta_{15\mathrm{bar}}$, $\hat{Y}_i$ is an estimated value of the same variable and N is the number of observations in the dataset. Lower values of both bias and RMSE indicate better performance of the model. While calculating these two indices, bias gives equal weight to all errors, whereas RMSE assigns more weight to larger errors than smaller errors. Therefore, RMSE can never be smaller than bias. More is the difference between bias and RMSE indicates presence of a few large errors.

Table 3. *List of published pedotransfer functions (PTFs) for estimating soil water content at FC and PWP considered in the comparative study.*

Authors	Region	Pedotransfer function#
Schaap *et al.* (2001)	USA	Artificial neural network based PTFs (Rosetta)
Tomasella and Hodnett (1998)	Brazil	*FC = 4.046 + 0.426 × silt + 0.404 × clay *PWP = 0.91 + 0.15 × silt + 0.396 × clay
Adhikary *et al.* (2008)	India	*FC = 56.37 − 0.51 × sand − 0.27 × silt *PWP = 0.71 + 0.44 × clay
Chakraborty *et al.* (2011)	India	**FC = 27.447 + 0.078 × clay + 0.248 × silt − 0.241 × sand **PWP = 20.695 + 0.021 × clay − 0.028 × silt − 0.179 × sand

*FC and PWP represent the water content (%, cm^3/cm^3) at 1/3 bar and 15 bar, respectively.
**FC and PWP represent the water content (%, g/g) at 1/3 bar and 15 bar, respectively.
#For this study, when testing and comparing the performance of the PTFs, units were converted to g/g (see text). The above PTFs are referred to as 'established' PTFs in the text.

2.6.4 *Testing of PTFs*

The performance of the PTFs developed from the SAWI database was further tested using the 'Jsm' and 'USA-arid' databases. While testing the developed PTFs using independent datasets, their performance was also compared with two national and two international 'established' PTFs; for details see table 3. It is noted here that the soil database from Arid Western India contains water retention data in gravimetric units (%, g/g). Therefore, throughout this study, gravimetric water content (%, g/g) data were used to develop PTFs for water retention at 1/3 bar and 15 bar. Some of the 'established' PTFs (Schaap *et al.* 2001; Tomasella and Hodnett 1998; Adhikary *et al.* 2008) estimate water retention in volumetric units; for comparison purposes, the estimated values were converted to gravimetric units using available data on bulk density.

The PTFs by Schaap *et al.* (2001), which are commonly known as 'rosetta', were considered here because of their widespread use and the requirement of similar inputs as with the developed PTFs in this study. The PTFs by Tomasella and Hodnett (1998) were selected because these were developed for a tropical/sub-tropical region, although soil conditions are very different. Besides these PTFs, two sets of PTFs developed for India (Adhikary *et al.* 2008; Chakraborty *et al.* 2011) were used; these PTFs were developed from a large number of soil samples distributed throughout India and hence may be considered 'national scale' PTFs. The estimation efficiency of the selected PTFs using the test databases was evaluated using RMSE. The PTFs with lower value of RMSE was considered better than the PTFs with higher value of RMSE.

2.7 *Preparation of PTF-based user interface*

For wide applicability of the developed PTFs, a user interface was prepared using Microsoft Visual Studio version 6.0. Drop-down menus were created to include options to choose a particular PTF model. Apart from PTFs developed in this study, the 'established' PTFs were also included in the list; for each of these, only the relevant predictor variables can be entered with simple checks on data entry (e.g., sum of sand, silt and clay should be 100%). Programming codes were written to estimate soil water content at FC and PWP following the selected PTF model, and to calculate available water capacity per soil layer using

$$\theta_{\mathrm{AWC}} = \frac{(\mathrm{FC}-\mathrm{PWP})}{100} \times \text{bulk density } (\mathrm{Mg\ m^{-3}}) \times \text{depth of soil layer (mm)} \quad (4)$$

where θ_{AWC} is the available water capacity of soil in mm, and FC and PWP are the estimated soil water content at 1/3 bar and 15 bar, respectively, in gravimetric unit (%, g/g).

