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# Predicted and measured soil retention curve parameters in Lombardy region north of Italy

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ABSTRACT

Water retention characteristics are fundamental input parameters in any modeling study on water flow and solute transport. These properties are difficult to measure and for that reason, we usually need to use direct and indirect methods to determine them. An extensive comparison between measured and estimated results is needed to determine their applicability for a range of different soils. However this study attempts to make a contribution specifically in this connection. These properties were determined in two representative sites located in Landriano field, in Lombardy region, northern Italy. In the laboratory we used the pressure plate apparatus and the tensiometric box. Field soil water retention was determined including measurements of soil water content with SENTEK probes and matric potential with tensiometers. The soil waer retention curves (SWRC) were also settled on with some recently developed pedo-transfert functions (PTFs). Field retention curves were compared against those obtained from PTFs estimations and laboratory measurements. The comparison showed that laboratory measurements were the most accurate. They had the highest ranking for the validation indices (RMSE ranging between 2.4% and 7.7% and bias between 0.1% and 6.4%). The second best technique was the PTF Rosetta (Schaap et al. 2001). They perform only slightly poorer than the laboratory measurements (RMSE ranging between 2.7% and 10% and bias between 0.3% and 7.7%). The lowest prediction accuracy is observed for the Rawls and Brakensiek (1985) PTF (RMSE ranging between 6.3% and 17% and bias between 5% and 10%) which is in contradiction with previous finding (Calzolari et al., 2001), showing that this function is well representing the retention characteristics of the area. Due to time and cost investments of laboratory and field measurements, we conclude that the Rosetta PTF developed by Schaap et al. (2001) appears to be the best to predict the soil moisture retention curve from easily available soil properties in the Lombardy area and further field investigations would be useful to support this finding.


## 1. Introduction

Water movement within the soil profile is an important component of agricultural and environmental studies and its understanding can help to solve many problems related to subsurface drainage contributions to groundwater, irrigation, water disposal, and growth of saline seeps. Effective and adequate management of water and soil therefore often requires hydraulic conductivity and water retention functions characterization of the concerned area. These functions jointly are the famous soil hydraulic properties (Klute & Dirksen, 1986).

The soil water retention curve can be described as the relationship between soil water content (θ) and the soil water potential (h). This curve depends mainly on soil texture, structure, organic matter content, and bulk density and it varies vertically and horizontally in any field. The θ-h relationship is a crucial soil property for many studies like drainage, infiltration, hydraulic conductivity, irrigation scheduling, plants water stress, etc (Kern, 1995) and is essential as inputs in most hydrological and water balance models (Bennie, Hoffman, Coetzee, & Vrey, 1994). Consequently, due to their importance in many fields, information about water retention characteristics can help farmers and governments

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on planning tool for investment and development strategies.

Selecting hydraulic properties method can depend on their accuracy, implementation difficulties, measurement range, and time consuming.

These properties are hard to measure and usually require the use of both indirect and direct methods to properly describe them. Numerous laboratory methods, field methods and theoretical models exist and each method can have both advantages and limitations (Stephens, 1996).

Several empirical models for SWRC have been developed (Brooks & Corey, 1964; Leij, Ghezzehei, & Or, 2002; Russo, 1988; Van Genuchten, 1980). These models are called Pedotransfer functions, PTFs (Bouma, 1989). In these models, the relationship between the parameters and basic soil data is described (Elsenbeer, 2001; Minasny, McBratney & Bristow, 1999; Schaap, Leij, Van Genuchten, 1998; Scheinost, Sinowski & Auerswald, 1997; Vereecken, Maes, Feyen & Darius, 1989; Wosten, Pachepsky & Rawls, 2001; Wosten and Van Genuchten, 1988).

It still requires extensive comparisons between the previously mentioned methods in order to determine their accuracy for a range of different soils. However this study attempts to make a contribution specifically in this connection.

Therefore, the aim of our study is the evaluation of the general applicability and the prediction accuracy of some of the most commonly used and some recently developed PTFs that use soil properties such as organic matter, soil content (sand, silt, and clay) and dry bulk density to predict our soil retention curve. Then to compare the estimated soil retention characteristics to those measured in the laboratory and field.

## 2. Materials and methods

The main objective of this work is to determine and compare laboratory, field, and estimated soil retention curve parameters of an experimental field in north of Italy. By the end of the season 2010, two undisturbed core samples with a volume of 235.5 cm3 (10 cm diameter and 3 cm height) were collected from each different layer (7 cm, 27 cm, 47 cm and 67 cm) from both sites (PMI-1 and PMI-5) with minimum disturbance. The undisturbed samples were used to determine bulk density and θ-h relationship at low pressure ($<300$ kPa) using the tensiometric "sand box" technique (Stackman et al., 1969) and for which we started as close to saturation as possible to try to accurately identify the air entry suction. Disturbed soil samples (14 cm3) were used for soil analyses and for the determination of the θ-h relationship at higher pressure (300–1500 kPa) using a pressure plate apparatus (Richards, 1947). For both sites (PMI-1 and PMI-5) samples were collected at the midpoint of each of the forth selected layers (0-7, 7-27, 27-47, and 47–67 cm).Because of limited budget for this experiment, only two replicates for each sampling point were taken.

The field retention curves were performed on two sites (PMI-1 and PMI-5) during two agricultural seasons 2010 and 2011. The values of the field measured soil water content θ and soil water potential h at different depths were interpolated to the retention curves by analytical relation proposed by Van Genucthen (1980). The adopted procedures were:

1. Selection of data set for *θ-h* excluding incorrect and outliers
2. Selection of saturated soil humidity values $\theta_s$
3. Defining the humidity value for the "attractive pole" used for the calibration of residual humidity $\theta_r$
4. Automatic calibration by MATLAB algorithm using least square method for non-linear model (*lsqcurvefit.m* of the MATLAB *Optimization Toolbox*) for the parameters of Van Genucthen curve a, n, and $\theta_r$

The adopted procedure consists of the former points was pursued through the following observations.

