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Point pedotransfer functions for estimating soil water retention curve

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A b s t r a c t. Soil water retention curve (SWRC) is one of the most important soil hydraulic properties, whose estimation is still under consideration. In this study, we used 315 soil samples from the UNSODA database to develop three models of point pedotransfer functions (PTFs) and to verify them. We also used an independent database, GRIZZLY, with 59 samples, to verify the developed point PTFs and to compare them with the Rosetta model. Multiple linear regression and stepwise methods were used to derive pedotransfer functions. In the first model, soil texture data *ie* sand, silt, and clay content, geometric mean particle-size diameter and geometric standard deviation as well as bulk density were used to develop point PTFs at 10 matric potentials. In the second model, water content at field capacity, and in the third model water content at field capacity and permanent wilting point were also used for developing PTFs at 9 and 8 matric potentials, respectively. To evaluate the accuracy and reliability of the point PTFs, we used cross-validation *eg* repeated random splitting of the data set into subsets for development and validation. The calculated RMSE values showed that all three developed point PTFs estimated soil water retention curve better than the Rosetta model.

K e y w o r d s: field capacity, point pedotransfer functions, permanent wilting point, soil water retention curve

INTRODUCTION

Soil water retention curve (SWRC), as one of the most important soil hydraulic properties, is widely used in simulation of water flow in saturated and unsaturated zones and solute transport. However, its estimation using available parameters is still under consideration. In the estimation of SWRC from readily available parameters *eg* soil texture data, bulk density, organic matter and particle-size distribution several types of pedotransfer functions (PTFs) based on multiple linear regression, nonlinear regression, or artificial neural networks have been developed, such as class PTFs (Baker, 2008; Schaap *et al*., 2001; Wösten *et al*., 1999), point PTFs (Pachepsky and Rawls, 1999; Ungaro *et al*., 2005; Walczak *et al*., 2006; Nemes *et al*., 2006), and parametric PTFs (Minasny and McBrateny, 2002; Schaap *et al*., 2001; Tomasella *et al*., 2000; Vereecken *et al*., 1989; Wösten *et al*., 2001).

Rawls *et al*. (1982) developed three point PTFs to estimate water content at several matric potentials using:
– soil properties (sand, silt, and clay contents, organic matter, and bulk density);
– soil properties and water retained at -1500 kPa;
– soil properties and water retained at -33 and -1500 kPa.

Schaap *et al*. (2001) developed artificial neural networks (called Rosetta) to estimate vG and vG-Mualem models parameters based on textural classes (H1), soil texture data (sand, silt and clay content) (H2), soil texture data and bulk density (H3), soil texture data, bulk density and water content at field capacity, θ_{33}, (H4), and soil texture data, bulk density, θ_{33}, and water content at permanent wilting point, θ_{1500}, (H5). This model has been widely used in the literature for estimating vG model parameters.

Rajkai *et al*. (2004) developed parametric pedotransfer functions to estimate van Genuchten (1980) model parameters using 8 readily available parameters. Those authors also used one measured point of SWRC to improve the model estimation and showed that by using one measured point it was possible to increase the model efficiency about 25% for the verification data set. They also found that the best measured point was near the SWRC inflection point and used water content at -20 kPa. Whereas, Rawls and Brakensiek (1989) proposed to use the permanent wilting point for this purpose. However, the measurement of permanent wilting point is much more time consuming than the field capacity point.

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Minasny *et al.* (1999) presented both parametric and point PTFs using different approaches such as multiple linear regression, extended nonlinear regression and artificial neural network for estimating SWRC. Those authors found extended nonlinear regression and multiple linear regression to be the most appropriate for parametric and point PTFs, respectively.

Tomasella *et al.* (2003) compared two techniques, point-based method and a parametric approach, to develop a PTF for water retention of Brazilian soils using the group method of data handling (GMDH) and soil properties such as coarse sand, fine sand, silt, clay, organic carbon content, moisture equivalent, and bulk density. Those authors indicated that the point-based method provided better results. They explained the obtained results by the fact that water content is controlled by different independent variables at different matric potentials in soils, and the point-based method provided a more proper combination of the independent variables.

