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Abstract. The accuracy in predicting the water retention characteristics of some widely used pedotransfer functions (PTFs) was tested using a database of 149 soil samples collected in three Sicilian areas. The PTFs performance was assessed in terms of maximum error (*ME*), average error (*AE*) and root mean square error (*RMSE*) between predicted and measured water content data. The influence of pressure head and input soil attributes on the predictions was also evaluated. The PTF-VE by Vereecken *et al.* (1989) yielded the best result, even if it tended to underestimate the water contents in the considered pressure head range. Good results were also obtained with the PTF-HY by Wosten *et al.* (1999) and the PTF-S2 by Saxton and Rawls (2006). In particular, the PTF-HY was the less biased PTF among the five considered. The PTF-S1 by Saxton *et al.* (1986) had a little worse performance, but this result should be considered with particular interest given that only texture is required as input. Prediction obtained by the PTF-RB by Rawls and Brakensiek (1989) was affected by the highest mean *RMSE* value. Most of the considered PTFs tended to overestimate the water content at high pressure heads and to underestimate it at low pressure heads. The estimated water contents were affected by soil sample attributes like bulk density, clay and silt content whereas no substantial influence of organic matter and sand content was detected. Practically, the use of the PTF-VE or PTF-HY may be recommended when adequate on soil information is available. Alternatively, the use of the PFT-S1 is suggested if only soil texture is known.

Keywords. Soil water retention – PTF.

Titre : Prédiction de la retention hydrique des sols Siciliens à partir des fonctions de pédotransfert

Résumé. La précision de la prédiction des caractéristiques de la retention hydrique du sol à partir de quelques fonctions de pédotransfert (PTFs), largement utilisées, a été testée en utilisant une base de données de 149 échantillons de sol prélevés dans trois zones Siciliennes. . La performance des PTFs a été évaluée en termes d'erreur maximale (ME), erreur moyenne (AE) et racine de l'erreur moyenne quadratique (RMSE) entre les valeurs de la teneur en eau mesurées et estimées. L'influence de la pression et des variables d'entrée du sol sur les prédictions, ont été également évaluées. La PTF-VE proposée par Vereecken et al. (1989) a donné le meilleur résultat, même si elle tend à sous-estimer la teneur en eau dans l'intervalle des pressions considérées. De bons résultats ont aussi été obtenus avec la PTF-HY proposée par Wosten et al. (1999) et la PTF-S2 proposée par Saxton et Rawls (2006). En particulier, la PTF-HY a produit moins d'erreurs parmi les cinq PTF considérées. La PTF-S1 proposée par Saxton et al. (1986) a montré un résultat médiocre, qui devrait être interprété considérant que cette fonction n'exige que la texture comme donnée d'entrée. Les estimations obtenues par la PTF-RB proposée par Rawls et Brakensiek (1989) ont été caractérisées par les valeurs les plus élevées de la RMSE. . La plupart des PTFs considérées ont montré une tendance à surestimer la teneur en eau pour les hautes valeurs de pression et à la sous-estimer pour les valeurs inférieures. Les estimations de la teneur en eau ont été affectées par les propriétés du sol comme la densité apparente, le contenu en argile et limon, cependant, aucune influence n'a été attribuée à la teneur en matière organique et sable. En pratique, le recours à la PTF-VE ou à la PTF-HY peut être recommandé quand les informations sur les caractéristiques du sol sont disponibles. Alternativement, le recours à la PTF-S1 est recommandé dans les conditions où seulement la texture est connue.

Mots-clés. Retention hydrique du sol – Fonction de pédotransfert (PTF).

I – Introduction

Application of simulation models to predict transport of water and chemicals in unsaturated soils is often limited by the lack of representative data for soil hydraulic properties, i.e. the relationships between soil water pressure head, *h*, water content, θ, and hydraulic conductivity, *K*. Because of soil spatial variability, direct measurements of soil hydraulic properties are time consuming and require complex measurement devices and skilled operators which make them practically unfeasible at the scale of irrigation district. As a result, there is a great interest in developing pedotransfer functions (PTFs) that predict the soil hydraulic properties from more easily measured and/or routinely surveyed soil data such as particle size distribution, organic carbon content and bulk density.