1. The initial automatic calibration of $\theta_s$ together with all the other parameters of the retention curve has led to the selection of an intermediate value in the points of θ in correspondence to the values of water potential close to zero. The cloud of point is formed because of the non-consistency of the measured values by the humidity probe and the corresponding potentials at the same depth. The $\theta_s$ value for each depth was selected looking for a compromise value between the highest values measured by the probes;
2. The value of $\theta_r$, the lower limit of the water content in the soil, occurs in correspondence to particularly negative potential values that cannot occur in the field because of the limitation of tensiometers (tensiometers are emptied for potentials lower than $-800/-1000$ cm). Calibration of $\theta_r$ with the described data set cannot be carried out, therefore an attractive pole was added to the calibration data set: 100 identical data set of the couple θ-*h* with h = −15,000 cm and θ = 0.1. The attractive pole allow the calibration algorithm to choose the parameters α, n, and $\theta_r$ so as to approach to the attraction point, thus regulating the tail of the curve, and prevent obtaining erroneous values of $\theta_r$ from the calibration. In some cases, the humidity of 0.1 was found to deform the fitting curve away from the observed values. In these cases it is then modified by assuming values slightly lower or higher, in the range of 0.05–0.25.

3. Estimated soil retention curve: Pedotransfert Functions (PTFs)

A PTF is a function that uses basic data describing the soil such as particle size distribution, bulk density and organic carbon content as inputs and its outputs are an estimation of the water retention curve and/or the hydraulic conductivity function (Tietje & Tapkenhinrichs, 1993).

In this study, two PTFs were applied and which are mainly based on the same input data: soil texture, organic matter and bulk density. PTFs were selected according to their reliability and earlier studies in the same region (Baroni et al., 2010; Calzolari, Ungaro, Busono, & Salvador Sanchiz, 2001). In particular, the followings were selected:

1. Rawls and Brakensiek (1989) PTF (PTF-RB) which estimates the parameters of the Van Genuchten retention function in particular residual water content, $\theta_{r,}$ saturated water content, $\theta_s$.

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

2. The PTF Rosetta (Schaap, Leij, & Van Genuchten, 2001, PTF-R), which is based on artificial neural networks (Minasny, McBratney, & Bristow, 1999; Pachepsky, Rawls, & Gimenez, 2000) and it works in a hierarchical approach employing five different PTF to predict water retention curves (Schaap & Leij, 1998; Schaap et al., 2001). The main advantage of neural network in comparison to usual PTFs, is that neural networks require no a priori model concept. Rosetta is a computer program that uses some of the PTFs previously published by Schaap et al. (1998) and Schaap and Leij (1998).

The necessary data for these PTFs (Table 1) were determined from soil samples at different soil horizons in which are installed the humidity probes and tensiometers.

**Table 1**
soil properties used as input parameter in PTFs.

| | Organic Carbon (%) | Mineral bulk density (g/cm$^3$) | Sand (%) | Clay (%) | Loam (%) |
|---|---|---|---|---|---|
| PMI-1_7 cm | 1.23 | 1.50 | 63.02 | 29.34 | 7.64 |
| PMI-1_27 cm | 1.23 | 1.47 | 62.413 | 30.52 | 7.06 |
| PMI-1_47 cm | 1.10 | 1.46 | 60.284 | 27.07 | 12.65 |
| PMI-1_67 cm | 0.17 | 1.60 | 76.913 | 14.39 | 8.70 |
| PMI-5_7 cm | 1.10 | 1.46 | 59.002 | 32.99 | 8.00 |
| PMI-5_27 cm | 1.10 | 1.45 | 56.967 | 33.77 | 9.26 |
| PMI-5_47 cm | 1.10 | 1.40 | 49.281 | 39.26 | 11.46 |
| PMI-5_67 cm | 0.17 | 1.36 | 31.605 | 47.58 | 20.82 |

4. Van Genuchten model: RETC code
The unknown parameters (θs,θr, n, α and m) from field and laboratory measurements were determined from the nonlinear least-squares optimization program RETC (Van Genuchten, Leij & Yates, 1991) using measured soil water retention data (field and laboratory). This model is expressed as:

$$S_e = \left[1+(\alpha h)^n\right]^{1-\frac{1}{n}} \tag{2}$$

Where $h$ is the soil water pressure head, α and n are curve shape parameters. $S_e$ is the relative saturation expressed as following:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{3}$$

5. Statistical Analysis

The performances of PTFs and laboratory in predicting measured data were assessed using four error measures. To test the match between fitted and predicted parameters, a coefficient of determination ($R^2$) was calculated. The root mean square error *RMSE* between estimated and field measured water content with different methods was computed as:

$$RMSE = \sqrt{\frac{\sum_1^N \left(y_i - \hat{y}_i\right)^2}{N}} \tag{4}$$

We computed also the mean error or bias (ME) and the mean absolute error (MAE) to quantify systematic errors:

$$ME\ \ (bias) = \frac{\sum_1^N \left(y_i - \hat{y}_i\right)}{N} \tag{5}$$

$$\mathrm{MAE} = \frac{\sum_1^N \left|y_i - \hat{y}_i\right|}{N} \tag{6}$$

Where: $y_i$ represents the measured value, is the predicted value, and $N$ is the total number of observations.

## 3. Results

Soil water characteristic curves (θ, $h$) obtained by different methods in the two experimental sites PMI-1 and PMI-5 and during the two agricultural seasons (2010 and 2011) are presented in the following figures (Figs. 1, 2, 3, and 4).

For the years 2010 and 2011, the obtained curves for the same sites can be very different from each other. This may depend on the fact that probes of humidity have been uninstalled before field cultural practices at the beginning of the agricultural season 2011 and reinstalled immediately later. Therefore, the monitoring was not performed continuously for two years at the same site. This phenomenon can however influence more the top soil. The retention curves for the deepest layers may appear different in the two years, but these curves are usually the result of the wider range of values obtained from the extrapolation.