Recently, Børgesen and Schaap (2005) developed a point model to estimate water content at -1, -10, -100, and -1 500 kPa, and a parametric model to estimate vG retention model parameters using neural networks and Bootsrap method for a large database of Danish soils. Those authors found that adding organic matter and bulk density as the input parameters of neural networks could improve the estimation of SWRC. Adding water content measured at -1, -100, and -1 500 kPa noticeably improved the SWRC estimation as well. They also found that point PTF models over- come parametric PTF models, which could be due to imper- fect fit of vG model to the retention data at -1500 kPa in parametric models procedure.

The objective of this study was to develop point PTFs in order to estimate water content at different matric potentials using available parameters such as sand, silt and clay contents, geometric mean particle-size diameter, geometric standard deviation, and bulk density. Since two common measured water contents are those corresponding to soil matric potential of -33 and -1500 kPa, we also developed two point PTFs using these measured water contents to improve the estimation of SWRC.

MATERIALS AND METHODS

In this study, the UNSODA database (Leij *et al*., 1996), which contains a wide range of soil texture classes, was used to develop and validate point PTFs with 250 and 65 soil samples, respectively. The random splitting of data into the development and validation subsets was repeated 10 times (Pachepsky and Rawls, 1999). We also used an independent database, GRIZZLY, (Haverkamp *et al*., 1997) which includes 59 soil samples, to compare the developed point PTFs with the Rosetta model. Figure 1 shows the location of each soil textural class used in the present study within the texture triangle.

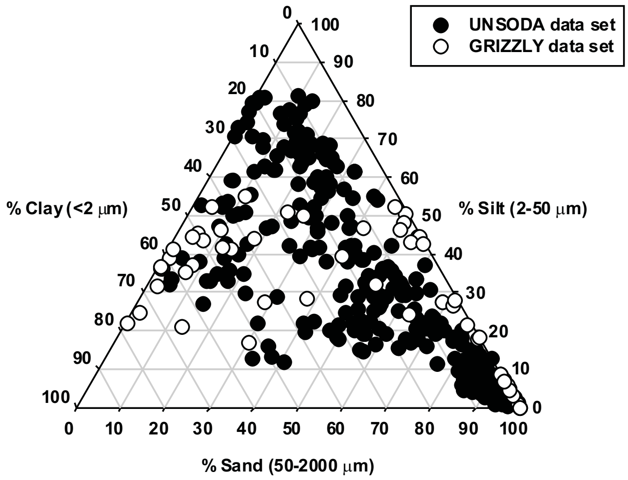

Fig. 1. Soil textural classes considered for the UNSODA and GRIZZLY databases used in this study.

The optimized vG model (van Genuchten, 1980) parameters, θ_r, θ_s, α and n, were used to determine water contents at 9 pressure heads, such as inflection point, -10, -33, -50, -100, -300, -500, -1000, -1500 kPa for each soil sample within the UNSODA database (Baker, 2008; Wösten and Nemes, 2004).

Geometric mean particle-size diameter, d_g (mm), and geometric standard deviation, σ_g (mm), were calculated based on three fractions such as clay, silt, and sand content (Shirazi and Boersma, 1984). Scheinost *et al*. (1997) found that calculations made from 18 rather than 4 fractions did not improve PTF performance.

Dexter (2004) showed that the slope of the soil water retention curve at the inflection point was strongly correlated with organic matter. Furthermore, we know that soil organic matter retains water well and does not allow it to flow freely (Walczak *et al*., 2004), and may also affect the pore-size distribution of the soil through soil structure development (Nemes *et al*., 2005). Organic matter was not included as a predictive variable for developing the PTFs because it was not available for all considered soil samples.

We also developed equations to estimate water content at the inflection point which, in turn, was computed using van Genuchten (1980) model parameters as follows (Dexter, 2004):

$$\theta_{\inf} = (\theta_s - \theta_r)[1+1/m]^{-m} + \theta_r \tag{1}$$

where: θ_s is saturated water content (cm^3 cm^{-3}), θ_r is residual water content (cm^3 cm^{-3}), and m is van Genuchten (1980) retention model parameter.

