Estimation of the Soil Water Retention Curve (SWRC) Using Pedotransfer Functions (PTFs)

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Abstract: Soil hydraulic characteristics, especially the soil water retention curve and hydraulic conductivity, are essential for many agricultural, environmental, and engineering applications. Their measurement is time-consuming and thus costly. Hence, many researchers focused on methods enabling their indirect estimation. In this paper, Wösten's continuous pedotransfer functions were applied to the data from a selected locality in the Czech Republic, Tišice. The available data set related to this locality consists of 140 measured soil water retention curves, and the information about the soil texture, bulk density ρ_d, and organic matter content determined at the same time. Own continuous pedotransfer functions were derived, following the methodology used in continuous pedotransfer functions. Two types of fitting, 4-parameters and 3-parameters, were tested. In 4-parameter fitting, all parameters of the van Genuchten's equation, θ_s, θ_r, α, n, were optimized; in 3-parameter fitting, only three parameters, θ_r, α, n, were optimised while the measured value of θ_s was set as constant. Based on the results, it can be concluded that the general equations of Wösten's pedotransfer functions are not very suitable to estimate the soil water retention curves for the locality Tišice in the Czech Republic. However, the parameters of the same Wösten's equations, which were calculated only from the data for each particular locality, performed much better. The estimates can be improved if the value for the saturated soil water content θ_s is known, applied and not optimised (the case of 3-parameter fitting). It can be advantageous to estimate SWRC for a locality with no data available, using PTFs and the available basic soil properties. In addition, to measure some retention curves and/or some their parameters, like θ_s, can improve the accuracy of the SWRC estimation.

Keywords: continuous pedotransfer function; soil water retention curve; fitting; parametric method; neural network

Soil hydraulic characteristics, like the soil water retention curve and hydraulic conductivity, are indispensable input data for the simulation in agriculture, landscape management, and water-resources engineering and all possible environmental incidences of assorted fields. However, the direct measurement is troublesome, time-consuming and expensive. Alternative approaches called pedotransfer functions (PTFs) for the predictions of the soil hydraulic parameters have been continuously developed by many researchers in the world. This work is focused on the estimation of the soil water retention, represented by the soil water retention curve (SWRC) or pF curve, respectively. The relatively large and in the Czech Republic unique collection of precisely measured soil water retention curves from the locality Tišice in Central Bohemia was used as the source of field data for the

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PTFs . The set consists of 140 measured retention curves (Matula 1988; Kuráž 1989).

A comparison of different approaches to the development of pedotransfer functions for SWRC was presented by Minasny *et al.* (1999). They divided PTFs into 3 types:

Point estimation – certain points can be estimated of the soil water retention curve (for example for –10, –33 = field capacity, –1500 kPa = permanent wilting point).

Parametric estimation – the relationship of the volumetric soil water content θ and pressure head *h* is described by closed-form equation (Brooks & Corey 1964; van Genuchten 1980).

Physico-empirical models – the retention curve is derived from physical attributes.

Three different methods were used to fit the soil water retention curve PTFs (Minasny *et al.* 1999):
Multiple Linear Regression (MLR)
Extended Nonlinear Regression (ENR)
Artificial Neural Network (ANN)

Cornelis *et al.* (2001) also divided the PTFs into three groups:

Group 1 – application of MLR (Gupta & Larson 1979; Rawls & Brakensiek 1982; Saxton *et al.* 1986; Šútor & Štekauerová 2000) and ANN (Pachepsky *et al.* 1996).

Group 2 – application of close-form analytical equation (for example Brooks & Corey 1964 or van Genuchten 1980) was used by Rawls and Brakensiek (1985); together with MLR (Vereecken *et al.* 1989; Scheinhost *et al.* 1997; Wösten *et al.* 1998; Minasny *et al.* 1999; Wösten *et al.* 1999) or ANN (Pachepsky *et al.* 1996; Minasny *et al.* 1999; Schaap *et al.* 1998a, b, 1999).

Group 3 – physico-conceptual approach of the water retention phenomenon (Arya & Paris 1981; Haverkamp & Parlange 1986) and the use of fractal mathematics and scaled similarities (Tyler & Wheatcraft 1989; Comegna *et al.* 1998).

A large and detailed overview of the status of PTFs was done by Wösten *et al.* (2001). Nemes *et al.* (2003) published an interesting functional evaluation of PTFs derived from different scales of data sets. They worked in three scales: national (Hungarian data), continental (HYPRES data), and intercontinental (US and European data) scales.