Most of the water retention curves show a fairly consistent slope, which indicates that the release of water was generally very gradual as tension was increased. A sudden steepening of the slope indicates a distinct air-entry tension value, common for coarse or highly aggregated soils. However, no distinct air-entry value could be determined for most of the cores tested in this study, indicating that the samples had a wide range of pore sizes. However, no distinct air-entry value could be determined for most of the retention curves.

All the curves showed that a very high level of water was still held by the soil at 10,480 cm tension. This water, which was held in the smallest pore spaces, was considered immobile or residual water. The values of residual water content ranged from 0.053 to 0.174 m$^3$/m$^3$.

Comparing to the field saturated water content, all the methods overestimate θs. The PTF-RB is always giving the highest saturated soil water content ranging from 0.401 to 0.503 m$^3$/m$^3$. That can be justified because a complete saturation cannot be occurred in the field.

From Table 2 we can deduce that for PMI-1 and PMI-5, estimations using the PTF-RB provide RMSE values that are greater than the RMSE using the PTF-R and laboratory measurements. With PTF-RB, RMSE values range from 0.063 to almost 0.171 m$^3$/m$^3$ for PMI-1 and from 0.086 to 0.160 m$^3$/m$^3$ for PMI-5 that is 0.045–0.51 m$^3$/m$^3$ and 0.088–0.40 greater than RMSE values of laboratory measurements. We can notice big improvements in some cases when going deeply in the soil profile. This is especially visible at 67 cm depth and at very low soil water potential (h lower than −600 cm) on the agricultural season 2010 for both sites. This is presumably due to the fact that many soils in the PTF data set come from areas where soil development conditions are different from northern Italy conditions.

Laboratory measurements show the lowest RMSE for both sites during 2010 agricultural season followed by PTF-R. However, the RMSE for PTF-R becomes lower than that of laboratory measurements for PMI-1, but remains higher for PMI-5.

For PMI-5, laboratory measurements show in most of the cases the lowest bias. The range values of bias is between −0.033 and 0.045 for both agricultural seasons. PTF-R showed bias from −0.019 to 0.077 for PMI-1 with slightly more accurate estimations for PMI-5.

As we can notice, bias remained positive most of the cases for both sites and during the two agricultural seasons, reflecting an overestimation of water content by all methods.

The mean absolute error (MAE) of laboratory data was the lowest for both sites during the agricultural season 2010 ranging between 0.012–0.065 m$^3$/m$^3$ for PMI-1 and between 0.023–0.046 m$^3$/m$^3$ for PMI-5.

The PTF-R provided lower mean absolute error than PTF-RB for both sites and during the two seasons.

For the 2011 season, MAE of PTF-R decreases in comparison to laboratory measurements for the PMI-1 and ranges between 0.044 and 0.084 m$^3$/m$^3$. However, it was greater for the PMI-5.

The MAE of PTF-RB was always very high with values between 0.060 and 0.151 m$^3$/m$^3$ for PMI-1 and 0.097 and 0.141 m$^3$/m$^3$ for PMI-5.

When considering the comparison between the two sites, different indices of performance show better results in PMI-5 than PMI-1 for the three methods.

From previous interpretation we can notice that the difference between the three methods and the field measurements is obvious when the soil water potential is lower or greater than −100 cm. So, we plan to statistically analyze the data into two separate sets

