Abstract

The knowledge of soil water retention vs. soil water matric potential is applied to study irrigation and drainage scheduling, soil water storage capacity (plant available water), solute movement, plant growth and water stress. To measure field capacity and wilting point is expensive, laborious and is time consuming, so, frequently, mathematic models, called pedo-transfer functions (PTFs) are utilized to estimate field capacity and wilting point through physical-chemical soil characteristics. Six PTFs have been evaluated (Gupta and Larson, 1979; Rawls et al., 1982; De Jong et al., 1983; Rawls and Brakensiek, 1985; Saxton et al., 1986; Vereecken et al., 1989) by comparing measured soil moisture values with estimated ones at soil water matric potential of -33 and -1500 kPa. Soil samples were collected (361) from 185 pedons of Apulian Region (Southern Italy).

Accuracy of the soil moisture predictions is quantified with Root Mean Square Deviation (RMSD) between estimated and measured water retention values.

In Apulia Region the tested PTFs give different results on soils grouped on the basis of textural composition and organic matter (O.M.) content both at the Field Capacity (FC) and Wilting Point (WP).

At the FC, Gupta and Larson model has given the best performance in Clayey (C), Sandy clay loam (SaCL), Sandy loam (SaL) and Silty (Si) soil, in loamy and tendency silty soils with O.M. content less than 1.9% and in tendency sandy soils with O.M. content less than 1.5% and greater than 2%; the Rawls model in Silty clay (SiC) and Silty loam (SiL) soils, in tendency clayey soils with O.M. less than 2.3% and in loamy and tendency silty soils with O.M. greater than 1.9%; the Rawls and Brakensiek model in tendency sandy soils with O.M. content between 1.5 and 2%; the Saxton model in Silty clay loam (SiCL), Loamy sand (LSa) soils and in tendency clayey soils with O.M. content greater than 2.3% and the Vereecken model in Sandy clay (SaC), Loamy (L), Clay loam (CL) and Sandy (Sa) soils. At the WP, the Gupta and Larson model has resulted the best in SiL, Si soils and, in general, in loamy and tendency silty and in tendency sandy soils with O.M. content greater than 1.9% and 2%, respectively; the Rawls model in Loamy soils and in loamy and tendency silty soils with O.M. between 1.0 and 1.9%; the De Jong model in C soils; the Rawls and Brakensiek model in SiC, SaC, CL, SiCL, SaCL soils and generally in tendency clayey soils with whatever O.M. content and in tendency sandy soils with O.M. content between 0.8 and 2%; the Saxton model in loamy and tendency silty soils with O.M. content less than 1% and in tendency sandy soils with O.M. less than 0.8%; the Vereecken model in SaL, Sa and LSa soils.

Key-words: field capacity and wilting point, pedo-transfer functions, soil water retention models.

1. Introduction

Field capacity and wilting point can be estimated with the application of pedo-transfer functions (Pedo-Transfer Function – PTF – expression used by Bouma in 1989) through physical-chemical characteristics of pedological horizons (Rawls et al., 1991), which affect soil water retention, such as sand, silt, clay content (particle size distribution), organic matter or organic carbon and total CaCO₃ content, soil bulk density, aggregate size distribution, free iron oxide (Jamison and Kroth, 1958; Prebble and Stirk, 1959; Salter and Williams, 1965a, b; Petersen et al., 1968; Wöstgen and van Genuchten, 1988). These last parameters, comparing with labora-
tory measures of field capacity and wilting point, are easily and quickly determined, and at low cost.

In a previous work carried out by Buccigrossi et al., (still in press) the applicability of six literature’ PTFs (Gupta and Larson, 1979, b; Rawls et al., 1982; De Jong et al., 1983; Rawls and Brakensiek, 1985; Saxton et al., 1986; Vereecken et al., 1989) has been evaluated in soils of Apulia Region (361 soil samples deriving from 185 pedons) regardless of their particle size distribution and organic matter content. The best accuracy of soil moisture predictions has been obtained: at the Field Capacity (-33 kPa) with Rawls PTF that shows the lowest values of WSEE (weighted standard error of estimate), MD (mean deviation) and RMSD (root mean squared deviation) (0.044, -0.007 e 0.059 m³ water m⁻³ soil, respectively); at the Wilting Point (-1500 kPa) with Rawls and Brakensiek model with values of WSEE, MD and RMSD of 0.034, -0.016 and 0.046 m³ water m⁻³ soil, respectively.

For further investigations, the applicability of the six PTFs to soils of Apulian Region grouped in textural classes and, within the three great textural grouping (tendency clayey soils; loamy and tendency silty soils; tendency sandy soils) in classes of organic matter content, has been evaluated.

2. Materials and methods

To evaluate the applicability of the six PTFs to the groupings of soils of Apulian Region, data sets of measured water content at field capacity and at wilting point of 361 soil samples collected from 185 pedological profiles on Apulian territory (Fig. 1) have been used.

Before making physical-chemical laboratory analysis, soil samples have been air-dried and 2 mm mesh sieved.

In laboratory, on sieved soil samples, organic matter content (% OM) (Walkley-Black method), particle size fraction, according with USDA textural classification (U.S. Dept. Agric., 1951) [sand [2 ≥ diameter (d) ≥ 0.05 mm], silt (0.05 ≥ d ≥ 0.002 mm) and clay (d ≤ 0.002 mm) (pipette method and determination of coarse sand with humid sieved)], water content (% of soil dry weight) at -33 kPa [Field Capacity (FC)] and -1500 kPa [Wilting Point (WP)], with porous plates in Richards pressure chambers (Richards e Weaver, 1947; Richards, 1949), have been measured.

The soils have been grouped in 12 textural classes according to USDA textural classification (Tab. 1), in 12 classes of organic matter content, 4 classes of organic matter content for each of the 3 great textural groupings, (Sequi and De Nobili, 2000) for a total of 24 soil groupings. On the basis of organic matter content, the great textural groupings are (Tab. 2):

a) tendency clayey soils, including Clayey (C), Silty clay (SiC), Clay loam (CL) and Silty clay loam (SiCL) soils;

b) loamy and tendency silty soils, including Loamy (L), Silty loam (SiL), Sandy clay loam (SaCL), Sandy clay (SaC) and Silty (Si) soils;

c) tendency sandy soils, including Sandy (Sa), Sandy loam (SaL) and Loamy sand (LSa) soils (Sequi and De Nobili, l.c.).