Indeed, at the inflection point, the behaviour of SWRC changes. For soil drying between saturation and the inflection point, it is mainly structural pores that are emptying. However, for soil drying below the inflection point, it is mainly textural pores that are emptying (Dexter, 2004).

For the first model (model 1 hereafter), we used a multiple linear regression model:

$$\theta_{\mathrm{x}} = a_0 + a_1 C + a_2 Si + a_3 S + a_4 BD + a_5 d_g + a_6 \sigma_g \quad (2)$$

where C, Si and S are clay, silt and sand contents (%), respectively, BD is bulk density (g cm^{-3}), d_g and σ_g are geometric mean diameter (mm) and geometric standard deviation (mm), respectively, x refers to the matric potential at saturation, inflection point, -10, -33, -50, -100, -300, -500, -1 000, and -1 500 kPa, and a_0 to a_6 regression coefficients. In the second model (model 2 hereafter), water content at field capacity (θ_{33}), and in the third model (model 3 hereafter), water content at field capacity and permanent wilting point ($\theta_{1\,500}$) were used as the multiple linear regression model inputs, respectively. In derivation of point PTFs, we used a stepwise method and SPSS statistical software package (SPSS, 1998).

We also used H3, H4, and H5 models from Rosetta (Schaap *et al.*, 2001) to estimate vG model parameters and, consequently, water content at the corresponding matric potentials for 59 soil samples from the GRIZZLY database.

For the development, validation and comparison procedures, the derived PTFs were statistically evaluated (Vereecken and Herbst, 2004) using statistical parameters such as mean of residuals (MR), coefficient of determination (R^2) and root mean square error (RMSE). The RMSE, MR and R^2 values were calculated for each of 10 replications. The average values of these statistical parameters, along with the estimates of standard deviations, were used to evaluate improvements in PTF performance and to compare performance of different PTFs. Statistical significance of differences was tested at the 0.05 significance level.

RESULTS FOR THE UNSODA DATABASE

Table 1 shows the average value of coefficient of determination (R^2) over replications for the linear regression between water content at different matric potentials using the development data sets (n=250). The higher R^2 values indicated that water content held at different matric potentials was linearly correlated to each other. This table also showed that water content at higher and lower matric potentials (degree of saturation) was strongly correlated with water content at field capacity and permanent wilting point, respectively, following a linear function. As we showed in Table 1, water content at inflection point was strongly correlated with saturated water content with a goodness of fit R^2 = 0.87. This means that 87% of θ_{inf} variability was explained only by the saturated water content. It could be understood by the fact that θ_{inf} is linearly related to θ_s (Eq. 1).

T a b l e 1. Average values of determination coefficient (R^2) and their standard deviations (in parentheses) for the linear regression between water content at different matric potentials calculated from 10 splits of development data set (n=250)

	θ_s	θ_{inf}	θ_{10}	θ_{33}	θ_{50}	θ_{100}	θ_{300}	θ_{500}	$\theta_{1\,000}$	$\theta_{1\,500}$
θ_s	1.00 (0.000)	0.87 (0.010)	0.44 (0.017)	0.39 (0.016)	0.38 (0.016)	0.37 (0.017)	0.37 (0.020)	0.36 (0.021)	0.34 (0.022)	0.32 (0.022)
θ_{inf}		1.00 (0.000)	0.65 (0.010)	0.64 (0.009)	0.64 (0.009)	0.66 (0.010)	0.67 (0.011)	0.67 (0.012)	0.66 (0.014)	0.62 (0.015)
θ_{10}			1.00 (0.000)	0.95 (0.004)	0.92 (0.005)	0.86 (0.007)	0.77 (0.011)	0.74 (0.013)	0.70 (0.014)	0.68 (0.014)
θ_{33}				1.00 (0.000)	1.00 (0.000)	0.97 (0.002)	0.90 (0.005)	0.86 (0.007)	0.83 (0.009)	0.80 (0.010)
θ_{50}					1.00 (0.000)	0.99 (0.001)	0.93 (0.003)	0.90 (0.005)	0.87 (0.007)	0.84 (0.009)
θ_{100}						1.00 (0.000)	0.98 (0.001)	0.96 (0.002)	0.92 (0.004)	0.89 (0.006)
θ_{300}							1.00 (0.000)	1.00 (0.000)	0.98 (0.001)	0.94 (0.003)
θ_{500}								1.00 (0.000)	0.99 (0.000)	0.96 (0.002)
θ_{1000}									1.00 (0.000)	0.99 (0.001)
$\theta_{1\,500}$										1.00 (0.000)