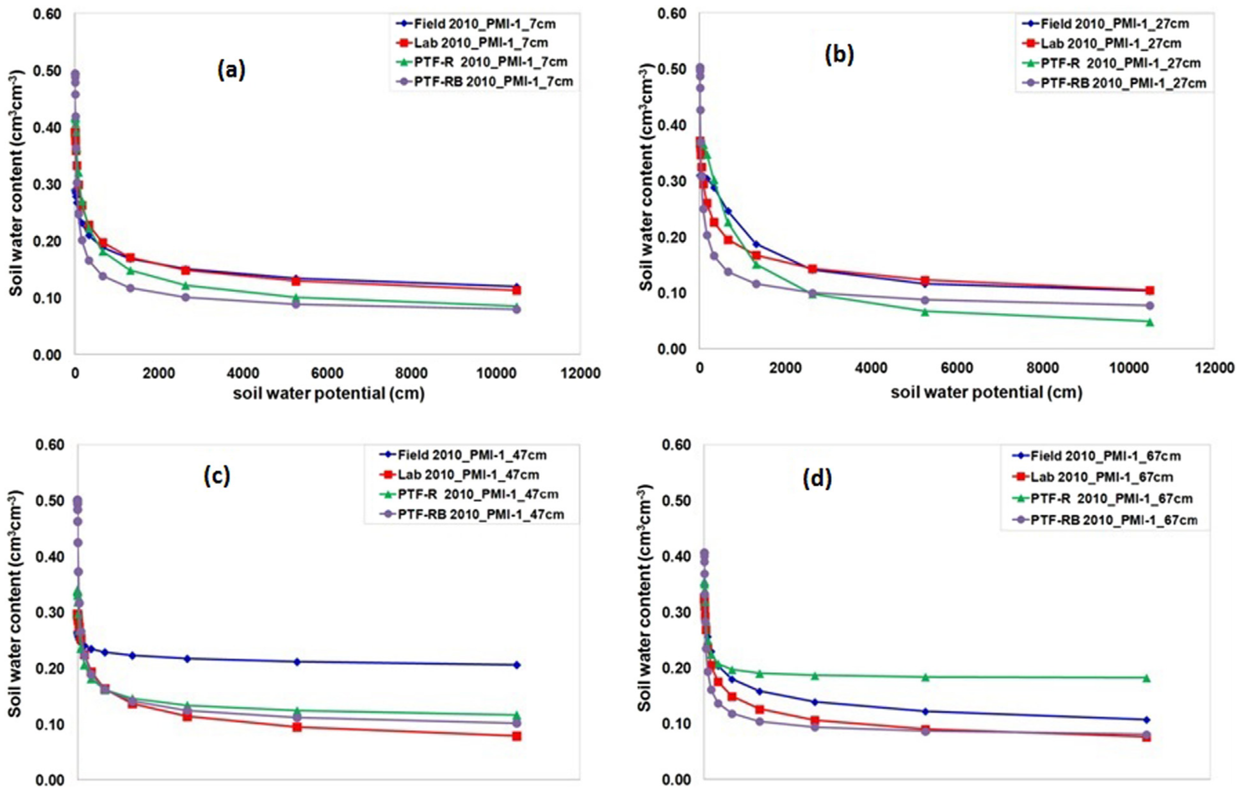


**Fig. 1.** Soil retention curve measured at different depth (a (7 cm); b (27 cm); c (47 cm); d (67 cm)) with different methods at PMI-1_2010.

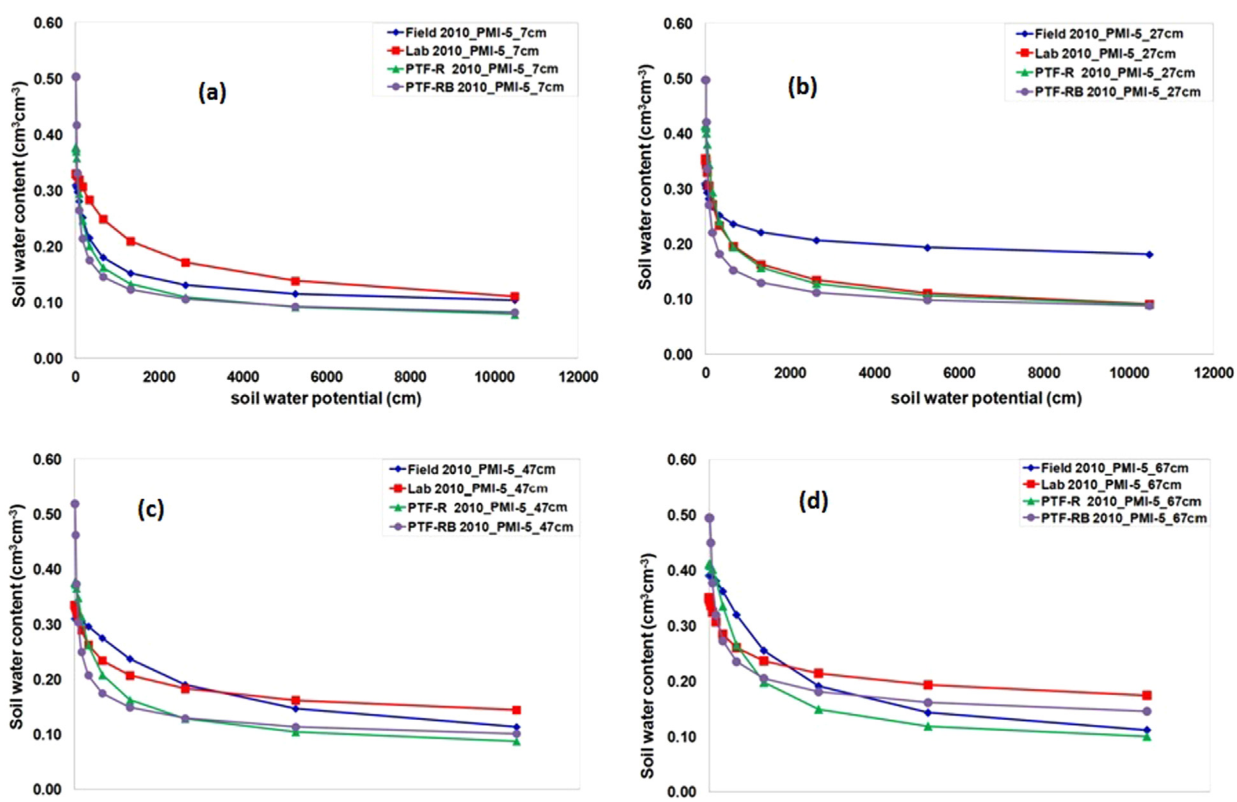


**Fig. 2.** retention curve measured at different depth (a (7 cm); b (27 cm); c (47 cm); d (67 cm)) with different methods at PMI-5_2010.

accounting soil water potential data. The first set includes values of h higher than $-100$ cm ("wet" part). While the second set contains values lower than this limit (we can consider it as a "dry" part). Table 3 represents the whole set of the data showing the difference between the "wet" and the "dry " part of the SWRC during the two agricultural years and for both sites.

Changes in the simulated moisture content in the dry part of the SWRC are apparent for laboratory and PTF-R. These changes