The saturated and near-saturated soil hydraulic conductivity is greatly controlled by soil structural features (e.g. macropores) and its prediction from bulk soil properties has met with limited success (Tietje and Tapkenhinrichs, 1993; Wosten *et al.*, 2001; Jarvis *et al.*, 2002). On the other hand, empirically or theoretically derived PTFs often proved to be good predictors of the soil water retention characteristic (e.g. Tietje and Tapkenhinrichs, 1993). A field strategy to facilitate determination of both the water retention curve, $\theta(h)$, and the hydraulic conductivity function, $K(\theta)$, may rely on the measurement of simple soil physical/chemical attributes and the saturated soil hydraulic conductivity by an infiltrometric technique. The $\theta(h)$ curve is estimated using existing or specifically developed PTFs. The $K(\theta)$ function can be obtained using the estimated water retention curve and a "matching *K* value" measured at saturation (e.g. Lassabatère *et al.*, 2006).

The first step in this strategy is the selection of appropriate PTFs for estimating the water retention curve. As most of available PTFs were developed empirically, their applicability may be limited to the data used to define them and their use for other soils may yield unreliable predictions (Wosten *et al.*, 2001). The accuracy of PTFs can only be evaluated using independent data sets (Schaap, 2004). This means that users should preliminarily obtain a data set and test several PTFs in order to decide whether or not a particular PTF is suitable for a particular application. However, the lack of truly representative information on soil hydraulic characteristics is the main drawback to PTFs validation in certain areas. In particular, soil databases contains mainly results for soils in Northern Europe and Northern America, whereas validation for soils in the Mediterranean region is very limited (Goncalves *et al.*, 1997).

With the aim to evaluate the accuracy in predicting the water retention characteristics for Sicily, some widely used PTFs (Saxton *et al.*, 1986; Rawls and Brakensiek, 1989; Vereecken *et al.*, 1989; Wosten *et al.*, 1999; Saxton and Rawls, 2006) were tested using a data set specifically collected in three areas characterized by different pedology and land use.

II – Materials and methods

1. Description of the pedotransfer functions

A PTF is a function that has as arguments basic data describing the soil (e.g., particle size distribution, bulk density and organic carbon content) and yields as a result the water retention function and/or the unsaturated hydraulic conductivity function (including saturated hydraulic conductivity) (Tietje and Tapkenhinrichs, 1993). The soil water retention function may be determined by estimating discrete water content values, θ_i, at specific pressure heads, h_i, or by estimating the parameters of selected closed-form analytical functions $\theta(h)$ (Romano and Santini, 1997). The former method is referred to as the Point Regression Method and the latter one as the Functional Parameter Regression Method (Tietje and Tapkenhinrichs, 1993). The Point Regression Method may result in non-monotonic retention functions mainly when water contents are calculated from different regressor variables at different pressure head values or when prediction is carried out for soils differing from those included in the calibration database. The PTFs that estimate the retention function parameters are easy to use for modeling purposes (Tietje and Tapkenhinrichs, 1993).

Five PTFs were chosen in this investigation. Selection of PTFs was conducted according to their reliability as well as to previous validations under different conditions (Tietje and Tapkenhinrichs, 1993; Romano and Santini, 1997). All selected PTFs were characterized by input data that are easily gathered by common soil survey (i.e. soil texture, organic matter content and bulk density).

The PTFs by Saxton *et al.* (1986) (PTF-S1) and Saxton and Rawls (2006) (PTF-S2) describe the water retention function with three equations for different pressure head subranges, and strictly speaking cannot be considered as Functional Parameter Regression Methods. In particular, the following relationships were considered: i) a constant water content equal to the saturated water content, θ_s, for pressure head ranging from zero to the air entry pressure head, h_b, that is itself estimated from soil physical attributes; ii) a linear relationship from h_b to an intermediate pressure head fixed to -102 cm (PTF-S1) or -336.6 cm (PTF-S2); iii) an exponential function for h values lower than -102 cm (or -336.6 cm). The database of soil attributes used to develop the PTF-S1 (Saxton *et al.*, 1986) included a very extensive set of 2541 soil horizons (Rawls *et al.*, 1982). The derived expressions are applicable to soils with the following ranges of clay, Cl, and sand, Sa, contents: 5% ≤ Sa ≤ 30% if 8% ≤ Cl ≤ 58% and 30% ≤ Sa ≤ 95% if 5% ≤ Cl ≤ 60%. As compared to PTF-S1, a wider dataset of approximately 2000 soil water characteristics from A-horizons and 2000 soil water characteristics from B- and C-horizons was used to derive the PTF-S2 (Saxton and Rawls, 2006) which is applicable for Cl < 60% and organic matter content, OM, lower than 8%.