Soil bulk density (ρb) can be estimated through specific models and/or PTFs (Curtis and Post, 1964; Saini, 1966; Heinonen, 1977; Gupta and Larson, 1979 a; Alexander, 1980; Rawls and Brakensiek, 1989; Leonavičiutė, 2000); in this case, the following equation (Adams, 1973; Rawls, 1982) has been applied:

\[
\rho_b = \frac{100}{\text{% o.m.}} \frac{\text{o.m.}}{\text{m.b.d.}} + \frac{100 - \text{% o.m.}}{\text{m.b.d.}}
\]

where:
- o.m.: organic matter;
- o.m.b.d.: organic matter bulk density, in average equal to 0.224 g·cm⁻³;
m.b.d.: mineral bulk density, graphically obtained through a mineral density map based on sand and clay percentages (Davis, 1973).

The computation of the bulk density through organic matter and mineral bulk density rather than measuring it in the field has been preferred, because its value is very changeable with the time, especially in clay or clay-silty soil and when the field is being cropped. Owing to the field experience of the authors, the clay-silty soil bulk density during the crop season varies as average of the cultivated layers (0 to 0.50 m) from 1.2 to 1.6 g/cm3. Therefore, in these conditions one can not know which value should consider.

This uncertainty is the reason which influenced the choice of the authors; using the formula found in literature and reported in this paper is equivalent to consider a standard method to which to refer.

### 3. Applied pedo-transfer functions

Many papers on this subject are reported in literature and most of them refers to undisturbed soil cores collected with the auger. In the mat-
The authors carried out on a clay silty soil (clay = 25%; silt = 35%; sand = 40%) a field experiment to study the differences in soil moisture determined at different potentials among undisturbed and sieved soil samples. The data are reported in the Figure 2, from which you can easily see that from Field Capacity (pF = 2.5 = -33 KPa) to Wilting Point (pF = 4.2 = -1500 KPa) there is no significant difference between undisturbed and sieved soil moisture. Above Field Capacity the differences among the two series of soil moisture values become more and more higher up to saturation (pF = 0).

For these reasons, the authors decided to carry out this study on sieved samples and they believe that the results obtained can be considered valid and applicable to other conditions and field studies in the range between Wilting Point and Field Capacity.

The PTFs studied and applied to estimate the volumetric water content (θ_est) at -33 and -1500 kPa matric potentials, are: Gupta and Larson, 1979 (model I); Rawls et al., 1982 (model II); De Jong et al., 1983 (model III); Rawls and Brakensiek, 1985 (model IV); Saxton et al., 1986 (model V); Vereecken et al., 1989 (model VI).

The algorithms, the equations of the parameters and the constants of each applied PTF are reported in Tables 3 and 4.

| PTF | Algorithm |
|-----|-----------|
| Model I (Gupta & Larson, 1979) | \[ \theta_{\text{est}} = (a \cdot S) + (b \cdot L) + (c \cdot A) + (d \cdot SO) + (e \cdot \rho_b) \] |
| Model II (Rawls et al., 1982) | \[ \theta_{\text{est}} = a + (b \cdot S) + (c \cdot L) + (d \cdot A) + (e \cdot SO) - (f \cdot \rho_b) \] |
| Model III (De Jong et al., 1983) | \[ \theta_{\text{est}} = \{a + [b_1 \cdot (\log P_{pm} - t)]\} \times \rho_b / 100, \text{ per } P_{pm} \leq 10^9 \] |
| Model IV (Rawls & Brakensiek, 1985) | \[ \theta_{\text{est}} = \{a + [b_2 \cdot (\log P_{pm} - t)]\} \times \rho_b / 100, \text{ per } P_{pm} > 10^9 \] |
| Model V (Saxton et al., 1986) | \[ \theta_{\text{est}} = \left( \frac{P_{pm}}{A} \right)^{1/\lambda} \] |
| Model VI (Vereecken et al., 1989) | \[ \theta_{\text{est}} = \theta_s + (\theta_s - \theta_r) \left[ (1 + \left| \frac{\Psi P_{pm}}{h_b} \right|^{\gamma}) \right]^{\gamma} \] |

where:
- \( \theta_{\text{est}} \): estimate of the volumetric water content;
- \( P_{pm} \): matric potential (in bar for De Jong et al., 1983; in dm for Rawls and Brakensiek, 1985 and Vereecken et al., 1989; in KPa for Saxton et al., 1986);
- \( h_b \): air entry potential;
- \( \lambda \): pore size distribution index;
- \( \theta_s \): residual water content;
- \( \theta_r \): saturation water content; it is assumed to be equal to porosity (Ø) which is:
- \( \Omega = 1 - (\rho_b / \rho_d) \) (% in volume) where:
  - \( \rho_d \): soil real density (g cm\(^{-3}\));
  - \( \rho_b \): soil bulk density (g cm\(^{-3}\));
  - \( \rho_{\text{OM}} \): soil real density that, on average, is equal to 2.65 g cm\(^{-3}\);
- Sa, Si, C and OM: sand, silt, clay percentages (limits of diameter according to USDA textural classification) and organic matter content.

Figure 2. Soil moisture values (% of dry weight) vs. matric potential (pF) of sieved and undisturbed soil samples.
4. Definition of evaluation criteria of the Pedo-Transfer functions applied to Apulian territory soils grouped on the basis of textural composition and organic matter content

For the soils grouped on the basis of textural composition and organic matter content, the following statistic errors and correlations of the differences among the values of water contents estimated by the six PTFs and those measured in laboratory (Wosten et al., 2001), have been calculated:

1. mean deviation (MD) or mean error (ME) among estimated and measured water retention values. MD is a positive or negative number according to whether the PTF overestimates or underestimates the water content, respectively;
2. root mean squared deviation (RMSD) or root mean square residual (RMSR) or root mean square error (RMSE);
3. determination coefficients ($R^2$) of the linear regressions among the values of water contents estimated with the six PTFs and measured in laboratory;
4. determination coefficients ($R^2$) of the linear regressions among the values of water contents estimated with the six PTFs and measured, setting intercepts to zero when their values have not been statistically different from zero;
5. Prediction efficiency (P Ef) also known as Nash Sutcliffe index (Romano and Palladino, 2002).

\[
\text{P Ef} (\%) = \frac{1 - \left( \frac{\theta_d - \theta_m}{\theta_d - \theta_{\text{est}}} \right)^2}{\theta_d - \theta_{\text{est}}} \times 100
\]

where:

- $\theta_d$: water content (% in volume) measured in laboratory;
- $\theta_{\text{est}}$: water content (% in volume) estimated with the PTF;
- $\theta_m$: mean value of water content (% in volume) measured in laboratory for a particular soil grouping.