3. Results and discussion

3.1 *Descriptive statistics*

3.1.1 *Development database*

Descriptive statistics of soil properties in the SAWI database are given in table 4. Soil texture was

Table 4. *Descriptive statistics of soil properties in development database from Arid Western India (SAWI) and testing database from Jaisalmer and arid region of USA.*

Soil properties	Total SAWI database ($N = 380$)			'Jsm' database ($N = 36$)			'USA-arid' database ($N = 1789$)		
	μ	σ	Range	μ	σ	Range	μ	σ	Range
Sand (%)	64	23	4–97	84	8	62–92	50	23	0.6–98
Silt (%)	14	11	1–68	8	6	1–26	32	17	0.2–89
Clay (%)	23	14	1–68	8	3	3–12	18	13	0.1–81
OC ($g\,kg^{-1}$)	2.6	1.9	0.1–11.0	1.0	0.9	0.3–5.6	6.5	9.6	0.1–144.6
Bulk density ($Mg\,m^{-3}$)	–	–	–	1.62	0.10	1.26–1.81	1.47	0.22	0.20–2.44
§FC (%, g/g)	18	9	3–48	9	4	4–19	21	11	2–69
§PWP (%, g/g)	7	4	1–19	3	1	1–5	10	7	1–41

§FC and PWP represent soil water content (%, g/g) at 1/3 bar and 15 bar, respectively.
N: number of samples.

sandy in most cases; however, clay and sandy clay soil texture were also observed for a few soil samples from the southern coastal region of the AWI. Organic carbon content of soils was low with an average content of $2.6\,g\,C\,kg^{-1}$. About half of the soil samples have OC between 0 and $2\,g\,C\,kg^{-1}$, while the minimum and maximum are 0.1 and $11\,g\,C\,kg^{-1}$, respectively. Average soil water content at FC was 18% (g/g) and observations varied from 3% to 48%; average soil water content at PWP was 7% (g/g), with a minimum of 1% for sandy textured soils and a maximum of 19% for clay textured soils.

3.1.2 *Testing database*

Descriptive statistics of the 'Jsm' and 'USA-arid' testing databases are given in table 4. Overall, soil properties in the 'Jsm' database are more similar to those of the SAWI database than those of the 'USA-Arid' database. However, overall, soils in 'Jsm' database are more sandy and lower in OC content than soils in the SAWI database, which was also reflected in the water retention at 1/3 bar and 15 bar. In contrast, soils in the 'USA-arid' database are quite different from those of the SAWI and 'Jsm' databases, in that there is greater diversity in soil types/series, although all three databases represent soils from arid climate regions. It should be noted that mean OC content in the 'USA-arid' database is higher than in the 'Jsm' and SAWI databases. Sand content of soils was lower, whereas silt and clay content were higher in 'USA-Arid' database than in the 'Jsm' and SAWI databases.

3.2 *Correlation matrix of soil properties from the SAWI database*

The Spearman correlation coefficients (r) among soil properties in the SAWI database are presented in table 5. Sand, silt, clay and OC content were found significantly correlated with soil water content at FC and PWP (figure 3). Soil water content at FC had the highest correlation with sand content ($r = -0.92$, $p < 0.01$), whereas soil water content at PWP had the highest correlation with clay content ($r = 0.95$, $p < 0.01$). Sand content was observed negatively correlated with water retention at FC and PWP whereas silt, clay and OC content showed positive correlation with water retention at FC and PWP. It indicates that higher is the sand content, lesser will be the soil water retention at

Table 5. *Correlation matrix among soil properties held in the soil database of Arid Western India (SAWI).*

	Sand (%)	Silt (%)	Clay (%)	OC ($g\,kg^{-1}$)	FC (%, g/g)	PWP (%, g/g)
Sand (%)	1					
Silt (%)	-0.85^{**}	1				
Clay (%)	-0.91^{**}	0.57^{**}	1			
OC ($g\,kg^{-1}$)	-0.51^{**}	0.35^{**}	0.53^{**}	1		
FC (%, g/g)	-0.92^{**}	0.72^{**}	0.89^{**}	0.49^{**}	1	
PWP (%, g/g)	-0.91^{**}	0.63^{**}	0.95^{**}	0.51^{**}	0.91^{**}	1