Point pedotransfer functions for model 1

The average values of statistical parameters and their standard deviations for model 1 development and validation are presented in Table 2. For the model development, the average value of RMSE was in the range of 0.037 to 0.059 (cm^3 cm^{-3}) for water content at the inflection point and -10 kPa, respectively. The average value of R^2 varied within the range of 0.772 to 0.851 for water content retained at saturation and -50 kPa, respectively. The negative MR values also indicated that water content at -50 and -100 kPa was slightly underestimated.

The results for the first model development indicated that bulk density, geometric mean particle-size diameter (d_g) and clay content were the main variables affecting water content retained at different matric potentials. However, sand content affects water contents near saturation (θ_{10}, θ_{33}, θ_{50}), which is in agreement with previous results by Tomasella *et al*. (2003). Those authors found that coarse-textured fractions affect water content near saturation while fine fractions are related to lower water content. The developed pedotransfer function for estimating saturated water content presented a similar form as compared to the Vereecken *et al*. (1989) model with a small change in the coefficients. Within the context of the present study, saturated water content can be mainly affected by clay content and bulk density. However, some workers have assumed the saturated water content to be equal to soil total porosity multiplied by 0.93 (Williams *et al*., 1992) or 0.90 (Pachepsky *et al*., 1999) where total porosity is calculated from bulk density and particle density (ρ_p=2.65).

For model 1 validation, the average value of RMSE was in the range of 0.040 to 0.060 for water content retained at the inflection point and -10 kPa, respectively, which is in agreement with the results of model development (Table 2). However, the values of standard deviation for model development are less than those of model validation. Ahuja *et al.* (1985) obtained an accuracy (RMSE) value around 0.05 cm^3 cm^{-3} for the point-based estimation. Schaap and Leij (1998) applied the parametric estimation method and obtained overall RMSE of approximately 0.1 cm^3 cm^{-3}. We also found that point PTFs developed for matric potential of -50 and -100 kPa underestimated the water content. For each point PTF developed in model 1 over the replications, the *t*-statistic test showed no significant difference among the RMSE values.

Point pedotransfer functions for model 2

For model 2 development, the average value of R^2 was in the range of 0.787 to 0.996 for water content at saturation and -50 kPa, respectively (Table 3). Furthermore, the average value of RMSE varied in the range of 0.011 to 0.044 (cm^3 cm^{-3}) for water content at saturation and -50 kPa, respectively.

In most cases, variables such as water content at -33 kPa, clay content and geometric mean particle-size diameter were the most important inputs. In addition to these variables, bulk density was another input considered for water contents near saturation ($\theta_s, \theta_{\text{inf}}, \theta_{10}$).

The average value of RMSE for model 2 validation was in the range of 0.011 to 0.045 (cm^3 cm^{-3}) for water content retained at -50 kPa and saturation, respectively (Table 3). The average values of RMSE in validation data sets were slightly greater than those in the development data sets. The *t*-statistic test also indicated that there is no significant difference among the RMSE values for each point PTF developed in model 2 over the replications. In addition, the negative average MR values showed that point PTFs developed for matric potential of -300 and -1500 kPa underestimated the water content.