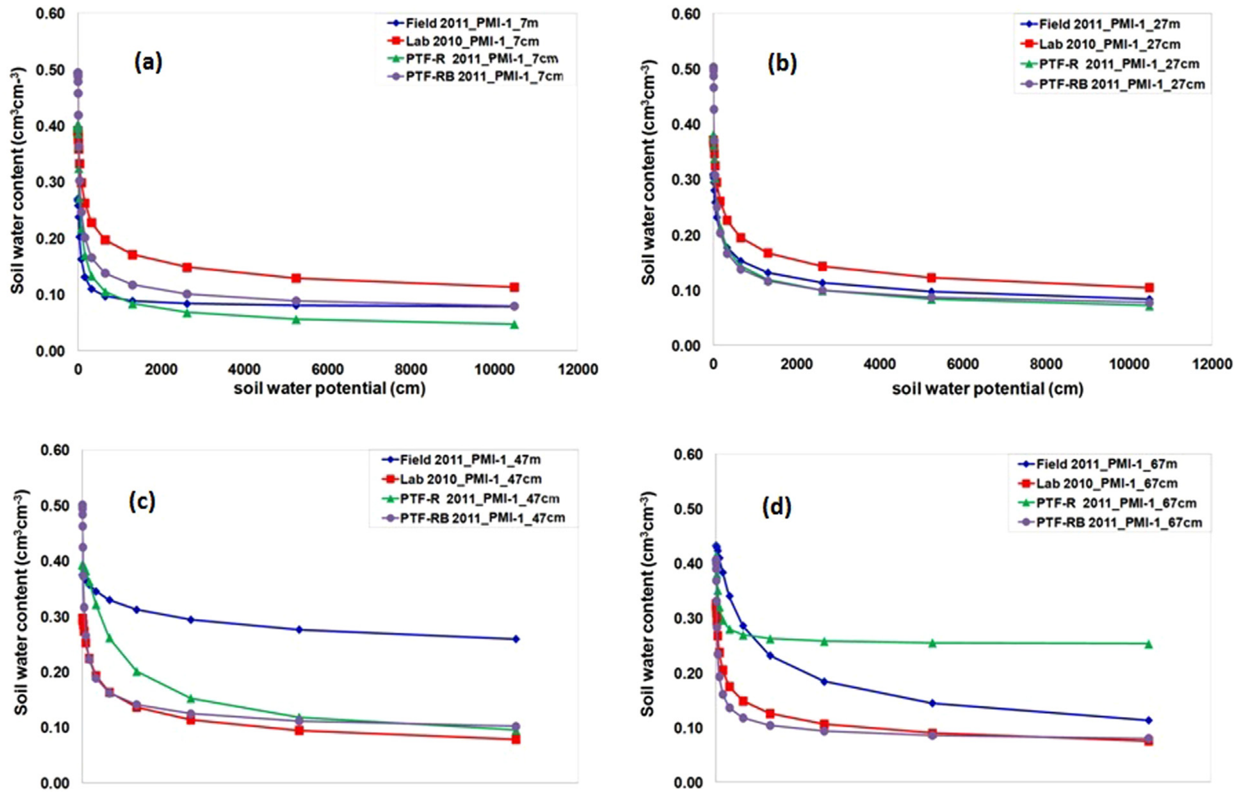


**Fig. 3.** Soil retention curve measured at different depth (a (7 cm); b (27 cm); c (47 cm); d (67 cm)) with different methods at PMI-1_2011.

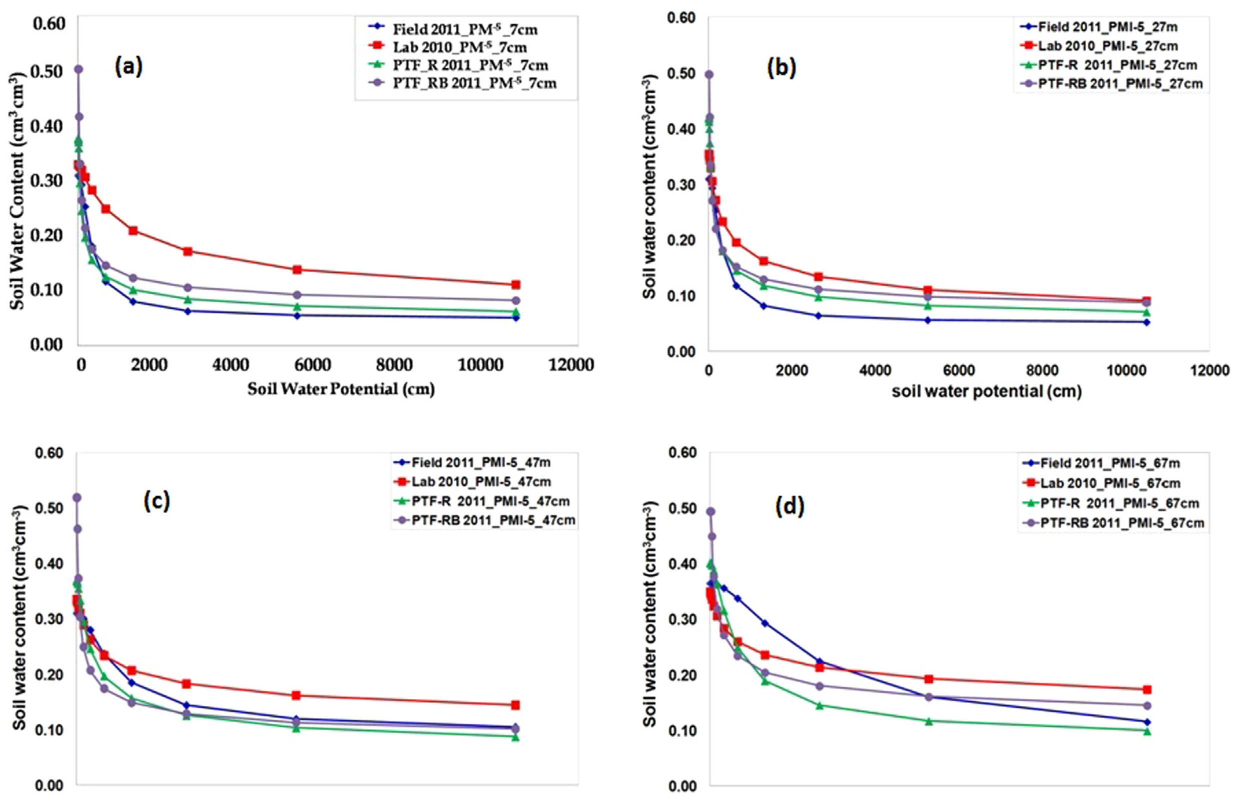


**Fig. 4.** Soil retention curve measured at different depth (a (7 cm); b (27 cm); c (47 cm); d (67 cm)) with different methods at PMI-5_2011.

gradually weaken with increase of depth and soil water potential (h). While for PTF-RB differences between estimated and measured soil water content are obvious when h is higher than −100 cm (wet part).