**Significance level at 1%.

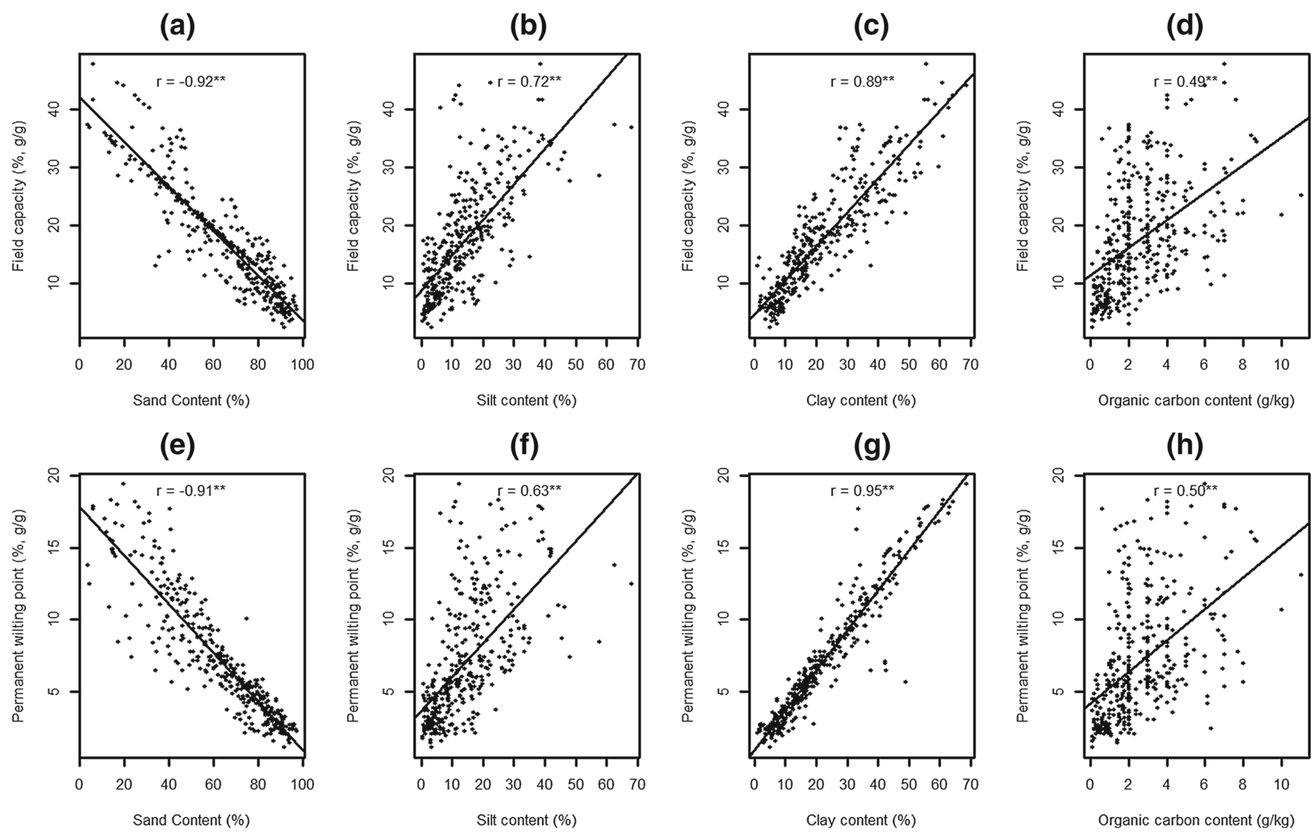

Figure 3. Scatter plots of sand content (%), silt content (%), clay content (%) and organic carbon content (g/kg) with soil water content at field capacity (%, g/g) and permanent wilting point (%, g/g).

FC and PWP whereas higher silt, clay and OC content, leads to higher soil water retention at FC and PWP. Data on particle size distribution showed stronger correlation with soil water retention than OC content. The correlations between OC content and soil water retention were 0.49 ($p < 0.01$) and 0.51 ($p < 0.01$), respectively, for FC and PWP.

3.3 *Pedotransfer functions (PTFs)*

Developed PTFs with significant selected inputs using the SAWI database, hereafter referred to as PTF_{SAWI}, are presented in table 6. The R^2 value of developed regression PTFs for both particle size distribution (PSD) category and PSD+OC category is similar. Including OC as an independent variable does not improve the regression significantly; this may be due to very low content of OC content in arid soils of India. The predictive performance of PTF models in terms of R^2 value was higher for PWP ($R^2 = 0.92$) than for FC ($R^2 = 0.87$). It indicates that predictor variables used in PTF model for PWP explained 92% variation in PWP data whereas in case of FC, 87% variation

Table 6. *Local pedotransfer functions (PTF_{SAWI}) developed with soil data from hot Arid Western India to estimate soil water retention at 1/3 bar and 15 bar.*