Prediction efficiency is an evaluation PTF index that ranged from 100% (it is a hypothetical case of an ideal PTF that estimates water content exactly equal to one determinated in laboratory) to $-\infty$ (when the soil grouping is so homogeneous that the deviations of the moisture values from the mean value is equal to zero).

The analysis of variance has been performed...
with SAS software (SAS INSTITUTE INC.-USA) with P values equal to 0.05 and 0.01. Then the protected SNK test has been performed for only significant parameters.

To understand the applicability of the six PTFs to the different soil types of the Apulian territory, grouped on the basis of textural composition and organic matter content, it has been investigated, for each PTF, the effect of the physical-chemical parameters on the magnitude of the statistical error, through the correlation among input parameters and the differences among soil moisture measured and estimated by the six PTFs ($\Delta\emptyset =$ error) (Tietje and Tapkenhinnrichs, 1993; Cornelis et al., 2001; Ungaro and Calzolari, 2001).

In this way, applying a given PTF to estimate soil moisture at the FC or at the WP in a given soil grouping, a high correlation coefficient would point out a high degree of association between an input parameter and soil moisture error, that is, the considered PTF would be hardly suitable for that soil type.

On the contrary, a low correlation coefficient has a low degree of association between an input parameter and the differences among soil moistures measured and estimated ($\Delta\emptyset$), that is, the considered PTF is suitable for the category of soil considered.

4.1 Choice of the best PTF for each soil grouping

In order to draw up the final score of the PTFs applied to estimate the soil moisture at -33 and -1500 KPa matric potentials for the soils grouped on the basis of textural composition and organic matter content. On a preliminary step, a ranking has been drawn for each index: in this way the “partial” rankings have been obtained. Further on, for each PTF, the final ranking has been calculated by means of the partial rankings, putting at the first place the PTF with the mean nearest to one, i.e. the PTF with: MD and RMSD indexes nearest to zero, the greatest determination coefficients and prediction efficiency and straight line slope, when intercept through zero was possible, nearest to one.

5. Results and discussion

The comparisons between estimated and measured soil moisture values, have permitted to select the best PTF for estimating soil moisture at the Field Capacity (FC) and Wilting Point (WP) of all Apulian soil groupings, having different textural composition and organic matter content.

The analysis of all evaluated PTF indexes show that the RMSD index alone provides excellent information on the PTF performances for a certain soil grouping; the ranking based on RMSD is equal to the final ranking obtained from all applied indexes: in Table 5 an example is reported. The same result has been obtained validating the PTFs on total data set independently from the textural composition and organic matter content (Buccigrossi et al., 2009).

### Table 5. Statistical indexes values (with partial rankings) used for PTFs evaluation for estimating water retention at the Field Capacity in Clayey soils.

| PTF          | Intercept | Straight line slope | Significance $Pr>|\beta|$ | $R^2$ | MD | RMSD | P Ef | final ranking |
|--------------|-----------|---------------------|--------------------------|------|----|------|------|---------------|
| (a)          | (b)       | ranking             | value ranking            |      |    |      |      |               |
| Gupt & Larson, 1979 | 0.099 | 0.785 | 0.37 | 0.0027 | 0.235 | 3 | - | 2 | 0.087 | 21.6 | 1 | 1 |
| Rawls et al., 1982 | 0.105 | 0.79 | 0.37 | 0.0046 | 0.230 | 4 | - | 0.005 | 0.089 | 2 | 18.0 | 2 | 2 |
| Rawl & Brak., 1985 | 0.007 | 0.0125 | 0.6 | 0.0003 | 0.32 | 1 | - | 0.047 | 0.094 | 3 | 7.2 | 3 | 3 |
| Vereeken et al., 1989 | -0.0827 | 1.298 | 0.62 | 0.0026 | 0.239 | 2 | - | 0.041 | 0.095 | 4 | 5.5 | 4 | 4 |
| De Jong et al., 1983 | 0.044 | 0.203 | 0.06 | 0.06 | 0.000 | 6 | - | 0.025 | 0.106 | 5 | -16.3 | 5 | 5 |
| Saxton et al., 1986 | 0.332 | 0.2636 | 0.0001 | 0.0043 | 0.022 | 5 | - | 0.002 | 0.0155 | 6 | -150.3 | 6 | 6 |

(1) regression parameters among soil moisture values measured and estimated with the six PTFs with intercepts;
(2) regression parameters among soil moisture values measured and estimated with the six PTFs setting intercepts to zero.
This result can be explained by taking into account that RMSD is a very restrictive index, more than the WSEE (weighted standard error of estimate) index (Buccigrossi et al., l.c.); moreover, it is intrinsically related to regression lines, in particular to the correlation coefficients between estimated and measured soil moistures (Kobayashi and Salam, 2000). The RMSD ranking is also equal to P EF ranking.

Thus, considering that 48 data sets regarding 24 soil groupings (both at the FC and WP) have been analyzed, to make the results presentation easier, only RMSD values are reported.

5.1 Soil grouped on the basis of textural composition

5.1.1 Soil moisture at the Field Capacity. For the 12 USDA textural classes the best estimated soil moisture values at the field capacity have been obtained with the model I, II, V and VI (table 6).

Model I shows the best results in Clayey (C), Sandy clay loam (SaCL), Sandy loam (SaL) and Silty (Si) soils. Nevertheless, in Clayey soils all compared PTFs have produced high RMSD values (all greater than 0.08 m$^3$ m$^{-3}$) but not statistically different among them.