Point pedotransfer functions for model 3

Table 4 shows the average values of statistical parameters for the development and validation of model 3. The average value of R^2 was in the range of 0.790 to 0.998 for water content at matric potential of 0 and -50 kPa, respectively. The highest and lowest average RMSE values were reached in PTFs developed for water content at saturation and -50 kPa, respectively, which is in agreement with the obtained results for model 2 development.

Water content at field capacity and permanent wilting point were the most important variables selected as the predictors in different matric potentials. For water content at matric potential of inflection point, -10 and -50, bulk density was one of the predictors as well. For water content at lower matric potentials such as -100, -300, -500, -1000 and -1500, clay content was selected as another predictor instead of bulk density. Although in model 3 water content at permanent wilting point was used instead of water content at field capacity, in most cases a similar equation was derived for estimating saturated water content in comparison to model 2.

For model 3 validation, the average value of R^2 varied in the range of 0.779 to 0.998 for water content at matric potential of 0 and -50 kPa, respectively. The average values of R^2 in validation data sets were very close to those in the development data sets. The highest and lowest average RMSE values were 0.044 and 0.009 (cm^3 cm^{-3}) for water content at matric potential of 0 and -50 kPa, respectively. The *t*-test showed that the RMSE values of validation data set did not differ significantly over the replications. Furthermore, the small positive average MR values indicated that model 3 overestimated the water content slightly.

DISCUSSION

One can note from Tables 2 to 4 is that increasing the measured points of SWRC such as water content at field capacity and permanent wilting point resulted in larger values of the coefficient of determination. Although in models

T a b l e 2. Average values of statistical parameters and their standard deviations (in parentheses) for the development and validation of model 1

θ	Development			Validation		
	R^2	MR	RMSE	R^2	MR	RMSE
θ_s	0.772 (0.024)	0.001 (0.006)	0.046 (0.003)	0.764 (0.080)	0.003 (0.009)	0.046 (0.008)
θ_{inf}	0.830 (0.018)	0.001 (0.006)	0.037 (0.002)	0.811 (0.070)	0.004 (0.009)	0.040 (0.005)
θ_{10}	0.830 (0.014)	0.007 0.009)	0.059 (0.001)	0.823 (0.059)	0.011 (0.012)	0.060 (0.007)
θ_{33}	0.850 (0.012)	0.003 (0.009)	0.053 (0.001)	0.831 (0.051)	0.006 (0.010)	0.055 (0.006)
θ_{50}	0.851 (0.012)	-0.009 (0.008)	0.051 (0.002)	0.829 (0.049)	-0.006 (0.012)	0.054 (0.005)
θ_{100}	0.848 (0.012)	-0.009 (0.018)	0.051 (0.003)	0.824 (0.050)	-0.007 (0.019)	0.054 (0.006)
θ_{300}	0.838 (0.014)	0.004 (0.005)	0.044 (0.002)	0.815 (0.054)	0.006 (0.006)	0.047 (0.005)
θ_{300}	0.830 (0.015)	0.005 (0.002)	0.043 (0.002)	0.805 (0.060)	0.007 (0.005)	0.047 (0.006)
$\theta_{1\,000}$	0.810 (0.017)	0.005 (0.002)	0.043 (0.002)	0.782 (0.063)	0.007 (0.005)	0.048 (0.005)
$\theta_{1\,500}$	0.774 (0.017)	0.000 (0.007)	0.047 (0.001)	0.744 (0.060)	0.002 (0.009)	0.052 (0.004)

T a b l e 3. Average values of statistical parameters and their standard deviations (in parentheses) for the development and validation of model 2