	Soil water content at FC (%, g/g)		Soil water content at PWP (%, g/g)	
Inputs	PSD	PSD + OC	PSD	PSD + OC
Intercept	29.79***	29.77***	5.04***	1.516***
Sand	−0.264***	−0.263***	−0.0385***	
Clay	0.207***	0.206***	0.232**	0.325***
OC		0.0110		
Sand × Clay			−0.00057**	−0.00147***
Sand × OC				0.00247**
Clay × OC				−0.00469**
	$R^2 = 0.87$	$R^2 = 0.87$	$R^2 = 0.92$	$R^2 = 0.92$

Values given in the table represents the coefficients of PTF model in the form of multiple linear regression equation as mentioned in equation (1) along with their significant levels.
*** and ** represent significance level at <0.1% and <1%, respectively.

in FC data was explained by predictor variables used in PTF model for FC. Sand content has negative influence on soil water contents at FC and PWP whereas clay content has positive influence. When OC content was considered as input in addition with PSD, it has been observed that interaction of sand and OC content has positive influence on water retention whereas interaction of clay and OC has negative influence on water retention at PWP.

Apart from PTF_{SAWI}, a set of global PTFs was also developed using the merged database from arid region of India and USA, keeping in mind their potential applicability in drylands anywhere in the world (see table 7). The predictive performances of the global PTFs in terms of R^2 value were lower than for PTF_{SAWI}; R^2 values were 0.73 and 0.72 for global PTF of FC and PWP, respectively, with PSD+OC category. It is noted here that unlike of PTF_{SAWI}'s inclusion of OC as input data improved the predictive performance of global PTFs developed from merged database since the OC content of arid soils in USA was comparatively higher than in the SAWI database, specifically for PTF of FC. Regression coefficients of developed global PTFs showed that clay has positive influence on water retention both at FC and PWP. Sand content has been observed to have a negative influence on water retention at FC as depicted by its negative coefficient. Larger influence of clay on soil water content than sand was observed in both SAWI and USA-arid database as depicted by their higher value of corresponding regression coefficients. Interaction of sand and clay showed negative influence on soil water content both at FC and PWP. When OC was introduced in PTF model as predictor variable, interaction of sand and clay with OC was found to positively influence PWP content.

3.4 *Performance of the developed PTFs*

3.4.1 *Cross-validation of PTFs*

Estimated values of soil water content at FC and PWP obtained from 10-fold cross validation of PTF_{SAWI} are plotted against observed values in figure 4. Mean absolute and mean squared error of estimated FC were found 2.49 and 11.9, respectively, whereas for PWP it was 0.73 and 1.47, respectively. Therefore, observed and estimated values are observed very close to the 1:1 line for both FC and PWP. The errors of estimations in terms of RMSE were also found very low for both FC and PWP and these were 3.44 and 1.17, respectively.

3.4.2 *Testing of PTFs*

Observed and estimated values of FC and PWP by PTF_{SAWI} and those obtained using selected 'established' PTFs were also computed for the independent testing databases, 'Jsm' and 'USA-arid' (figure 5). Scatter plots of observed and estimated values by PTF_{SAWI} and other 'established' PTFs in the 'Jsm' database are presented in figure 5(a and b). Bias of the estimated values of FC was found smaller for PTF_{SAWI}–PSD+OC ($-0.17\,g\,g^{-1}$) than for 'established' PTFs. Similarly, for PWP, bias was smaller for PTF_{SAWI}–PSD ($-0.17\,g\,g^{-1}$) than for other 'established' PTFs except for the PTF of Tomasella and Hodnett (1998) ($-0.14\,g\,g^{-1}$). In general, estimated values of soil water content at FC by the developed PTFs showed negative bias

Table 7. *Global pedotransfer functions (PTFs) developed with soil data from Arid Western Indian and arid regions of USA to estimate soil water retention at 1/3 bar and 15 bar.*

	Soil water content at FC (%, g/g)		Soil water content at PWP (%, g/g)	
Inputs	PSD	PSD + OC	PSD	PSD + OC
Intercept	27.80***	24.98***	10.06***	4.341***
Sand (%)	−0.231***	−0.205***	−0.0847***	
Clay (%)	0.262***	0.28***	0.303***	0.435***
OC (g kg^{-1})		0.192***		
Sand × Clay			−0.00186***	−0.00431***
Sand × OC				0.00190***
Clay × OC				0.00169***
	$R^2 = 0.61$	$R^2 = 0.63$	$R^2 = 0.73$	$R^2 = 0.72$

Values given in the table represents the coefficients of PTF model in the form of multiple linear regression equation as mentioned in equation (2) along with their significant levels.
*** and ** represent significance level at <0.1% and <1%, respectively.