In Sandy loam soils the differences between estimated and measured soil moisture are lower than those observed in Clayey soils. In fact, the RMSD values are equal to 0.043 m$^3$ m$^{-3}$ with the model I, to 0.051 and to 0.053 m$^3$ m$^{-3}$ with the models II and VI, respectively, without significant differences among them.

Also in Sandy clay loam soils, very low difference values have been observed between estimated and measured soil moisture (0.037 m$^3$ m$^{-3}$) with the model I, followed by VI and II models values, almost 4% and higher than the ones observed with the model I.

In the Sandy loam and Sandy clay loam soils, at the FC, the model V provides the highest differences between estimated and measured soil moistures.

In the Silty soils the lowest value of the RMSD index (0.14 m$^3$ m$^{-3}$) has been obtained with model I, statistically different from the values obtained by the other applied PTFs. However, considering that only one soil sample belongs to this textural grouping, these results are not applicable to all Apulian silty soils.

For the Sandy clay (SaC), Loamy (L), Clay loam (CL) and Sandy (Sa) soils, the lowest RMSD values have been obtained with the model VI; they resulted statistically equal to the values obtained with almost all the other applied PTFs and were around 0.050 m$^3$ m$^{-3}$ for the first three indicated textural classes and 0.016 m$^3$ m$^{-3}$ for the Sandy soils.

At the Field Capacity, in Silty clay (SiC) and Silty loam (SiL) soils, the best soil moisture estimates have been obtained with the model II, with RMSD value of 0.053 m$^3$ m$^{-3}$ not different from the ones obtained with the other PTFs.

For Silty clay loam (SiCL) and Loamy sandy (LSa), the more accurate soil moisture estimates have been obtained with the model V. However, even if the lowest RMSD value (0.055 m$^3$ m$^{-3}$) was obtained, it was not statistically different from the other RMSD values observed with the other PTFs. As concern LSa soils, instead, the RMSD value recorded with the model V (0.017 m$^3$ m$^{-3}$) is different from the ones observed from the other compared PTFs (Table 6).

5.1.2 Soil moisture at the Wilting Point. For soils with different textural composition, the most accurate estimate of soil moistures at the wilting point has been obtained with the following PTFs (Table 7): for Clayey soils (C) with the model III that shows a RMSD value equal to 0.0425 m$^3$ m$^{-3}$ and did not result statistically different from the value observed with model IV; for Silty clay (SiC), Clay loam (CL), Silty clay loam (SiCL), Sandy clay (SaC) and Sandy clay loam (SaCL), with the model IV, of which the RMSD values resulted equal to the ones obtained with the other applied PTFs; for Loamy (L) soils with the model II that shows RMSD index of 0.032 m$^3$ m$^{-3}$, equal to the indexes of the other PTFs; for Silty loam (SiL) and Silty (Si) soils with model I, with RMSD values of 0.037 and 0.12 m$^3$ m$^{-3}$, respectively, statistically different from the values recorded with other PTFs; for SaL, Sa and LSa with model V showing, for SaL and Sa soils, RMSD values equal to the ones obtained from other applied PTFs.

5.2 Soil grouped on the basis of organic matter content

5.2.1 Soil moisture at the Field Capacity. For the tendency clayey soils, the better soil moistures at the field capacity have been evaluated with: the model II with the organic matter content ranging from values lower than 1.2% to values included between 1.2 and 2.3%; the model V, with organic matter content between 2.3 and
Table 6. Values of root mean squared deviation (RMSD) index among soil moistures measured and estimated with the six PTFs at the Field Capacity within the soils grouped in USDA textural classes.