For instance, in PMI-1 and during the 2010 agricultural year, the RMSE of the laboratory measurements ranges between 0.006 and 0.093 $m^3/m^3$ going from 7 to 67 cm and for h going from 0 to −100 cm and from 0.014 and 0.088 $m^3/m^3$ for h lower than

**Table 2**
statistics for retention curve parameters values obtained from different method.

| | | | RMSE | | | Bias | | | MAE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Lab Vs field | PTF-R vs field | PTF-RB vs field | Lab Vs field | PTF-R Vs field | PTF-RB Vs field | Lab vs field | PTF-R Vs field | PTF-RB Vs field |
| Season 2010 | PMI-1 | 7 cm | 0.077 | 0.101 | 0.144 | 0.064 | 0.077 | 0.092 | 0.065 | 0.089 | 0.122 |
| | | 27 cm | 0.049 | 0.056 | 0.141 | 0.025 | 0.034 | 0.071 | 0.043 | 0.054 | 0.124 |
| | | 47 cm | 0.056 | 0.068 | 0.171 | −0.007 | 0.017 | 0.103 | 0.046 | 0.065 | 0.151 |
| | | 67 cm | 0.018 | 0.034 | 0.064 | −0.011 | 0.028 | 0.014 | 0.012 | 0.029 | 0.060 |
| | PMI-5 | 7 cm | 0.035 | 0.052 | 0.144 | 0.027 | 0.031 | 0.094 | 0.031 | 0.046 | 0.120 |
| | | 27 cm | 0.049 | 0.091 | 0.147 | 0.011 | 0.051 | 0.078 | 0.046 | 0.086 | 0.134 |
| | | 47 cm | 0.024 | 0.059 | 0.161 | 0.011 | 0.028 | 0.099 | 0.023 | 0.057 | 0.141 |
| | | 67 cm | 0.048 | 0.027 | 0.087 | −0.033 | 0.003 | 0.050 | 0.046 | 0.024 | 0.080 |
| Season 2011 | PMI-1 | 7 cm | 0.112 | 0.098 | 0.162 | 0.109 | 0.077 | 0.137 | 0.109 | 0.084 | 0.137 |
| | | 27 cm | 0.056 | 0.054 | 0.135 | 0.054 | 0.040 | 0.100 | 0.054 | 0.046 | 0.107 |
| | | 47 cm | 0.119 | 0.067 | 0.127 | −0.111 | −0.019 | −0.002 | 0.111 | 0.044 | 0.120 |
| | | 67 cm | 0.120 | 0.058 | 0.114 | −0.115 | −0.012 | −0.090 | 0.115 | 0.045 | 0.090 |
| | PMI-5 | 7 cm | 0.060 | 0.051 | 0.144 | 0.045 | 0.033 | 0.113 | 0.045 | 0.046 | 0.120 |
| | | 27 cm | 0.048 | 0.081 | 0.140 | 0.045 | 0.065 | 0.112 | 0.045 | 0.070 | 0.117 |
| | | 47 cm | 0.025 | 0.049 | 0.157 | 0.020 | 0.030 | 0.108 | 0.023 | 0.045 | 0.132 |
| | | 67 cm | 0.036 | 0.047 | 0.106 | −0.021 | 0.006 | 0.063 | 0.030 | 0.042 | 0.097 |

**Table 3**
RMSE for the “wet” and “dry” part of the retention curve obtained from different method at different depths during the two agricultural seasons and for both sites (a and c for PMI-1 and b and d for PMI-5).

a)

| PMI-1 2010 | Lab vs field | | PTF-R vs field | | PTF-RB vs field | |
|---|---|---|---|---|---|---|
| | RMSE 0–100 cm | RMSE 100–10,485 cm | RMSE 0–100 cm | RMSE 100–10,485 cm | RMSE 0–100 cm | RMSE 100–10,485 cm |
| 7 cm | 0.093 | 0.014 | 0.122 | 0.027 | 0.174 | 0.045 |
| 27 cm | 0.054 | 0.035 | 0.062 | 0.040 | 0.163 | 0.080 |
| 47 cm | 0.030 | 0.088 | 0.066 | 0.073 | 0.202 | 0.078 |
| 67 cm | 0.006 | 0.030 | 0.028 | 0.043 | 0.069 | 0.053 |

b)

| PMI-5 2010 | Lab vs field | | PTF-R vs field | | PTF-RB vs field | |
|---|---|---|---|---|---|---|
| | RMSE 0–100 cm | RMSE 100–10,485 cm | RMSE 0–100 cm | RMSE 100–10,485 cm | RMSE 0–100 cm | RMSE 100–10,485 cm |
| 7 cm | 0.023 | 0.050 | 0.062 | 0.019 | 0.175 | 0.031 |
| 27 cm | 0.043 | 0.060 | 0.101 | 0.064 | 0.170 | 0.084 |
| 47 cm | 0.023 | 0.027 | 0.063 | 0.050 | 0.190 | 0.069 |
| 67 cm | 0.044 | 0.056 | 0.020 | 0.037 | 0.098 | 0.057 |

c)

| PMI-1 2011 | Lab vs field | | PTF-R vs field | | PTF-RB vs field | |
|---|---|---|---|---|---|---|
| | RMSE 0–100 cm | RMSE 100–10,485 cm | RMSE 0–100 cm | RMSE 100–10,485 cm | RMSE 0–100 cm | RMSE 100–10,485 cm |
| 7 cm | 0.122 | 0.089 | 0.118 | 0.024 | 0.196 | 0.039 |
| 27 cm | 0.063 | 0.039 | 0.066 | 0.011 | 0.165 | 0.041 |
| 47 cm | 0.084 | 0.168 | 0.018 | 0.113 | 0.106 | 0.161 |
| 67 cm | 0.121 | 0.120 | 0.038 | 0.084 | 0.045 | 0.084 |

d)

| PMI-5 2011 | Lab vs field | | PTF-R vs field | | PTF-RB vs field | |
|---|---|---|---|---|---|---|
| | RMSE 0–100 cm | RMSE 100–10,485 cm | RMSE 0–100 cm | RMSE 100–10,485 cm | RMSE 0–100 cm | RMSE 100–10,485 cm |
| 7 cm | 0.020 | 0.100 | 0.060 | 0.027 | 0.174 | 0.035 |
| 27 cm | 0.041 | 0.059 | 0.098 | 0.027 | 0.169 | 0.037 |
| 47 cm | 0.023 | 0.029 | 0.057 | 0.025 | 0.190 | 0.044 |
| 67 cm | 0.020 | 0.056 | 0.036 | 0.064 | 0.122 | 0.066 |