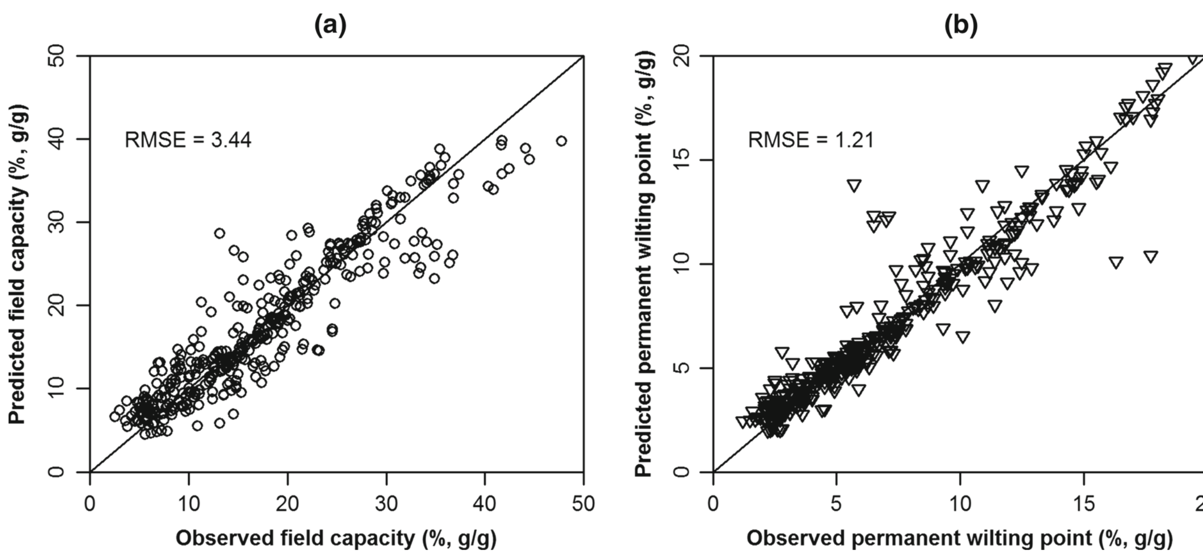

Figure 4. Cross validation of observed and PTF_{SAWI} (PSD+OC)-estimated water content at field capacity (%, g/g) and permanent wilting point (%, g/g). Solid line is the 1:1 line.

indicating that predicted values are larger than observed values. The 'established' PTFs showed positive bias in estimation of FC except in comparison with the PTF by Chakraborty *et al.* (2011). In case of PWP, bias was found negative for both the developed PTFs and 'established' PTFs except for the PTF by Adhikary *et al.* (2008). However, when the developed PTFs as well as 'established' PTFs were tested using the independent dataset from an arid region of USA, overall positive bias was observed, indicating a tendency for underprediction. The difference in observed and estimated values by 'established' PTFs was due to differences in soil properties represented in the testing database versus the range of soil properties from which the 'established' PTFs were developed. For example, sand content was very high and OC content very low in the testing database 'Jsm', in comparison to the range of soil properties using which 'established' PTFs were developed. Similar observations on non-portability of PTFs to other regions have been reported elsewhere (van Den Berg *et al.* 1997; Wösten *et al.* 1999; Hodnett and Tomasella 2002; Balland *et al.* 2008). The estimation performance of PTF_{SAWI} in 'USA-arid' database is also presented in figure 5(c and d). Overall, the estimated values of soil water content at FC were evenly distributed around the 1:1 line whereas for PWP, it showed negative bias.