The PTF from Rawls and Brakensiek (1989) (PTF-RB) estimates the parameters (residual water content, θ_r, saturated water content, θ_s, air-entry pressure head, h_b, and pore size index, λ) of the Brooks and Corey (1964) retention function:

$$\theta = \theta_s \qquad \text{for } h_b \leq h \leq 0 \tag{1a}$$

$$\theta = \theta_r + (\theta_s - \theta_r)(h_b/h)^{\lambda} \qquad \text{for } h < h_b \tag{1b}$$

The regression equations, were based on the same database from Rawls *et al.* (1982) and are valid for 5 ≤ Sa ≤ 70% and 5 ≤ Cl ≤ 60%.

The European soil database HYPRES was used by Wosten *et al.* (1999) to develop a PTF (PTF-HY) giving the parameters of the van Genuchten's water retention function (van Genuchten, 1980):

$$\theta = \theta_r + (\theta_s - \theta_r)\left(1 + |\alpha h|^n\right)^{-m} \tag{2}$$

in which α (cm^{-1}), n and m are empirical parameters with $m = 1 - 1/n$. Note that eq. (2) is structurally similar to eq. (1b) with $\alpha = h_b$–1, $n = \lambda + 1$ and $m = \lambda/(\lambda + 1)$ (Romano and Santini, 1997).

A modified form of the van Genuchten function was used by Vereckeen *et al.* (1989), who reduced the number of parameters to be estimated with the simplifying assumption m = 1 (PTF-VE). Expressions for parameters α, n, θ_s and θ_r, were derived for 182 horizons in Belgium, with Cl < 54.5 %, Si < 80.7%, 5.6 < Sa < 97.8%, organic carbon content, OC < 6.6% and bulk density, 1.04 < ρ_b < 1.23 Mg m^{-3}. It should be noted that the modified form of eq. (2) results in different values for α and n, so that they cannot be compared with the corresponding values of the original van Genuchten equation.

Figure 1. Locations of the three sampling areas.

The five PTFs chosen for this comparison are characterized by an increasing level of soil attributes needed for estimation: two textural fractions for PTF-S1; two textural fractions plus soil porosity or organic matter content for PTF-S2 and PTF-RB; two textural fractions plus bulk density and organic matter content for PTF-HY and PTF-VE.

2. Sampled areas and laboratory measurements

Application of the selected PTFs was conducted on a data set made up by soil properties collected in three areas in Sicily (Figure 1). The first data sampling was conducted in the wine-specialized area of *Menfi*. Soil samples were collected in the upper horizon of 84 sampling points located in an area of approximately 850 ha. The second data sampling was conducted in the lower valley of *Dirillo*, in a 3000 ha area characterized by different pedology and land use with prevailing horticultural and herbaceous crops. The data set consists of data for 61 sampling points located in both the upper (A horizon) and the lower (B and/or C horizons) parts of 29 soil profiles. The third data sampling was conducted in an environmental protection area of 140 ha named *Riserva Naturale Integrale Grotta di Santa Ninfa* including both extensive crops and non-agricultural crops. A total of 54 sampling points were established in six plots characterized by a different land use (Bagarello *et al.*, 2008). Additional information on the data set is given in Table 1.

For each sampling point, the clay, *Cl*, silt, *Si*, and sand, *Sa*, percentages were determined according to the USDA classification (Gee and Or, 2002). The organic carbon, *OC*, content was determined by the Walkley-Black method (Nelson and Sommers, 1996). Where required, the organic matter, *OM*, content was estimated to be 1.724 times *OC*.

Water retention data were determined on undisturbed soil core (inside diameter = 0.08 m, height = 0.05 m) by a hanging water column apparatus (Burke *et al.*, 1986) for *h* values ranging from –0.05 to –1.5 m.

At the end of experiment, the undisturbed soil cores were used to determine the dry bulk density, ρ_b (Mg m^{-3}). Soil porosity, Φ (m^3 m^{-3}) was calculated from ρ_b assuming a particle density of 2.6 Mg m^{-3}. For each sampling point, sieved soil was packed to the ρ_b value of the undisturbed core in rings having an inside diameter of 0.05 m and a height of 0.01 m. These soil samples were used to determine the soil water content corresponding to *h* = –3.37, –10.2, –30.6, and –153.0 m by a pressure plate apparatus (Dane and Hopmans, 2002). For a small number of the undisturbed soil cores collected in the *Menfi* area (*N* = 22), two additional points of the water retention curve were determined by the pressure plate apparatus (*h* = –3 and –6 m) on the same sample used in the hanging water columns apparatus.