−100 cm (dry part). The PTF-R, the RMSE presents values between 0.028 and 0.122 $m^3/m^3$ for h varying from 0 to −100 cm and between 0.027 and 0.073 $m^3/m^3$ for h lower than −100 cm.

In addition, the PTF-RB shows a RMSE between 0.069 and 0.202 $m^3/m^3$ for the first range and from 0.045 and 0.080 for lowers values of h.

The results of the division of the SWRC into two parts highlight again what we previously said about larger differences in the top layers. This is showed by higher values of RMSE.

When applying a correlation (which is considered to be a good indices of performance used by many authors, Majou et al., 2007; Matula et al., 2007; Merdun, 2006) between measured and simulated water content for both sites (PMI-1 and PMI-5) and at each depth during the two agricultural seasons (Table 4), the matching between predicted and measured retention curve is still the highest for laboratory and PTF-R. The $R^2$ values of laboratory range from 0.44 to 0.99 for PMI-1 and from 0.41 to 0.92 for PMI-5. For PTF-R, $R^2$ values ranges between 0.37 and 0.96 for PMI-1 and 0.68–0.94 for PMI-5.

**Table 4**
parameters of the correlation between measured (field) and simulated soil water content obtained from different method at different depths during the two agricultural seasons and for both sites.

| | | | M | | | $R^2$ | | |
|---|---|---|---|---|---|---|---|---|
| | | | Lab Vs field | PTF-R vs field | PTF-RB vs field | Lab Vs field | PTF-R Vs field | PTF-RB Vs field |
| 2010 | PMI-1 | 7 cm | 1.282 | 1.354 | 1.439 | 0.920 | 0.858 | 0.689 |
| | | 27 cm | 1.101 | 1.155 | 1.299 | 0.82 | 0.90 | 0.55 |
| | | 47 cm | 0.989 | 1.088 | 1.453 | 0.446 | 0.433 | 0.321 |
| | | 67 cm | 0.974 | 1.091 | 1.100 | 0.960 | 0.903 | 0.806 |
| | PMI-5 | 7 cm | 1.1 | 1.158 | 1.435 | 0.90 | 0.92 | 0.761 |
| | | 27 cm | 1.066 | 1.218 | 1.338 | 0.747 | 0.680 | 0.534 |
| | | 47 cm | 1.211 | 1.038 | 1.287 | 0.774 | 0.883 | 0.512 |
| | | 67 cm | 0.877 | 1.021 | 1.158 | 0.774 | 0.941 | 0.750 |
| 2011 | PMI-1 | 7 cm | 1.499 | 1.431 | 1.73 | 0.909 | 0.957 | 0.958 |
| | | 27 cm | 1.216 | 1.192 | 1.472 | 0.994 | 0.964 | 0.872 |
| | | 47 cm | 0.698 | 0.964 | 1.023 | 0.530 | 0.563 | 0.343 |
| | | 67 cm | 0.695 | 0.937 | 0.778 | 0.879 | 0.376 | 0.656 |
| | PMI-5 | 7 cm | 1.109 | 1.137 | 1.476 | 0.410 | 0.911 | 0.831 |
| | | 27 cm | 1.145 | 1.270 | 1.460 | 0.900 | 0.914 | 0.841 |
| | | 47 cm | 1.063 | 1.129 | 1.435 | 0.925 | 0.893 | 0.641 |
| | | 67 cm | 0.927 | 1.034 | 1.202 | 0.780 | 0.808 | 0.620 |

For the PMI-1 we can see that for 2010, laboratory measurements show largest $R^2$ (0.44- 0.99) but for 2011 PTF-R become better and show highest value of $R^2$ (0.37–0.96). However for PMI-5, PTF-R provides the largest $R^2$.

PTF-RB is always showing the lowest coefficient of determination $R^2$, with values ranging from 0.32 to 0.95 for PMI-1 and between 0.53 and 0.94 for PMI-5.

Depending on angular coefficient (M) obtained with linear regressions imposing a zero intercept, i.e. the average proportion coefficient, most of the considered methods show a tendency to overestimate soil water content (Table 4). During 2010 season, the laboratory measurements show a coefficient between 0.97 and 1.28 for PMI-1 and between 0.87 and 1.21 for PMI-5. While for PTF-R values ranges between 1.088 and 1.35 for PMI-1 and between 1.021 and 1.21 for PMI-5. Whereas, PTF-RB shows the highest overestimation of soil water content (1.1–1.35 for PMI-1 and 1.15–1.43 for PMI-5). Furthermore, during 2011 season and for PMI-1, angular coefficient is between 0.69 and 1.49 for laboratory measurements, between 0.93 and 1.43 for PTF-R and 0.77–1.73 for PTF-RB. For PMI-5, laboratory measurements present a coefficient between 0.92 and 1.1 and PTF-R between 0.92 and 1.14. The angular coefficient in the case of PTF-RB ranges between 1.034 and 1.27.