Comparative performance of the PTFs developed in this study and the 'established' PTFs using both test datasets, 'Jsm' and 'USA-arid', in terms

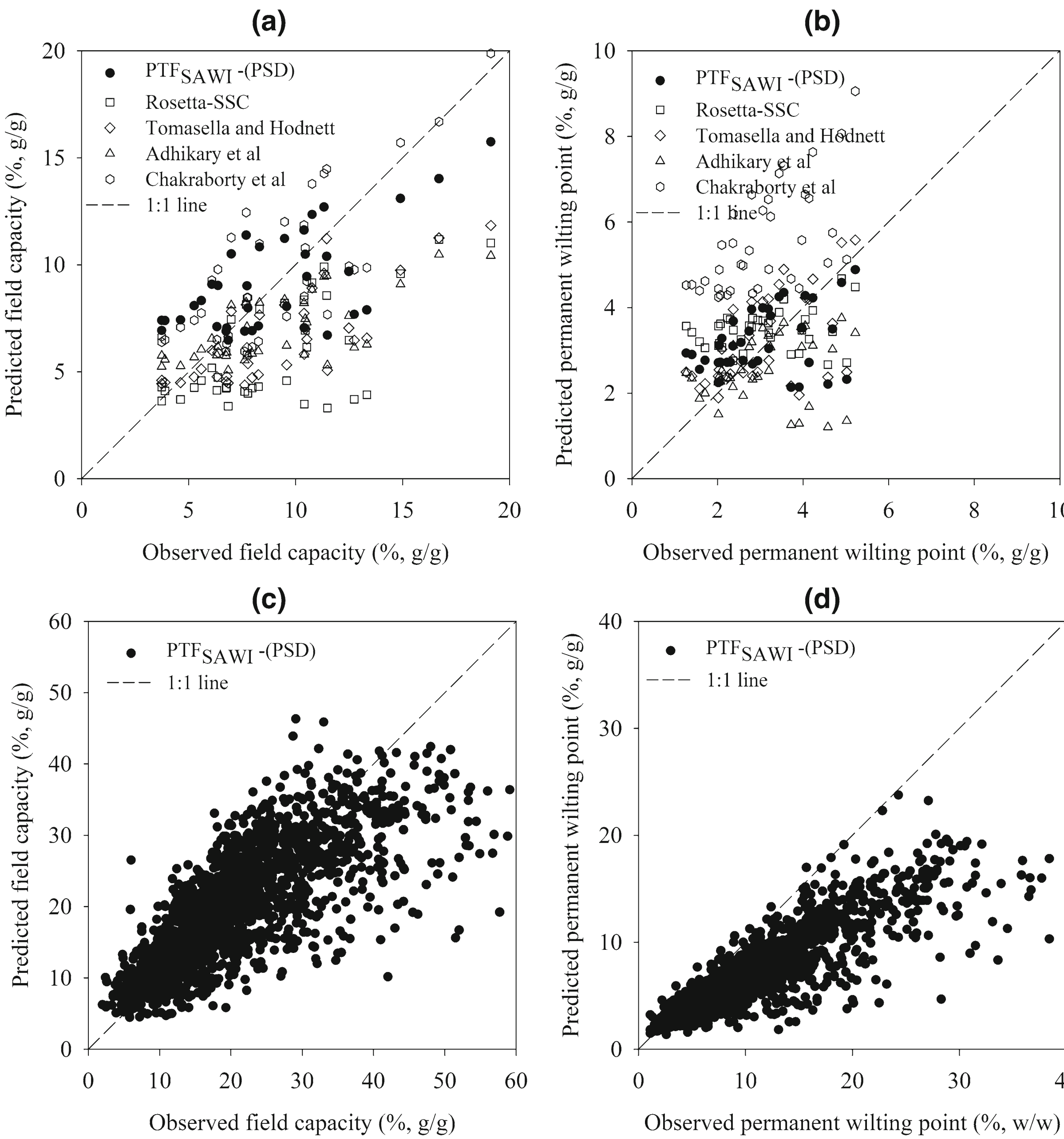

Figure 5. Comparative performance of PTFs developed in this study with selected 'established' PTFs to estimate soil water content at FC (%, g/g) and PWP (%, g/g), using independent soil databases (**a** and **b**) from Jaisalmer region of hot Arid Western India; (**c** and **d**) from arid region of USA.

of RMSE, is presented in table 8. Performance of PTF$_{SAWI}$ was better in 'Jsm' database as shown by lower RMSE values as compared to other 'established' PTFs. However, when PTF$_{SAWI}$ was applied to data from an arid region of the USA to estimate soil water content at FC and PWP, the performance was better than for other 'established' PTFs, but not better than for global PTFs.