| Field Capacity         | PTF       | RMSD m³·m⁻³ | ranking | PTF       | RMSD m³·m⁻³ | ranking |
|------------------------|-----------|-------------|---------|-----------|-------------|---------|
| Clayey soils (C)       | Model I (Gupta & Larson) | 0.087 | A 1  | Model I | 0.037 | A 1  |
|                        | Model II (Rawls et al.) | 0.089 | A 2  | Model II | 0.039 | B 2  |
|                        | Model IV (Rawls & Brak.) | 0.094 | A 3  | Model II | 0.043 | B 3  |
|                        | Model VI (Vereecken et al.) | 0.095 | A 4  | Model IV | 0.056 | B 4  |
|                        | Model III (De Jong et al.) | 0.106 | A 5  | Model III | 0.059 | B 5  |
|                        | Model V (Saxton et al.) | 0.155 | A 6  | Model V | 0.127 | B 6  |
| Silty clay soils (SiC) | Model II | 0.053 | A 1  | Model II | 0.053 | A 1  |
|                        | Model III | 0.060 | A 2  | Model VI | 0.059 | A 2  |
|                        | Model VI | 0.065 | A 3  | Model IV | 0.0732 | B 3  |
|                        | Model I | 0.066 | A 4  | Model I | 0.0734 | B 4  |
|                        | Model IV | 0.070 | A 5  | Model V | 0.079 | B 5  |
|                        | Model V | 0.084 | A 6  | Model III | 0.184 | C 6  |
| Sandy clay (SaC)       | Model VI | 0.050 | A 1  | Model I | 0.043 | A 1  |
|                        | Model I | 0.056 | A 2  | Model II | 0.051 | A 2  |
|                        | Model III | 0.059 | A 3  | Model VI | 0.053 | A 3  |
|                        | Model II | 0.061 | A 4  | Model IV | 0.061 | AB 4 |
|                        | Model IV | 0.065 | A 5  | Model III | 0.076 | B 5  |
|                        | Model V | 0.150 | B 6  | Model V | 0.103 | C 6  |
| Silty loam soils (SiL) | Model I | 0.058 | A 1  | Model VI | 0.14 | A 1  |
|                        | Model II | 0.052 | A 2  | Model V | 0.21 | B 2  |
|                        | Model I | 0.058 | AB 3 | Model II | 0.25 | C 3  |
|                        | Model IV | 0.068 | B 4  | Model VI | 0.26 | D 4  |
|                        | Model V | 0.102 | C 5  | Model IV | 0.27 | D 5  |
|                        | Model III | 0.128 | D 6  | Model III | 0.43 | E 6  |
| Loamy soils (L)        | Model VI | 0.050 | A 1  | Model I | 0.14 | A 1  |
|                        | Model II | 0.052 | A 2  | Model V | 0.21 | B 2  |
|                        | Model I | 0.058 | AB 3 | Model II | 0.25 | C 3  |
|                        | Model IV | 0.068 | B 4  | Model VI | 0.26 | D 4  |
|                        | Model V | 0.102 | C 5  | Model IV | 0.27 | D 5  |
|                        | Model III | 0.128 | D 6  | Model III | 0.43 | E 6  |
| Silty soils (Si)       | Model I | 0.058 | A 1  | Model VI | 0.016 | A 1  |
|                        | Model II | 0.055 | AB 2 | Model V | 0.017 | A 2  |
|                        | Model IV | 0.061 | AB 3 | Model II | 0.048 | A 3  |
|                        | Model I | 0.065 | AB 4 | Model IV | 0.056 | A 4  |
|                        | Model III | 0.074 | BC 5 | Model III | 0.059 | A 5  |
|                        | Model V | 0.094 | C 6  | Model I | 0.071 | A 6  |
| Clay loam soils (CL)   | Model I | 0.058 | A 1  | Model VI | 0.016 | A 1  |
|                        | Model II | 0.055 | AB 2 | Model V | 0.017 | A 2  |
|                        | Model IV | 0.061 | AB 3 | Model II | 0.048 | A 3  |
|                        | Model I | 0.065 | AB 4 | Model IV | 0.056 | A 4  |
|                        | Model III | 0.074 | BC 5 | Model III | 0.059 | A 5  |
|                        | Model V | 0.094 | C 6  | Model I | 0.071 | A 6  |
| Sandy soils (Sa)       | Model V | 0.055 | A 1  | Model VI | 0.016 | A 1  |
|                        | Model VI | 0.063 | A 2  | Model VI | 0.040 | B 2  |
|                        | Model II | 0.064 | A 3  | Model IV | 0.043 | B 3  |
|                        | Model IV | 0.067 | A 4  | Model III | 0.046 | B 4  |
|                        | Model I | 0.086 | A 5  | Model II | 0.049 | BC 5 |
|                        | Model III | 0.089 | A 6  | Model I | 0.064 | C 6  |
Table 7. Values of root mean squared deviation (RMSD) index among soil moistures measured and estimated with the six PTFs at the Wilting Point within the soils grouped in USDA textural classes.

| Wilting Point | PTF | RMSD m³·m⁻³ | ranking | PTF | RMSD m³·m⁻³ | ranking |
|---------------|-----|-------------|---------|-----|-------------|---------|
| Clayey soils (C) | Model III (De Jong et al.) | 0,0425 | A 1 | | | |
| | Model IV (Rawls & Brak.) | 0,0434 | A 2 | | | |
| | Model V (Saxton et al.) | 0,0649 | B 3 | | | |
| | Model II (Rawls et al.) | 0,0652 | B 4 | | | |
| | Model VI (Vereecken et al.) | 0,080 | C 5 | | | |
| | Model I (Gupta & Larson) | 0,117 | D 6 | | | |
| | Sandy clay loam soils (SaCL) | Model IV | 0,017 | A 1 | | |
| | | Model V | 0,019 | A 2 | | |
| | | Model III | 0,021 | A 3 | | |
| | | Model VI | 0,031 | B 4 | | |
| | | Model II | 0,035 | B 5 | | |
| | | Model I | 0,067 | C 6 | | |
| Silty clay (SiC) | Model IV | 0,038 | A 1 | | | |
| | Model III | 0,043 | A 2 | | | |
| | Model V | 0,046 | A 3 | | | |
| | Model II | 0,053 | A 4 | | | |
| | Model VI | 0,073 | B 5 | | | |
| | Model I | 0,124 | C 6 | | | |
| | Silty loam soils (SiL) | Model I | 0,037 | A 1 | | | |
| | Model II | 0,056 | B 2 | | | |
| | Model V | 0,062 | B 3 | | | |
| | Model IV | 0,068 | C 4 | | | |
| | Model III | 0,082 | D 5 | | | |
| | Model VI | 0,114 | E 6 | | | |
| Sandy clay loam soils (SiCL) | Model IV | 0,036 | A 1 | | | |
| | Model III | 0,036 | AB 2 | | | |
| | Model IV | 0,041 | AB 3 | | | |
| | Model V | 0,046 | AB 4 | | | |
| | Model I | 0,051 | B 5 | | | |
| | Model III | 0,065 | C 6 | | | |
| | Model VI | 0,027 | A 1 | | | |
| | Clay loam soils (CL) | Model II | 0,032 | A 1 | | | |
| | | Model VI | 0,018 | AB 2 | | | |
| | | Model IV | 0,024 | AB 3 | | | |
| | | Model V | 0,029 | AB 4 | | | |
| | | Model I | 0,031 | AB 5 | | | |
| | | Model III | 0,035 | B 6 | | | |
| | Loamy soils (L) | Model III | 0,065 | C 6 | | | |
| | Silty soils (Si) | Model I | 0,12 | A 1 | | | |
| | Model IV | 0,20 | B 2 | | | |
| | | Model V | 0,21 | C 3 | | | |
| | | Model VI | 0,228 | D 4 | | | |
| | | Model II | 0,229 | D 5 | | | |
| | | Model III | 0,300 | E 6 | | | |
| | Sandy soils (Sa) | Model I | 0,036 | A 1 | | | |
| | | Model VI | 0,018 | AB 2 | | | |
| | | Model II | 0,024 | AB 3 | | | |
| | | Model V | 0,029 | AB 4 | | | |
| | | Model I | 0,031 | AB 5 | | | |
| | | Model III | 0,035 | B 6 | | | |
| | Silty clay loam soils (SiCL) | Model IV | 0,0407 | A 1 | | | |
| | | Model VI | 0,009 | A 1 | | | |
| | | Model IV | 0,037 | B 2 | | | |
| | | Model II | 0,0397 | B 3 | | | |
| | | Model V | 0,0397 | B 4 | | | |
| | | Model III | 0,035 | B 5 | | | |
| | | Model I | 0,051 | C 6 | | | |
| | Loamy sand soils (LSa) | Model I | 0,047 | B 6 | | | |
Table 8. Values of root mean squared deviation (RMSD) index among soil moistures measured and estimated with the six PTFs at the Field Capacity of the soils, grouped in classes of organic matter content within the three great textural groupings.