## 4. Discussion

Differences between soil water retention obtained with the four methods in this study (field, laboratory, PTF-R and PTF-RB) confirm some reported results in the literature (Baroni et al., 2010; Field, Parker, & Powell, 1985; Merdun, 2006; Nemes, Schaap, & Wosten, 2003; Parkes and Waters, 1980; Shein, Gudima, & Mokeichev, 1993; Wosten, Pachepsky, & Rawls, 2001).

According to the literature, differences between data from different sources were mainly due to the poor representation of large soil pores in the laboratory (Field et al., 1985), to the inadequate depth resolution of the humidity probes (Parkes & Waters, 1980), to the disturbance and spatial variability (Field et al., 1985; Shuh, Cline, & Sweeney, 1988), to the overestimation of the soil water matric potential during tensiometer readings (Shein et al., 1993) and to the soil sample size which can have a scale effect (Shuh et al., 1988).

Accounting possible errors in the field data, we must underline that, during the two agricultural seasons, we faced some problems with tensiometers particularly during the summer period when absence of precipitations within high temperatures emptied tensiometers and influenced readings.

The differences in location and scale of water content and pressure potential measurements in the field can result in differences in water retention data obtained in the field and in the laboratory.

Laboratory methods are conducted in a controlled environment which is considered as their main advantage, but can be limited with the accuracy of some disturbance when manipulating the sample, although the use of undisturbed soil samples. In addition, laboratory measurements are subject of hydraulic effects which are not present in the field (Munoz-Carpena, Regalado, Alvarez-Benedi, & Bartoli, 2002). Similarly to Chahal and Yong (1965) finding, we have observed trapped air or nucleation of air bubbles during the de-pressurization stage which can explain some how the discrepancies.

Another explanation can be related to the drainage of the samples in the pressure plate apparatus which was very slow or sometimes completely stops when an interruption happens during the samples water phase or between plate and samples.

Despite the methodology used to develop it, any PTF can give less accurate or even very poor predictions if we use it outside the range of soils initially used. In this study, Rawls and Brakensiek (1985) PTF give the lowest accuracy. These results are in disagreement with the finding of Calzolari et al. (2001) and Baroni et al., (2010). They concluded that the PTF-RB is well presenting the hydraulic characteristics of Lombardy plain.

This weakness cannot be attributed to the lower performance of the Brooks and Corey (1964) previously proved (Merdun, 2006) because in this study PTF-RB was implemented using the Van Genuchten equation. Prediction errors are found large near-saturation range of the measured and predicted moisture contents but also quite considerable in the drier range of the retention curve, which can exclude the above assumption.

In this study, it was found that for PTF-RB, soil water retention at the “wet” end ($<100$ cm) strongly influences different indices by showing a big digression between measured and simulated data in the wet part of the curve. Similar results were reported by Antinoro et al. (2008), Calzolari et al. (2001) and Cornelis, Ronsyn, Van Meirvenne, and Hartmann (2001), where they got an overestimation of soil water content especially near the saturation using the same PTF.

The weak estimations of PTF-RB were proved previously by Antinoro et al. (2008) and Romano and Santini (1997). While the well performance of PTF-R in Landriano field confirms the results found by Baroni et al., (2010).

A difference with field data in particular for laboratory measurements and PTF-R estimations was shown especially for low pressure (dry part) which confirms results of Bouma and Dekkerl (1984). They compared the soil retention curve obtained in the laboratory and in the field and found small differences above $-100$ cm potential but differences were very big between $-100$ cm and $-800$ cm. As we previously described, the field soil retention curve was estimated for soil water potential lower than $-800$ cm, because actual tensiometer measurements can never approach such potential. Therefore, the error could be attributed to the inaccurate field retention curve in the dry part. In such case, laboratory estimated would be considered as more precious.

PMI-5 has higher clay content than PMI-1, and for both sites at the top layers, soil has higher clay content than the deepest layers. According to Reichardt (1990), one of the main factors affecting soil water retention is soil texture, as it determines the contact area between the solid particles and the water. Buckman and Brady (1979) mentioned that sand has reduced water retention capacity due to its large space between granulometric particles and the quick water percolation flow which may explain the highest performance of the 3 methods in PMI-5.

The PTF of Rawls and Brakensiek (1985) is accurate for soils with a 5–70% clay and sand content. In our study, the PMI-1 presents a percentage of sand (77%) at 67 cm depth exceeding this range which can explain the bad simulation of this method especially at that depth.

Donatelli, Wosten, and Belocchi (2004) considered that the RMSE normally takes priority over the other statistics when evaluating different methods. According to this criterion, laboratory measurements yield the most accurate results among the tested methods during the agricultural season 2010 and for both sites. For 2011 season, PTF-R replaces laboratory measurements as better estimator for PMI-1, while for PMI-5 laboratory measurements remains as better method. Soil samples for the laboratory measurements that were carried out on 2010 were limited to the field conditions at that time, and this could explain the decrease in the rank of laboratory measurements.

## 5. Conclusion

Considering the comparison and the evaluation of the field, laboratory and estimated method to obtain the soil retention curve parameters, we can conclude as following:

Laboratory measurements are the most precise. They have the highest ranking for the five validation indices considered in this study.

The second best technique is the PTF Rosetta (Schaap et al., 2001). This method shows slightly poorer accuracy than the laboratory measurements and its ranking is quite consistent for the five validation indices, and varies between one and two when we consider the range-dependent evaluation.

The results obtained from Rawls and Brakensiek (1989) PTF are also acceptable. Although the RMSE, Bias and MAE are relatively high, their determination coefficient is rather poor.

On the case of PTF-RB, the uncertainty is found very large between saturation and −100 cm (very wet range. Therefore it will not be recommended to use this function near saturation conditions. While for laboratory and PFT-R, the uncertainty was higher below −100 cm.

Finally we can conclude saying that due to time and cost investments of laboratory measurements, Rosetta PTF developed by Schaap et al. (2001) can be the best alternative to predict the soil retention curve parameters from easily available soil properties.

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