3. Method of evaluation

The considered PTFs were calibrated within different ranges of soil physical variables, depending on the PTF. Even if PTFs were sometimes applied to soils with properties differing from those of the calibration data set (Tietje and Tapkenhinrichs, 1993), they should not be used to make predictions for soils that are outside the range of soils used to derive them (Wosten *et al.*, 2001). Therefore, we considered only the soils for which all the selected PTFs could be applied. This resulted in a reduced data set of 149 soil data covering a broad range of textures (Figure 2). Information on the ranges of the variables used for PTF evaluation is given in Table 2.

Three out of the selected PTFs (PTF-RB, PTF-HY and PTF-VE) predict the parameters of the closed form functions used to describe the water retention curve, whereas PTF-S1 and PTF-S2 give the water content at fixed pressure head values. In order to make the comparison of the selected PTFs homogeneous, we decided to use the parameters estimated by PTF-RB, PFT-HY and PTF-VE with the appropriate water retention function (i.e. Brooks and Corey or van Genuchten) to estimate the water content at the experimentally imposed pressure heads. In this way, five estimated θ values (one for each selected PTF) were obtained for each soil of the validation data set and for each measured θ value.

The water content estimates were evaluated using the following statistics (Wosten *et al.*, 2001):

Maximum Error, $$ME = max\left|P_i - O_i\right| \quad (3)$$

Table 1. Description of the data set used to evaluate the pedotransfer functions

	Menfi	Dirillo	Santa Ninfa
N. of soil samples	84	61	54
N. of soil units	8	28	n.a.
Date of sampling	Jan. – Feb. 2002	March 2006	May 2006
Pressure heads for water retention measurements (m)	-0.05, - 0.1, -0.2, -0.4, -0.7, -1, -1.2, -1.5, -3, -3.37, -6, -10.2, - 30.6, -153	-0.05, - 0.1, -0.2, -0.4, -0.7, -1, -3.37, -10.2, - 30.6, -153	-0.05, - 0.1, -0.2, -0.4, -0.7, -1.2, -3.37, -10.2, - 30.6, -153

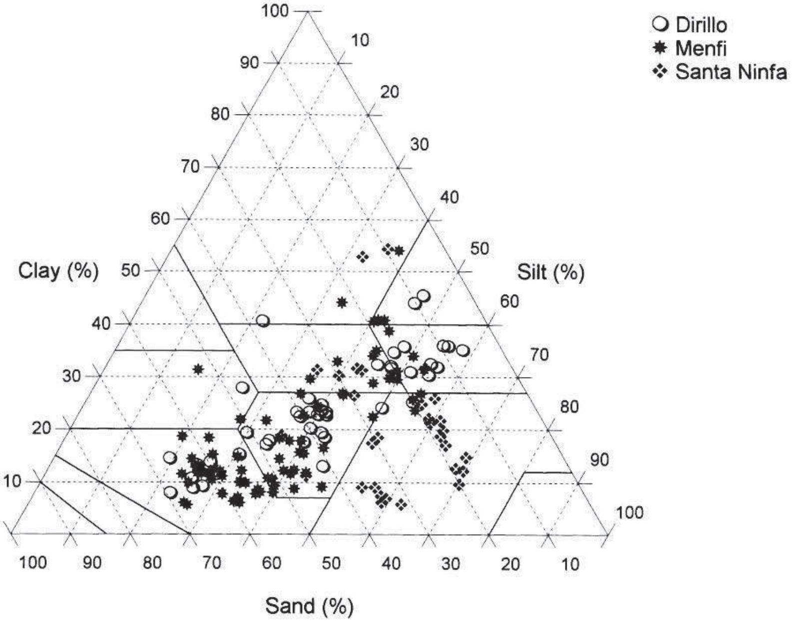

Figure 2. Texture classification, according to USDA, of the experimental data set.

Average Error,
$$AE = \frac{\sum_{i=1}^{N}(P_i - O_i)}{N} \quad (4)$$

Root Mean Square Error
$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (5)$$

where N is the number of observations, O_i is the measured value of θ and P_i is the predicted value of θ. The *ME* value can be considered as a local indicator of the goodness of the estimate provided by a certain PTF. The *AE* value reveals the presence of a systematic over- or under-estimation. The *RMSE* is a measure of the dispersion between measured and estimated values (Romano and Santini, 1997). Three statistical indices were used for PTFs evaluation given that each index serves different purposes and it is not possible to define a single statistic that adequately describe the PTFs performance (Donatelli *et al.*, 2004).