Comparative analysis of developed PTFs and 'established' PTFs in both datasets indicated that the performance of global PTFs was best, whereas in 'Jsm' database performance of PTF$_{SAWI}$ was superior. This indicates the problem of limited portability of PTFs, even within similar soil-climatic regions. Soil properties or pedological features of the dataset to which a given PTF is to be applied need to be similar to those represented in the original dataset from which a PTF was developed. However, when global PTFs developed from the merged database from arid regions

Table 8. *Comparative performance of the developed pedotransfer functions (PTFs) for two independent databases.*

Pedotransfer functions (PTFs)	RMSE				Bias			
	'Jsm' database		'USA-Arid' database		'Jsm' database		'USA-Arid' database	
	FC*	PWP*	FC*	PWP*	FC*	PWP*	FC*	PWP*
PTF_{SAWI} (PSD)	2.65	1.08	7.16	5.19	−0.18	−0.17	0.91	3.54
PTF_{SAWI} (PSD+OC)	2.65	1.10	7.13	5.64	−0.17	−0.20	0.87	4.01
Global PTF for dryland (PSD)	3.07	1.47	7.05	3.32	−1.36	−1.01	0.28	0.47
Global PTF for dryland (PSD+OC)	2.97	2.28	6.82	3.35	−1.06	−2.06	0.22	0.52
Schaap *et al.* (2001) (Rosetta-SSC)	4.20	1.15	12.22	7.68	3.13	−0.40	6.07	4.26
Tomasella and Hodnett (1998)	3.42	1.00	8.30	4.03	2.44	−0.14	3.53	1.41
Adhikary *et al.* (2008)	3.41	1.30	8.76	5.76	2.04	0.52	5.57	4.45
Chakraborty *et al.* (2011)	2.43	2.71	9.32	4.31	−0.69	−2.48	−3.48	−0.79

*FC and PWP represent the soil water content (%, g/g) at 1/3 bar and 15 bar, respectively.

of India and USA were tested, they showed better performance in both the testing dataset, whether from India or USA. Therefore, we recommend the PTF_{SAWI} for more accurate estimation of FC and PWP within hot Arid Western India, while global PTFs will be more accurate for drylands elsewhere in the world. Among the 'established' PTFs, those of Tomasella and Hodnett (1998) performed better than others in this study, both for the 'Jsm' and 'USA-arid' databases (see table 8). Specifically, it may be noted here that the PTFs by Tomasella and Hodnett (1998) outperformed the PTF_{SAWI} and global PTF in the 'Jsm' database, when estimating soil water content at PWP. Alternatively, the PTF by Chakraborty *et al.* (2011) outperformed PTF_{SAWI} and global PTF while estimating soil water content at FC in the 'Jsm' database.

3.5 *PTF based soil moisture calculator*

For wide applicability of the developed PTFs, a user-friendly soil moisture calculator, 'CAZRI soil moisture calculator' was developed; it may be downloaded from http://www.cazri.res.in/soil-moisture-calc.php (figure 6). First, using a pull-down menu, users must choose the appropriate PTF. Subsequently, for any field, users must enter the sand, silt, clay and OC content. Upon pressing 'enter', the FC and PWP are calculated.

For arid regions in India, we recommend the PTF_{SAWI} models that consider either the PSD or PSD+OC category depending on the availability of input data. In the CAZRI soil moisture calculator these models are referred to as CAZRI PTF model. However, for dry lands elsewhere in the world, global PTFs may be selected using the drop-down menu for model selection. Apart from dry lands, the calculator may also be used elsewhere in India or tropical countries of the world, since it also contains the robust PTF model of Tomasella and Hodnett (1998), Adhikary *et al.* (2008) and Chakraborty *et al.* (2011).

Knowledge on estimated critical soil moisture constants may guide the farmers to apply the right amount of irrigation water at the right time, possibly with support of an extension service. For example, in a farmer's field with sand, silt and clay content of 87, 8 and 5%, respectively, the estimate of soil water content at FC and PWP will be 7.90 and 2.60% (g/g), respectively, if CAZRI PTF model (PTF_{SAWI}) with PSD category of input data is selected. These estimates will further lead to an estimate of maximum plant available soil water