| Field Capacity | Tendency clayey soils | O.M.: < 1.2 % | PTF | RMSD m³ m⁻³ | ranking | PTF | RMSD m³ m⁻³ | ranking |
|----------------|----------------------|---------------|-----|-------------|---------|-----|-------------|---------|
|                |                      |               | Model II (Rawls et al.) | 0.08295 | A | 1 | Model II | 0.058 | A | 1 |
|                |                      |               | Model I (Gupta & Larson) | 0.08299 | A | 2 | Model I | 0.067 | AB | 2 |
|                |                      |               | Model IV (Rawls & Brak.) | 0.090 | A | 3 | Model IV | 0.069 | AB | 3 |
|                |                      |               | Model III (De Jong et al.) | 0.097 | A | 4 | Model III | 0.083 | B | 4 |
|                |                      |               | Model VI (Vereecken et al.) | 0.104 | A | 5 | Model V | 0.084 | B | 5 |
|                |                      |               | Model V (Saxton et al.) | 0.158 | A | 6 | Model VI | 0.088 | B | 6 |

|                | O.M.: 1.2-2.3 % | PTF | RMSD m³ m⁻³ | ranking | PTF | RMSD m³ m⁻³ | ranking |
|----------------|----------------|-----|-------------|---------|-----|-------------|---------|
|                | Model V | 0.029 | A | 1 | Model V | 0.037 | A | 1 |
|                | Model III | 0.0427 | AB | 2 | Model IV | 0.042 | A | 2 |
|                | Model IV | 0.0431 | A | 2 | Model VI | 0.051 | A | 3 |
|                | Model II | 0.065 | AB | 4 | Model III | 0.056 | A | 4 |
|                | Model VI | 0.076 | AB | 5 | Model II | 0.066 | A | 5 |
|                | Model I | 0.098 | B | 6 | Model I | 0.087 | A | 6 |

|                | O.M.: 2.3-3.0 % | PTF | RMSD m³ m⁻³ | ranking | PTF | RMSD m³ m⁻³ | ranking |
|----------------|----------------|-----|-------------|---------|-----|-------------|---------|
|                | Model II | 0.033 | A | 1 | Model III | 0.031 | A | 2 |
|                | Model IV | 0.054 | A | 2 | Model IV | 0.057 | AB | 2 |
|                | Model VI | 0.059 | B | 3 | Model VI | 0.061 | AB | 3 |
|                | Model I | 0.061 | B | 4 | Model V | 0.069 | AB | 4 |
|                | Model V | 0.084 | C | 5 | Model I | 0.085 | B | 5 |
|                | Model III | 0.149 | D | 6 | Model III | 0.156 | C | 6 |

|                | O.M.: > 3.0 % | PTF | RMSD m³ m⁻³ | ranking | PTF | RMSD m³ m⁻³ | ranking |
|----------------|----------------|-----|-------------|---------|-----|-------------|---------|
|                | Model II | 0.026 | A | 1 | Model I | 0.046 | A | 1 |
|                | Model III | 0.031 | A | 2 | Model II | 0.051 | A | 2 |
|                | Model IV | 0.034 | A | 3 | Model IV | 0.076 | A | 3 |
|                | Model I | 0.038 | A | 4 | Model III | 0.088 | AB | 4 |
|                | Model V | 0.076 | A | 5 | Model VI | 0.110 | AB | 5 |
|                | Model VI | 0.089 | A | 6 | Model V | 0.125 | B | 6 |
Table 9. Values of root mean squared deviation (RMSD) index among soil moistures measured and estimated with the six PTFs at the Wilting Point of the soils, grouped in classes of organic matter content within the three great textural groupings.

| Wilting Point | Tendency clayey soils | Tendency sandy soils |
|---------------|-----------------------|-----------------------|
|               | PTF RMSD ranking      | PTF RMSD ranking      |
|               | m³·m⁻³                 | m³·m⁻³                 |
|               |                       |                       |
| O.M.: < 1,2 % |                       |                       |
| Model IV (Rawls & Brak.) | 0,046 A 1 | Model IV | 0,039 A 1 |
| Model II (Rawls & al.)   | 0,053 A 2 | Model V | 0,046 AB 2 |
| Model III (De Jong et al.) | 0,058 A 3 | Model II | 0,053 ABC 3 |
| Model V (Saxton et al.)  | 0,063 A 4 | Model III | 0,056 BC 4 |
| Model I (Gupta & Larson) | 0,105 B 5 | Model VI | 0,071 C 5 |
| Model VI (Vereecken et al.) | 0,117 B 6 | Model I | 0,102 D 6 |
| O.M.: 1,2-2,3 % |                       |                       |
| Model IV | 0,014 A 1 | Model IV | 0,012 A 1 |
| Model V | 0,023 A 2 | Model V | 0,021 A 2 |
| Model III | 0,042 A 3 | Model VI | 0,039 A 3 |
| Model II | 0,047 A 4 | Model II | 0,0436 A 4 |
| Model VI | 0,049 A 5 | Model III | 0,0444 A 5 |
| Model I | 0,092 B 6 | Model I | 0,087 B 6 |
| O.M.: 2,3-3,0 % |                       |                       |
| O.M.: > 3,0 % |                       |                       |
| Model I | 0,037 A 1 | Model I | 0,04317 A 1 |
| Model II | 0,042 AB 2 | Model II | 0,04321 A 2 |
| Model IV | 0,054 BC 3 | Model VI | 0,049 A 3 |
| Model VI | 0,056 BC 4 | Model IV | 0,059 AB 4 |
| Model V | 0,065 C 5 | Model V | 0,071 B 5 |
| Model III | 0,075 D 6 | Model III | 0,091 C 6 |
| O.M.: 1,9-2,5 % |                       |                       |
| O.M.: > 2,5 % |                       |                       |
| Model V | 0,0295 A 1 | Model IV | 0,025 A 1 |
| Model IV | 0,0299 A 2 | Model V | 0,026 A 2 |
| Model II | 0,031 A 3 | Model VI | 0,0323 A 3 |
| Model III | 0,035 A 4 | Model III | 0,0328 A 4 |
| Model VI | 0,042 A 5 | Model II | 0,0331 A 5 |
| Model I | 0,048 A 6 | Model I | 0,050 B 6 |
| O.M.: < 0,8 % |                       |                       |
| O.M.: 0,8-1,5 % |                       |                       |
| O.M.: 1,5-2,0 % |                       |                       |
| O.M.: > 2,0 % |                       |                       |
| Model IV | 0,017 A 1 | Model I | 0,030 A 1 |
| Model V | 0,021 A 2 | Model II | 0,036 A 2 |
| Model III | 0,027 AB 3 | Model III | 0,037 A 3 |
| Model II | 0,038 AB 4 | Model V | 0,038 A 4 |
| Model VI | 0,041 AB 5 | Model IV | 0,040 A 5 |
| Model I | 0,051 B 6 | Model VI | 0,044 A 6 |
In relation to loamy and tendency silty soils, the lowest difference values between soil moisture estimated and measured have been obtained: with the model I when the organic matter content is lower than 1.0% and is included between 1.0 and 1.9%; with the model II, when the organic matter content varies between 1.9% and greater than 3.0%. With the lowest and the highest organic matter contents, the RMSD values varied between 0.083 and 0.058 m$^3$·m$^{-3}$ with the model II and between 0.029 and 0.037 m$^3$·m$^{-3}$ with model V, respectively. However, these values are not different from the ones obtained with the most applied PTFs (Tab. 8).