θ	Development			Validation		
	R^2	MR	RMSE	R^2	MR	RMSE
θ_s	0.787 (0.022)	0.001 (0.005)	0.044 (0.002)	0.776 (0.077)	0.002 (0.009)	0.045 (0.008)
θ_{inf}	0.852 (0.015)	0.010 (0.007)	0.036 (0.004)	0.838 (0.053)	0.009 (0.005)	0.037 (0.005)
θ_{10}	0.958 (0.004)	0.001 (0.001)	0.029 (0.001)	0.963 (0.017)	0.002 (0.005)	0.027 (0.005)
θ_{50}	0.996 (0.001)	0.000 (0.005)	0.011 (0.002)	0.995 (0.001)	0.000 (0.005)	0.011 (0.002)
θ_{100}	0.978 (0.002)	0.001 (0.010)	0.021 (0.003)	0.976 (0.005)	0.001 (0.010)	0.021 (0.003)
θ_{300}	0.936 (0.007)	-0.004 (0.013)	0.030 (0.004)	0.927 (0.024)	-0.004 (0.014)	0.032 (0.004)
θ_{500}	0.917 (0.010)	0.002 (0.012)	0.032 (0.003)	0.905 (0.031)	0.002 (0.012)	0.035 (0.005)
$\theta_{1\,000}$	0.891 (0.010)	0.004 (0.015)	0.036 (0.004)	0.879 (0.046)	0.004 (0.015)	0.038 (0.007)
$\theta_{1\,500}$	0.862 (0.012)	0.000 (0.010)	0.038 (0.003)	0.857 (0.040)	-0.001 (0.010)	0.039 (0.004)

Table 4. Average values of statistical parameters and their standard deviations (in parentheses) for the development and validation of model 3

θ	Development			Validation		
	R^2	MR	RMSE	R^2	MR	RMSE
θ_s	0.790 (0.022)	0.000 (0.003)	0.043 (0.002)	0.779 (0.076)	0.002 (0.006)	0.044 (0.008)
θ_{inf}	0.859 (0.013)	0.003 (0.014)	0.036 (0.004)	0.845 (0.052)	0.007 (0.007)	0.036 (0.005)
θ_{10}	0.964 (0.004)	0.000 (0.001)	0.027 (0.001)	0.969 (0.015)	0.001 (0.005)	0.025 (0.005)
θ_{50}	0.998 (0.000)	0.001 (0.008)	0.009 (0.005)	0.998 (0.000)	0.001 (0.008)	0.009 (0.005)
θ_{100}	0.986 (0.006)	0.007 (0.007)	0.018 (0.004)	0.984 (0.008)	0.007 (0.006)	0.019 (0.004)
θ_{300}	0.977 (0.001)	0.009 (0.002)	0.019 (0.002)	0.977 (0.005)	0.009 (0.003)	0.020 (0.002)
θ_{500}	0.978 (0.001)	0.008 (0.002)	0.018 (0.002)	0.978 (0.005)	0.009 (0.003)	0.019 (0.002)
$\theta_{1\,000}$	0.990 (0.001)	0.008 (0.006)	0.015 (0.002)	0.989 (0.003)	0.008 (0.006)	0.016 (0.003)

2 and 3 one and two measured points of SWRC were applied to develop PTFs, the average R^2 values did not increase considerably for estimating water content at saturation and inflection point with regard to model 1. This may be due to the fact that SWRC behaviour between saturation and inflection points depends more on the soil structure and macropores, whereas, beyond the inflection point it mostly depends on the soil textural properties and micropores, so that adding one or two measured points in the dry section of SWRC does not improve the estimation of water content near the saturation point notably.

RESULTS AND DISCUSSION

The developed point PTFs of models 1, 2 and 3 for split 6 are presented in Table 5, and their performances were compared with models H3, H4, and H5 of the Rosetta software using the independent GRIZZLY data set.

The statistical parameters of point PTFs and the Rosetta model for the GRIZZLY data sets are presented in Figs 2 and 3. The lower values of RMSE for models 1, 2 and 3, as compared to those representing models H3, H4 and H5, showed that the developed point PTFs estimated water content better than the Rosetta model. The RMSE values for models 1, 2 and 3 were 0.059, 0.044 and 0.028 (cm^3 cm^{-3}), respectively. Whereas, for the models H3, H4 and H5 of Rosetta, the RMSE values were 0.084, 0.056 and 0.043 (cm^3 cm^{-3}), respectively. These results indicated to some extent that all developed point PTFs estimated water content better than the Rosetta model using an independent database. Even though Rosetta was trained using a larger data set of the UNSODA database, it did not perform as well as the developed point PTFs. In addition, the positive MR values indicated that the point PTFs extracted in this study overestimated the water content, while the Rosetta model tended to underestimate the water content, as we have showed in Fig. 3, with negative MR values, which is in agreement with previous results obtained by Schaap *et al.* (2001) and Minasny and McBratney (2002).