Table 2. Value ranges and statistics of the 149 soil samples considered for PTF comparison

	Cl (%)	Si (%)	Sa (%)	OC (%)	ρ_b (Mg m^{-3})	Φ (m^3 m^{-3})
min	5.7	15.8	6.5	0.10	0.830	0.332
max	54.3	70.3	69.2	3.70	1.769	0.687
mean	21.0	41.3	37.7	1.01	1.271	0.515
st. dev.	11.0	11.9	17.6	0.67	0.172	0.062

The statistics were calculated separately for each soil sample thus obtaining 149 values of *ME*, *AE* and *RMSE*, respectively. This approach is somewhat similar to that of Tietje and Tapkenhinrichs (1993) who defined the mean error and the root mean square error of a single water retention curve by integration over a certain pressure head range. In our case, from a minimum of 10 to a maximum of 14 water content data were obtained for a given soil sample (Table 1). Therefore, the *ME*, *AE* and *RMSE* statistics were calculated for each soil sample using a relatively similar, but not identical, *N* value. For comparative purposes, *RMSE* was also calculated for a given PTF by considering simultaneously all available predicted vs. measured data points. In this case, the statistic was denoted as total *RMSE*.

The influence of the pressure head value on the estimated θ values was evaluated by calculating the *ME*, *AE* and *RMSE* statistics at selected *h* values ranging from ˜0.1 to ˜153 m. To better investigate the PTFs performances, an analysis of the patterns of the errors was also conducted (Ungaro and Calzolari, 2001; Donatelli *et al.*, 2004). The *RMSE* values calculated for each soil sample were correlated to the input variables (*Cl*, *Si*, *Sa*, *OM* and ρ_b) and an F-test was conducted to evaluate the statistical significance of the calculated correlation coefficients ($P = 0.05$).

III – Results and discussion

The tested PTFs produced mean *ME* values ranging from 0.084 to 0.116 m^3 m^{-3} (Table 3) but, for a few soil samples, *ME* raised up to 0.23 – 0.28 m^3 m^{-3} showing that, for a given pressure head value, application of PTFs may yield a large error in predicted water content.

The mean *AE* values ranged from –0.0087 to 0.0082 m^3 m^{-3}. In absolute terms, the lowest mean *AE* value (*AE* = –0.0052 m^3 m^{-3}) was obtained for the PTF-HY that was the less biased PTF among the five considered. The second best result was obtained with the PTF-S1 (mean *AE* = 0.0062 m^3 m^{-3}), whereas the PTF-RB, PTF-S2 and PTF-VE yielded worse results (Table 3). Negative values of the mean *AE* were obtained with the PTFs by Wosten *et al.* (1999) (PTF-HY) and Vereecken *et al.* (1989) (PFT-VE), indicating that, generally, an underestimation of soil water content should be expected with these PTFs. Conversely, PTF-S1, PTF-S2 and PTF-RB yielded positive mean *AE* values.

Table 3. Minimum, maximun and mean values of the statistics ME, AE and RMSE resulting from application of the selected PTFs to the samples of the data set. Total AE and RMSE are also reported

		PTF-S1	PTF-S2	PTF-RB	PTF-HY	PTF-VE
ME	min	0.0442	0.0283	0.0266	0.0214	0.0244
	max	0.2409	0.2315	0.2768	0.2689	0.2508
	mean	0.1064	0.0962	0.1158	0.0920	0.0835
AE	min	-0.1347	-0.1460	-0.1065	-0.1182	-0.1566
	max	0.1091	0.0955	0.1338	0.1744	0.1078
	mean	0.0062	0.0082	0.0080	-0.0052	-0.0087
RMSE	min	0.0279	0.0174	0.0150	0.0091	0.0141
	max	0.1455	0.1561	0.1682	0.2003	0.1586
	mean	0.0629	0.0579	0.0684	0.0566	0.0517
Total RMSE		0.0667	0.0617	0.0975	0.0637	0.0576