Table 10. Correlation coefficients between input parameters and the differences among estimated and measured soil moistures ($\Delta \theta$) regarding the PTFs and soil groupings where they produce the best performance at the field capacity.

**Field Capacity**

| Soil grouping       | Input parameters | Clay | Silt | Sand | Organic matter | Soil bulk density |
|---------------------|------------------|------|------|------|----------------|-------------------|
|                     |                  | %    | %    | %    | %              | g/cm$^3$          |
| **Model I** (Gupta & Larson, 1979) |                  |      |      |      |                |                   |
| Clayey              | -0.02 ns         | 0.25 ns | -0.15 ns | 0.37 * | -0.34 *         |                   |
| Sandy clay loam    | -0.35 ns         | 0.08 ns | 0.16 ns | 0.57 ** | -0.41 *         |                   |
| Sandy loam         | 0.18 ns          | -0.15 ns | 0.08 ns | 0.11 ns | -0.01 ns         |                   |
| Silty              | -                | -     | -     | -     |                |                   |
| loamy and tendency silty | O.M. < 1.9 %    | -0.14 ns | 0.29 ** | -0.30 ** | 0.46 ** | -0.46 **        |
| tendency sandy     | O.M. < 1.5 %     | -0.17 ns | -0.53 ** | 0.50 ** | 0.05 ns | 0.26 ns         |
|                   | O.M. > 2 %       | -0.22 ns | 0.13 ns | -0.08 ns | -0.17 ns | -0.01 ns         |
| **Model II** (Rawls et al., 1982) |                  |      |      |      |                |                   |
| Silty clay         | 0.05 ns          | -0.25 | 0.12 ns | -0.05 ns |                |                   |
| Silty loam         | 0.02 ns          | 0.23  | -0.25 * | 0.63 ** |                |                   |
| tendency clayey    | O.M. < 2.3 %     | -0.026 ns | -0.08 ns | 0.305 ** |                |                   |
| loamy and tendency silty | O.M. > 1.9 %     | 0.16 ns | -0.035 ns | 0.475 ** |                |                   |
| **Model IV** (Rawls & Brakensiek, 1985) |                  |      |      |      |                |                   |
| tendency sandy     | O.M. 1.5-2 %     | -0.43 ns | 0.75 ns | 0.61 ns |                |                   |
| **Model V** (Saxton et al., 1986) |                  |      |      |      |                |                   |
| Silty clay loam    | -0.08 ns         | 0.11 ns |                   |                   |                   |
| Loamy sand         | 0.47 ns          | 0.48 ns |                   |                   |                   |
| tendency clayey    | O.M. > 2.3 %     | -0.58 * | -0.29 ns |                   |                   |                   |
| **Model VI** (Vereecken et al., 1989) |                  |      |      |      |                |                   |
| Sandy clay         | -0.17 ns         | -0.21 ns | 0.65 ns | -0.50 ns |                |                   |
| Loamy              | 0.32 **          | -0.18 ns | 0.30 * | -0.22 ns |                |                   |
| Clay loam          | -0.15 ns         | 0.00 ns | 0.45 ** | -0.22 ns |                |                   |
| Sandy              | -                | -     | -     | -     |                |                   |
with organic matter content lower than 0.8%, between 0.8 and 1.5% and higher than 2.0%; with the model IV in soils having organic matter content between 1.5 and 2.0%.

In any case the RMSD index values are not statistically different from those obtained with the other applied PTFs (Tab. 8).

Table 11. Correlation coefficients between input parameters and the differences among estimated and measured soil moistures ($\Delta \theta$) regarding the PTFs and soil groupings where they produce the best performance at the wilting point.