CONCLUSIONS

1. It was found that water content at different matric potentials is linearly correlated with each other. Therefore, as confirmed by the other researches, multiple linear regression could be an appropriate approach to develop point PTFs, especially when one or more measured points of SWRC are used.

2. The calculated RMSE values showed that all three models of point PTFs developed in this study estimated water content better than the Rosetta model for the independent GRIZZLY database.

3. It was also developed point PTFs to estimate water content at the inflection point which is considered as the index of soil structure and showed that its value is strongly correlated with saturated water content.

T a b l e 5. Selected multiple linear regressions for models 1, 2 and 3 obtained from split 6 using development data sets

Model	R^2
Model 1	
$\theta_s = 0.876 - 0.326BD + 0.002C$	0.783
$\theta_{inf} = 0.601 - 0.40d_g - 0.227BD + 0.003C$	0.847
$\theta_{10} = 0.565 - 0.202d_g - 0.132BD + 0.002C - 0.001S$	0.851
$\theta_{33} = 0.401 - 0.165d_g - 0.079BD + 0.003C - 0.001S$	0.865
$\theta_{50} = 0.352 - 0.150d_g - 0.069BD + 0.003C - 0.001S$	0.864
$\theta_{100} = 0.283 - 0.125d_g - 0.061BD + 0.004C - 0.001S$	0.862
$\theta_{300} = 0.207 - 0.110d_g - 0.058BD + 0.005C$	0.852
$\theta_{500} = 0.188 - 0.089d_g - 0.056BD + 0.005C$	0.845
$\theta_{1\,000} = 0.172 - 0.072d_g - 0.054BD + 0.005C$	0.825
$\theta_{1\,500} = 0.170 - 0.072d_g - 0.052BD + 0.004C$	0.788
Model 2	
$\theta_s = 0.791 + 0.233\theta_{33} - 0.305BD + 0.054d_g + 0.001C$	0.799
$\theta_{inf} = 0.525 + 0.279\theta_{33} - 0.205BD + 0.001C$	0.871
$\theta_{10} = 0.185 + 0.945\theta_{33} - 0.054BD - 0.001C - 0.072d_g - 0.001\sigma_g$	0.960
$\theta_{50} = -0.010 + 0.944\theta_{33} + 0.005BD$	0.997
$\theta_{100} = -0.001 + 0.825\theta_{33} + 0.001C$	0.983
$\theta_{300} = 0.003 + 0.660\theta_{33} + 0.002C - 0.001Si$	0.951
$\theta_{500} = 0.005 + 0.602\theta_{33} + 0.002C - 0.001Si$	0.934
$\theta_{1\,000} = -0.070 + 0.583\theta_{33} + 0.003C + 0.001S + 0.033dg$	0.910
$\theta_{1\,500} = -0.070 + 0.598\theta_{33} + 0.003C + 0.041dg$	0.880
Model 3	
$\theta_s = 0.784 + 0.339\theta_{33} - 0.306BD + 0.067d_g + 0.001C - 0.191\theta_{1500}$	0.804
$\theta_{inf} = 0.525 + 0.279\theta_{33} - 0.205BD + 0.001C$	0.871
$\theta_{10} = 0.161 + 1.139\theta_{33} - 0.336\theta_{1500} - 0.058BD - 0.035d_g$	0.964
$\theta_{50} = 0.006 + 0.880\theta_{33} + 0.116\theta_{1500} - 0.006BD$	0.998
$\theta_{100} = -0.003 + 0.665\theta_{33} + 0.284\theta_{1500} + 0.001C$	0.990
$\theta_{300} = -0.001 + 0.361\theta_{33} + 0.532\theta_{1500} + 0.001C$	0.979
$\theta_{500} = 0.241 + 0.642\theta_{33} + 0.001C$	0.980
$\theta_{1\,000} = 0.001 + 0.090\theta_{33} + 0.826\theta_{1500} + 0.001C$	0.991