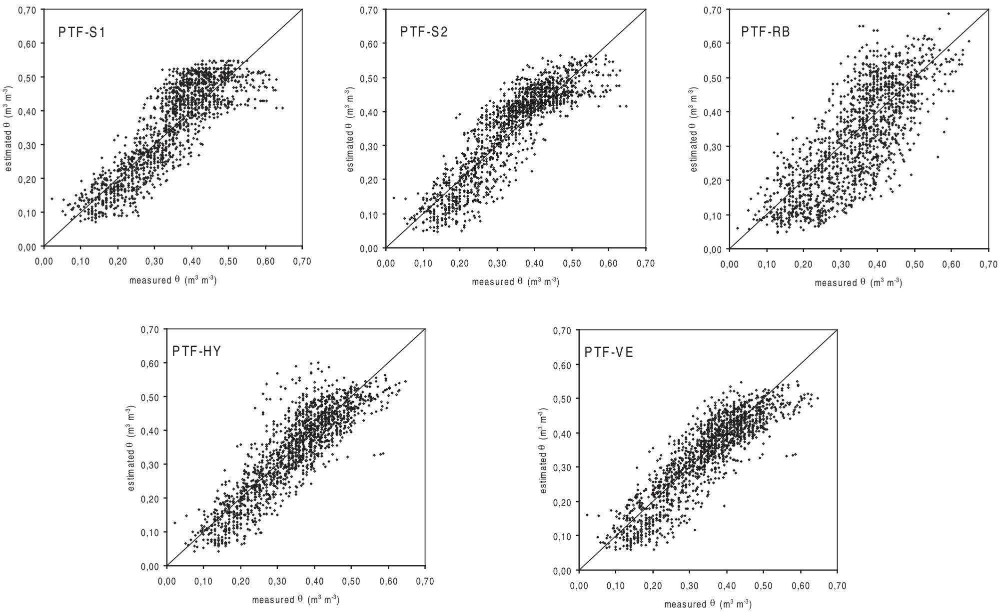

Figure 3. Estimated vs. measured water content, θ, values for the tested PTFs.

The *RMSE* values calculated for each soil sample and for each PTF ranged from 0.009 to 0.200 $m^3\ m^{-3}$. The best result in terms of mean *RMSE* was achieved by the PTF-VE, followed by the PTF-HY and PTF-S2 (Table 3). A higher mean *RMSE* value was obtained with the PTF-S1 whereas PTF-RB produced the worst mean *RMSE* value. The total *RMSE* values did not coincide with the corresponding mean *RMSE* values and a slightly different ranking of the considered PTFs was obtained with the two procedures for *RMSE* calculation (Table 3). However, the best (PTF-VE) and the worst (PTF-RB) PTF did not change between the two sets of *RMSE* values (Figure 3). A difference between total and mean *RMSE* was not surprising since the number of θ data was not exactly constant (i.e., it varied between 10 and 14) among samples.

Donatelli *et al.* (2004) suggested that *RMSE* normally takes precedence over the other statistics in the evaluation procedure of different PTFs. According to this criterion, PTF-VE yielded the most reliable results among the tested PTFs for the considered data set. However, the best *AE* result was obtained with the PTF-HY that also yielded the second best results in terms of both (mean) *RMSE* and *ME*. Moreover, both visual inspection of the estimated vs. measured plot (Figure 3) and examination of the calculated statistics (Table 3) suggested that using the PTF-S1 and PTF-S2 did not introduce substantial additional errors as compared to the PTF-VE and PTF-HY. This last result is important because the PTF-S1 uses only soil textural fractions to predict θ.

For a broad range of soils in Germany, Tietje and Tapkenhinrichs (1993) also found an overall better performance of the PTF-VE with a mean *RMSE* value of 0.0531 $m^3\ m^{-3}$ very close to the one obtained in this evaluation. In their case, the PTF-VE also resulted in a general underestimation of the water content (AE = –0.0145 $m^3\ m^{-3}$). A comparison of the PTF-RB and PTF-VE conducted by Romano and Santini (1997) showed that the water retention curves were better described using the PTF proposed by Vereecken *et al.* (1989). Moreover, these authors detected that the largest deviations between the measured and the estimated water content were chiefly associated to those samples having low sand content and/or low values of bulk density. Ungaro and Calzolari (2001) reported a better performance of the PTF-S1 as compared to the PTF-RB and PTF-VE (mean *RMSE* equal to 0.0698, 0.0882 and 0.0915 m^3 m^{-3}, respectively). However, the different behavior could be attributed to differences in texture of the soils considered for comparison. In this investigation also, the PTF-S1, using two textural fractions, performed better than the PTF-RB, using two textural fractions plus porosity.