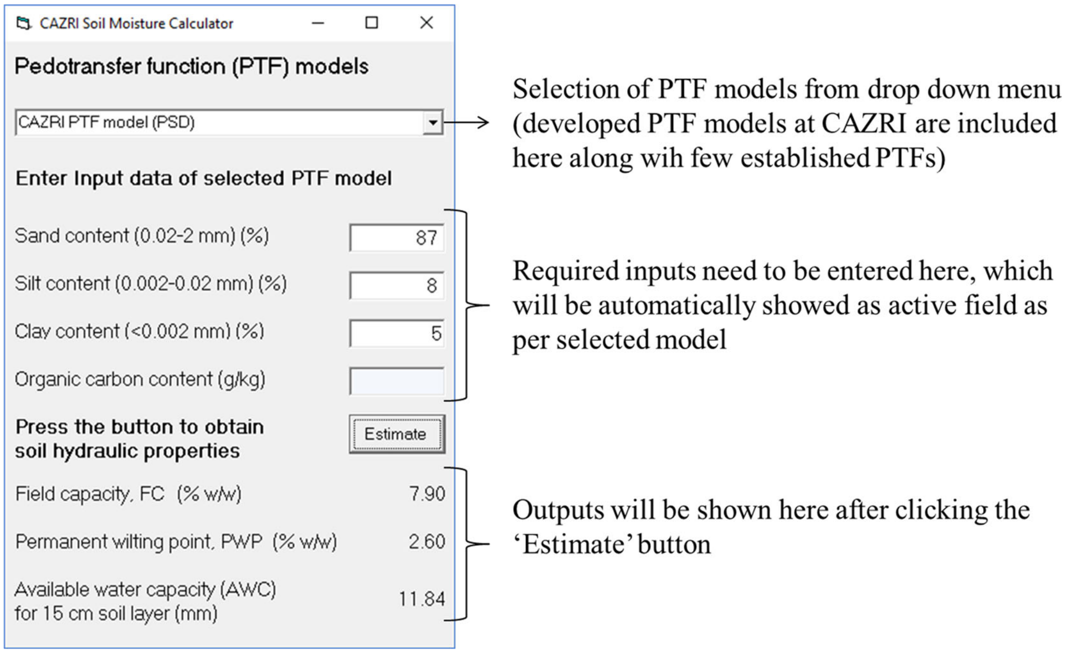

Figure 6. Software console of PTF based CAZRI soil moisture calculator.

of 11.8 mm in surface soil (0–15 cm) assuming an average bulk density of 1.49 $\mathrm{Mg\,m^{-3}}$ for arid western India, as found in the SAWI database. For example, if a farmer wishes to apply irrigation at 50% soil moisture depletion then he should irrigate the field when soil water content dries to 5.25% (g/g) from FC level [soil moisture content after 50% depletion = FC − 0.5×(FC–PWP)] and the required quantity of irrigation water will be 59.2 $\mathrm{m^3\,ha^{-1}}$ for bringing the soil moisture level of the 0–15 cm soil layer again to FC level [required amount of water = (FC − soil moisture) × bulk density × soil depth × area to be irrigated]. In the above calculation, a linear decrease in soil water content during the process of soil drying was assumed. For a more accurate estimation of the required amount of water, a curvilinear relationship between water potential (h) and soil water content (θ) may be considered, but this would require tedious field monitoring of soil water suction levels using a tensiometer. The CAZRI soil moisture calculator developed in the context of this study may help extension workers to assist farmers in saving the scarce water resources, while maintaining the required productivity.

4. Conclusions

PTFs were developed to estimate soil water content at FC and PWP, drawing on a soil database for Arid Western India, with the aim to allow for judicious use of scarce water resources in dry land agriculture. Evaluation of the developed PTFs showed satisfactory performance in cross-validation. However, when these local PTFs were applied to a soil dataset for arid USA, the performance was not satisfactory. To address the problem of lack of portability of local PTFs across regions, we developed a set of global PTFs using the merged database for soils from arid regions of India and USA. These global PTFs performed better than other 'established' PTFs, both for the test dataset from India and from the USA. The PTFs developed in this study will be used by extension workers to help dry land farmers save scarce irrigation water through judicious irrigation scheduling.

Acknowledgements

We express our sincere thanks to the Director, ICAR-CAZRI Jodhpur for providing necessary support to carry out the present study (CAZRI/T-04/31). The senior author (PS) also expresses his sincere thanks to the National Director, NAIP (ICAR), Director CAZRI and Dr P C Pande, Head of Division CAZRI for providing the opportunity for foreign training in Geoinformatics, and to Dr H M C van Holsteijn, Director a.i. of ISRIC–World Soil Information, The Netherlands, for hosting PS as a guest researcher working on 'spatial assessment of soil properties using digital soil mapping techniques' (Sept.–Dec. 2013). We thank the Editor and reviewers for their detailed and insightful comments that helped to improve the paper.

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Corresponding editor: Prashant K Srivastava