**Wilting Point**

| Soil grouping                        | Input parameters | Clay | Silt | Sand | Organic matter | Soil bulk density |
|--------------------------------------|------------------|------|------|------|----------------|------------------|
|                                      |                  | %    | %    | %    | %              | g/cm³             |
| Model I (Gupta & Larson, 1979)       | Silty loamy and  | 0.52 | -0.05 | -0.32 | 0.17 | -0.08 |
| tendency silty                       | Silty            | -    | -    | -    | -              | -                |
|                                      | O.M. > 1.9 %     | 0.66 | -0.32 | 0.06  | -0.06 | 0.36  |
|                                      | tendency sandy   | 0.30 | -0.31 | 0.40  | -0.06 | 0.16  |
|                                      | O.M. > 2 %       | 0.50 | -0.31 | 0.17  | -0.64 | 0.76  |
| Model II (Rawls et al., 1982)        | Loamy            | 0.48 | -0.02 | 0.16  | -0.21 |
| loamy and tendency                   |                  |      |      |      |      |      |
| sandy                               |                  |      |      |      |      |      |
|                                      | O.M. 1.0-1.9 %   | 0.64 | -0.02 | 0.16  | -0.21 |
| Model III (De Jong et al., 1983)     | Clayey           | -0.02| -0.17 | 0.29  | 0.00  |      |
|                                      |                  |      |      |      |      |      |
| Model IV (Rawls & Brakensiek, 1985)  | Silty clay       | 0.47 | -0.27 | 0.42  |      |
| Sandy clay                          | -0.26            | -0.30 | -0.57 |      |
| Clay loam                           | 0.11             | 0.25  | 0.12  |      |
| Silty clay loam                     | -0.01            | 0.51  | -0.27 |      |
| Sandy clay loam                     | -0.20            | 0.51  | -0.27 |      |
| tendency clayey                     | O.M. > 0 %       | 0.42 | -0.045| 0.15  |      |
| sandy                               | O.M. 0.8-2 %     | 0.23 | 0.58  | 0.72  |      |
| Model V (Saxton et al., 1986)        | loamy and tendency |      |      |      |      |
| sandy                               | O.M. < 1 %       | 0.55 | -0.64 |      |      |
| tendency sandy                      | O.M. < 0.8 %     | 0.08 | 0.55  |      |      |
| Model VI (Vereecken et al., 1989)    | Sandy leam       | 0.63 |       | 0.46  | -0.12 | 0.48  |
| sandy                               | -                |       |       | -    | -    |      |
| Loamy sand                          | 0.51             |       | 0.35  | -0.53 | 0.46  |      |

and 2.5% and is greater than 2.5%. Also in these soil types the RMSD values calculated with the suggested PTFs are not different from RMSD values calculated with the others (Tab. 8).

For tendency sandy soils, the most accurate of the estimate of soil moisture at field capacity has been obtained with the model I in soils with organic matter content lower than 0.8%, between 0.8 and 1.5% and higher than 2.0%; with the model IV in soils having organic matter content between 1.5 and 2.0%.

In any case the RMSD index values are not statistically different from those obtained with the other applied PTFs (Tab. 8).
5.2.2 Soil moisture at the Wilting Point. At the wilting point, for the tendency clayey soils with whatever organic matter content, soil moisture has been estimated with reasonable approximation with the most applied PTFs; however, applying model IV the RMSD values obtained have been the lowest, varying from 0.046 to 0.039, 0.014 and 0.012 m$^3$ m$^{-3}$, for soils with organic matter content lower than 1.2%, between 1.2 and 2.3%, between 2.3 and 3.0% and higher than 3.0%, respectively (Tab. 9).

For loamy and tendency silty soils, the most accurate soil moisture estimates at the wilting point have been obtained with models V, II and I in soils with organic matter content lower than 1.0%, between 1.0 e 1.9% and higher than 1.9%, respectively. Applying these models, the RMSD values vary from 0.050 to 0.037 m$^3$ m$^{-3}$ and are not always different from those obtained with other applied PTFs (Tab. 9).

For tendency sandy soils, the lowest RMSD values have been observed applying the models V, IV and I when the soil organic matter content was lower than 0.8%, between 0.8 and 2.0% and higher than 2.0%, respectively (table 9); these RMSD values were not statistically different from the values obtained with the most of the applied PTFs.

Comparing soil moistures measured in laboratory and estimated with the six pedotransfer functions (PTFs), it appears that the most careful evaluations have been obtained with different PTFs in relation to the textural classes, organic matter content and the matric potential considered (FC or WP).

In Tables 10 and 11, the correlation coefficients (those underlined affect less the statistical errors) among the input parameters and the differences among soil moistures estimated and determined in laboratory ($\Delta\phi$), regarding the PTFs and soil grouping wherein they provide the best performances at the FC and the WP, respectively, are reported.

6. Conclusions

In conclusion, considering these results, in Apulian soils grouped on a basis of the textural composition and organic matter content, it is possible to suggest the PTFs that provide the estimated soil moisture values almost equal to the measured ones at the Field Capacity and the Wilting Point.

A) For soil moisture at the field capacity:
1) model I (Gupta and Larson, 1979) in Clayey, Sandy clay loam, sandy loam and Silty soil, in loamy and tendency silty soils with O.M. content less than 1.9% and in tendency sandy soils with O.M. content less than 1.5% and greater than 2%;
2) model II (Rawls et al., 1982) in Silty clay and Silty loam soils, in tendency clayey soils with O.M. less than 2.3% and in loamy and tendency silty soils with O.M. greater than 1.9%;
3) model IV (Rawls and Brakensiek, 1985) in tendency sandy soils with O.M. content between 1.5 and 2%;
4) model V (Saxton et al., 1986) in Silty clay loam, Loamy sand soils and in tendency clayey soils with O.M. content greater than 2.3%
5) model VI (Vereecken et al., 1989) in Sandy clay, Loamy, Clay loam and Sandy soils.

B) For soil moisture at the wilting point:
1) model I (Gupta and Larson, 1979) in Silty loam, Silty soils and in general in loamy and tendency silty in tendency sandy soils with O.M. content greater than 1.9% and than 2%, respectively;
2) model II (Rawls et al., 1982) in Loamy soils and in loamy and tendency silty soils with O.M. between 1.0 and 1.9%;
3) model III (De Jong et al., 1983) in Clayey soils;
4) model IV (Rawls and Brakensiek, 1985) in Silty clay, Sandy clay, Clay loam, Silty clay loam, Sandy clay loam soils and generally in tendency clayey soils with whatever O.M. content and in tendency sandy soils with O.M. content between 0.8 and 2%;
5) model V (Saxton et al., 1986) in loamy and tendency silty soils with O.M. content less than 1% and in tendency sandy soils with O.M. less than 0.8%;
6) model VI (Vereecken et al., 1989) in Sandy loam, Sandy and Loamy sand soils.

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