Wösten *et al.* (1998) derived either Class PTFs, based on 11 texture/pedological classes, or Continuous PTFs to get θ_r, θ_s, α, *n* soil hydrophysical parameters in both cases. The HYPRES database of hydraulic properties of European soils was created. The works of Wösten *et al.* (1998) and Matula and Špongrová (2007) were widely used in this study.

Table 1. The borrow pits and undisturbed soil samples (Matula 1988)

	Borrow pit	Depth (cm)	Number of samples
Permanent meadow	K1	20	20
		50	20
		70	4
		120	4
Permanent meadow	K2	20	20
		50	20
		100	3
		130	3
Permanent grass (close to meteorological station)	K3	20	20
		40	20
		70	3
		90	3
Number of samples in total			140

MATERIALS AND METHODS

Our objective in this study was to apply the model of Continuous PTFs (Wösten *et al.* 1998) to the selected locality with sufficient sets of measured water retention data, then to develop the local model coefficients and to evaluate the accuracy of the prediction. The data sets were collected at the locality Tišice, north of Prague, Central Bohemia, the Czech Republic. The soil in this locality is Chernozem (CH in WRB: IUSS/FAO/ISRIC Soil Classification).

Three borrow pits (K1, K2, K3) were dug out and 140 undisturbed soil samples (Kopecký's ring 100cm^3) were taken. Table 1 shows the sampling.

The soil water retention curves measured were carefully evaluated and other important physical soil parameters (particle size distribution analysis results in Table 2, organic matter contents, soil particle densities in Table 3, and dry bulk densities in Table 4) were added. The particle-size analysis was carried out using the standard procedure, i.e. sieving and sedimentation analysis based on Stokes' Law (hydrometer method). A water pycnometer was employed to find the soil particle density ρ_z. The organic matter content was measured as the C_{ox} in %. These values were converted into the organic matter in percentage using the conversion equation OM = 1.724 C_{ox} (%).

Those soil samples, taken from the depth below 50 cm, were not used in the PTFs calculations of the final experimental data set of 121 data units.

The inputs for the calculations of the PTFs were:

Contents of clay and silt after FAO system (%)
Dry bulk density ρ_d (g/cm^3)
Organic matter OM fraction (%)
Qualitative parameter 1 or 0 for topsoil or subsoil, respectively

The parameterisation procedure was used and the soil water retention curves were fitted by the well known van Genuchten's equation:

$$\theta_e(h) = \theta_r \frac{(\theta_s - \theta_r)}{\left(1 + (\alpha\, h)^n\right)^{1-1/n}} \qquad h < 0 \qquad (1)$$

where:
$\theta_e(h)$ – effective soil water content as a function of pressure head
$\theta_e(h) = (\theta - \theta_s)/(\theta_s - \theta_r)$ (2)
θ_s – saturated soil water content – parameter (m^3/m^3)
θ_r – residual soil water content – parameter (m^3/m^3)
θ – actual soil water content (m^3/m^3)
α, n – empirical parameters

The computer code RETC (van Genuchten *et al.* 1991) was employed in order to optimise θ_r, θ_s, α, n parameters applying two different systems of fitting; 4-parameter fitting (represents fitting

Table 2. Soil texture classes in different classifications

Diameter of particles *d* (mm)	Borrow pit and the depth of sampling/% of content					
	K1 – 15 cm	K1 – 40 cm	K2 – 15 cm	K2 – 45 cm	K3 – 25 cm	K3 – 40 cm
< 0.002 mm (physical clay)	14.63	13.07	14.44	16.25	13.47	17.93
< 0.01 mm (I. category)	23.09	24.09	24.11	28.72	23.38	32.96
0.01–0.05 mm (II. category)	17.97	17.51	18.32	18.21	14.17	10.97
0.05–0.1 mm (III. category)	19.34	19.20	19.58	17.27	15.75	17.98
0.1–2 mm (IV. category)	39.60	39.20	38.00	35.80	46.70	38.10
FAO (1990)/USDA (1951)						
Sand 0.05–2 mm	58.94	58.40	57.58	53.07	62.45	56.08
Silt 0.002–0.05 mm	26.43	28.53	27.99	30.68	24.08	25.99
Clay < 0.002 mm	14.63	13.07	14.44	16.25	13.47	17.93
Soil Geographical Data Base classes (the EU)	medium M	medium M	medium M	medium M	medium M	medium M
FAO/USDA textural classes	sandy loam	sandy loam	sandy loam	sandy loam	sandy loam	sandy loam