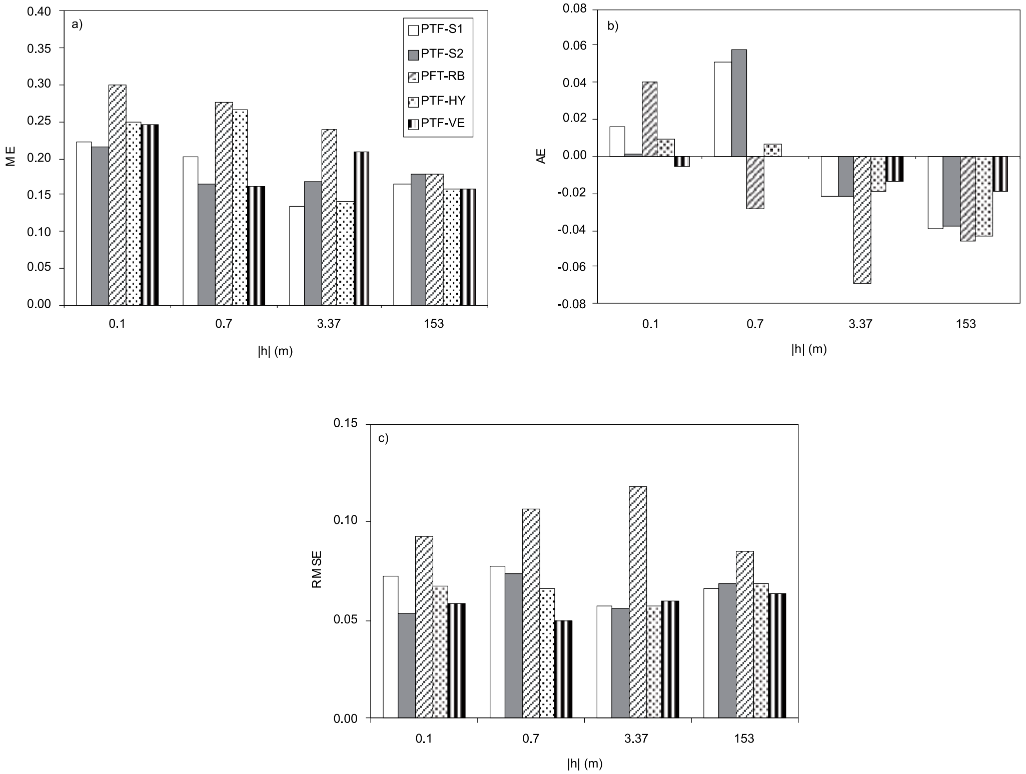

Figure 4. Statistics ME, AE and RMSE for the tested PTFs at specific pressure head, h, values.

The influence of the selected pressure head value on the water content estimates was assessed by calculating the *ME*, *AE* and *RMSE* statistics corresponding to four *h* values (*h* = –0.1, –0.7, –3.37 and –153 m) to explore a wide range of pressure heads. These *h* values were chosen because the maximum number of θ measurements (*N* = 149) were performed for each of them. Therefore, the comparison of *AE* and *RMSE* results was not distorted by *N*.

A general decrease of *ME* was detected as *h* decreased from –0.1 to –3.37 m, even if a moderate increase of *ME* was observed at *h* = –153 m (Figure 4a). Therefore, prediction of water content at high *h* values (i.e. less negative) is expected to be more prone to the occurrence of particularly high absolute deviations between measured and estimated θ values. Most of the considered PTFs showed a tendency to overestimate θ at high *h* values and to underestimate θ at low *h* values (Figure 4b). The only exception was for the PTF-VE that always underestimated θ, thus explaining the negatively biased estimation of water retention (Table 3). For the PTF-HY, a result similar to the one obtained in this investigation was reported by Ungaro e Calzolari (2001) who observed that the most significant discrepancies between measured and estimated θ values were localised at the wet and the dry end of the water retention curve. Influence of pressure head on *RMSE* was less pronounced and a common trend with *h* was not observed (Figure 4c). In most cases, *RMSE* decreased as *h* decreased from –0.1 to –3.37 m and then increased slightly at *h* = –153 m. A similar influence of the pressure head on the performances of the PTF-VE and PTF-RB was also observed by Wosten *et al.* (2001).

Plot of errors allows detecting if the goodness of the prediction changes according to the input value (Donatelli *et al.*, 2004). The error indices *RMSE* calculated for each soil sample with the five selected PFTs were therefore plotted vs. texture, organic matter content and bulk density and correlations analyses were performed. Only the *RMSE* was considered for this analysis due to the following reasons: i) interpretation of regression between *AE* and a selected soil attribute may be complicated by the sign of *AE* given, for example, that a significant negative correlation could be indicative of both a reducing positive bias or an increasing negative bias; ii) in absolute terms, a low bias in the estimation of θ, suggesting a good performance of the tested PTF, could be associated with large maximum errors and highly scattered data; and iii) a highly significant linear correlation (P = 0.05) was detected between *ME* and *RMSE* (r^2 > 0.824, N = 149) suggesting that the patterns for *ME* could be explained by the analysis of *RMSE* correlations.