Note: C – clay content (%), S – sand content (%), Si – silt content (%), BD – bulk density (g cm^{-3}), and d_g – geometric mean particle-size diameter (mm), σ_g – geometric standard deviation (mm), θ_{33} – water content at -33 kPa (cm^3 cm^{-3}), and $\theta_{1\,500}$ – water content at -1 500 kPa (cm^3 cm^{-3}).

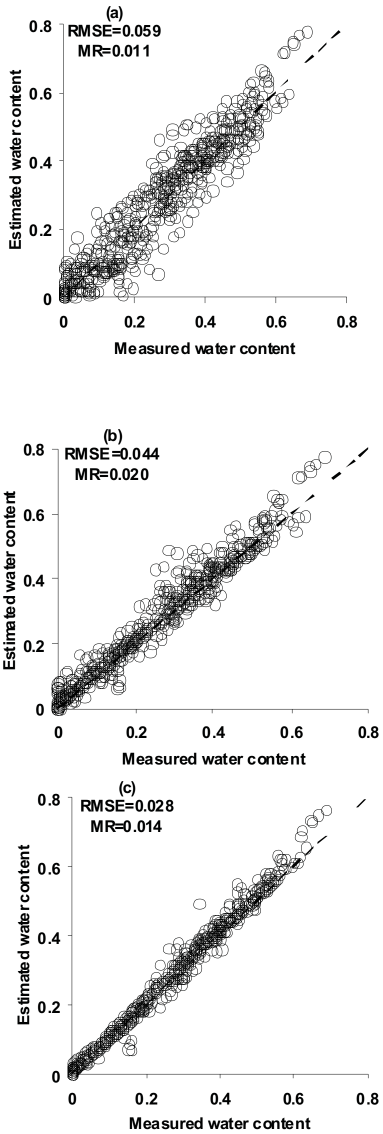

Fig. 2. Estimated water content (cm^3 cm^{-3}) using point PTFs: a – model 1, b – model 2, c – model 3 versus measured one (cm^3 cm^{-3}) for 59 samples of the GRIZZLY data set.

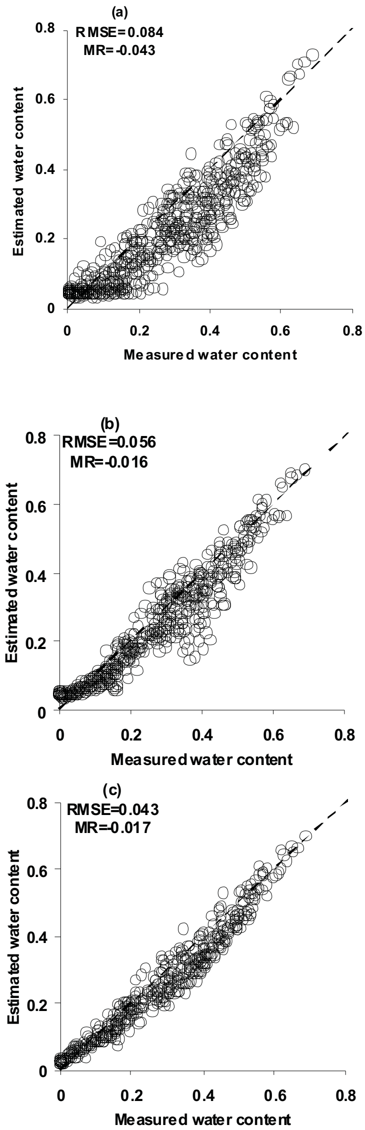

Fig. 3. Estimated water content (cm^3 cm^{-3}) using Rosetta: a – model H3, b – model H4, c – model H5 versus measured one (cm^3 cm^{-3}) for 59 samples of the GRIZZLY data set.

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