RMSE was generally independent of *Sa*, given that a significant negative correlation with *Sa* was detected only for the PTF-S1 (Table 4). All the selected PTFs tended to yield less accurate estimations of θ for high *Si* values. However, it should be considered that, for the PTF-S2, PTF-RB, PTF-HY and PTF-VE, *RMSE* was also negatively correlated with *Cl*. Therefore, in fine textured soils high in both clay and silt content, the increase in the estimation error due to positive correlation with *Si* may be partly compensated by the negative correlation with *Cl*. When considered separately, the estimation accuracy will improve at increasing *Cl* and decline at increasing *Si*. The *RMSE* values exhibited a low but significant negative correlation with *OM* only for the PTF-VE. For the remaining cases, no correlation was found between *RMSE* and *OM*. It could be concluded that organic matter content did not influence appreciably the accuracy of water content estimates for the selected PTFs. In all cases but one (PTF-S1), the *RMSE* values were negatively correlated with bulk density (Table 4), denoting that more accurate estimates of θ could be obtained at high ρ_b values. As an example, Figure 5 shows the mean *RMSE* vs. bulk density plot for the PTF-RB. In this case, the bulk density explained up to 47% of the variability of *RMSE*. A marked influence of ρ_b on the water content predicted by the PTF-S1, PTF-RB and PTF-VE was also reported by Ungaro and Calzolari (2001) for 139 soil horizons in the Pianura Padano-Veneta (Italy). Tietje and Tapkenhinrichs (1993) also reported a similar trend for the PTF-VE with errors that were higher for soils with low bulk density values.

Table 4. Regression coefficients for *RMSE* correlations with *Cl, Si, Sa, OM* and ρ_b

	Cl	*Si*	*Sa*	*OM*	ρ_b
PTF-S1	0.0357	**0.4510**	**-0.3274**	0.0557	-0.1434
PTF-S2	**-0.2359**	**0.3948**	-0.1185	0.1197	**-0.3584**
PTF-RB	**-0.2366**	**0.2476**	-0.0186	0.0080	**-0.4652**
PTF-HY	**-0.2133**	**0.1814**	0.0115	0.0076	**-0.3465**
PTF-VE	**-0.1688**	**0.3311**	-0.1177	**0.2022**	**-0.3091**

Correlation coefficients in bold are statistically significant at P = 0.05 level according to an F-test.

Overall, it may be concluded that the performance of the selected PFTs was generally independent of organic matter content but depended on bulk density. Regarding the influence of texture, where significant correlations were found, the clay and silt content influenced the *RMSE* value in an opposite way. Therefore, their effects could partly compensate for fine textured soils with high clay and silt content. However, the risk that water retention predictions could be less accurate for soil with high *Cl* is real for all the considered PTFs.

IV – Conclusions

The performance of five PTFs was compared for a database of 149 water retention characteristics of Sicilian soils covering a broad range of texture. Evaluated PTFs included three of the most widely applied and recommended PTFs (i.e. PTF from Saxton *et al.* (1986), Rawls and Brakensiek (1989) and Vereecken *et al.* (1989)) as well as the two more recently developed PTFs from Wosten *et al.* (1999) and Saxton and Rawls (2006). The procedure applied to calculate the error indices influenced the ranking of the evaluated PTFs, but the best result in terms of *RMSE* was undoubtedly obtained by the PTF-VE. A similar result was found by Tietje and Tapkenhinrichs (1993) and Romano and Santini (1997). Comparison of the PTF-S2 and PTF-HY with other PTFs is lacking in literature. In our case, they behaved almost as well as the PTF-VE, with the PTF-HY showing the best results in terms of unbiased predictions. Comparatively reliable results were obtained with the PFT-S1 that requires only texture as input. This result is of outmost practical interest given that soil particle size distribution is generally determined in routinely conducted soil survey, whereas bulk density measurements are often neglected.

Pressure head generally affected the PTFs performances as four out of the considered PTFs tended to overestimate θ at high h values and to underestimate θ at low h values. The only exception was for the PFT-VE that underestimated the predicted water contents in the entire range of considered pressure head values.

A similar level of accuracy can be obtained for the entire range of the organic matter values explored. Conversely, the soil bulk density significantly influenced the accuracy of water content estimates given that, in all cases but one (PTF-S1), more accurate estimates of θ were obtained at high ρ_b values. In general, the sand content did not influence the performances of the considered PTFs whereas the clay and silt contents had an opposite influence on the *RMSE* statistic. In fine textured soils with both *Cl* and *Si* content, these effects may partly compensate each other but poor water content estimates should be expected for soil with low clay content and high silt content.

The evaluation performed is the first conducted in Sicily on a large soil database. Its results confirmed that most of the considered PTFs allow reliable estimations of soil water retention characteristics and, if coupled with field measured hydraulic conductivity values, are potentially capable to yield soil hydraulic properties sufficiently accurate for large scale simulation of the soil water balance.

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