Table 3. Values of C_{ox}, organic matter content OM, and soil particle density ρ_z

Borrow pit	Depth (cm)	C_{ox} (%)	Organic matter OM (%)	Particle density ρ_z (g/cm^3)
K1	15–20	2.1	3.62	2.64
	35–40	1.3	2.24	2.60
K2	15–20	2.1	3.62	2.63
	50	1.6	2.76	2.65
K3	15–20	1.9	3.28	2.63
	40	0.7	1.21	2.65

Table 4. Basic statistics for dry bulk densities ρ_d determined in each individual sample from borrow pits K1, K2, K3

	Number of samples	Mean (g/cm^3)	Median (g/cm^3)	Mode (g/cm^3)	Frequency of mode	Minimum (g/cm^3)	Maximum (g/cm^3)
Borrow pit K1	41	1.48	1.49	1.50	4	1.32	1.65
Borrow pit K2	40	1.57	1.58	1.66	4	1.41	1.74
Borrow pit K3	40	1.45	1.46	1.38	5	1.33	1.59

Table 5. Continuous pedotransfer functions (according to Wösten *et al.* 1998)

Model parameters of van Genuchten's equation
θ_s = 0.7919 + 0.001691 C – 0.29619 D – 0.000001491 S^2 + 0.0000821 OM^2 + 0.02427 C^{-1} + 0.01113 S^{-1} + 0.01472 ln(S) – 0.0000733 OM C – 0.000619 D C – 0.001183 D OM – 0.0001664 topsoil S
α^* = –14.96 + 0.03135 C + 0.0351 S + 0.646 OM + 15.29 D – 0.192 topsoil – 4.671 D^2 – 0.000781 C^2 – 0.00687 OM^2 + 0.0449 OM^{-1} + 0.0663 ln(S) + 0.1482 ln(OM) – 0.04546 D S – 0.4852 D OM + 0.00673 topsoil C
n^* = –25.23 – 0.02195 C + 0.0074 S – 0.1940 OM + 45.5 D – 7.24 D^2 + 0.0003658 C^2 + 0.002885 OM – 12.81 D^{-1} – 0.1524 S^{-1} – 0.01958 OM^{-1} – 0.2876 ln(S) – 0.0709 ln(OM) – 44.6 ln(D) – 0.02264 D C + 0.0896 D OM + 0.00718 topsoil C

θ_s –model parameter (m^3/m^3); α^*, n^* – transformed model parameters (α^* = ln (α); n^* = ln (n – 1)); C – content of clay (%); S – content of silt (%); OM – content of organic matter (%); D – dry bulk density ρ_d (g/cm^3); Topsoil/subsoil – qualitative variables (values 1 or 0 respectively); ln – natural logarithm

of all four parameters), and 3-parameter fitting (represents fitting of three parameters, leaving out θ_s, which is given as a constant value, taken from the measurement). In the RETC code, the Artificial Neural Network (ANN) is implemented as the code ROSETTA Lite v. 1.0. This code was used to calculate the initial estimates for the respective parameters. These parameters were applied into the RETC code for the calculation of the SWRC model parameters. Then, the results of RETC were used as the input data in the software STATISTICA CZ to derive the coefficients of the PTFs. Continuous PTFs of Wösten *et al.* (1998) presented in Table 5 were tested as first. In this case, a different 3-parameter fitting was applied, the parameters θ_s, α, n were optimised, while the parameter θ_r was fixed at the value of 0.01 following the Wösten's methodology.

The statistical software package STATISTICA CZ v. 7.0 was the tool for the calculations of the coefficients of the Continuous PTFs in the case of the own parameter calculations. In the case of the own parameter calculations, two methods for the coefficient calculation were selected:

Independent calculation for each borrow pit (K1, K2, K3) for 3- and 4-parameter fittings;

Calculation of the parameters using the data from all borrow pits together also for 3- and 4-parameter fittings.

In all cases, the estimated points (being equivalent to the data measured) of the retention curves expressed as pF were calculated by the application of the own and Wösten's PTFs.

RESULTS AND DISCUSSION

This study elaborates 121 data units collected from three borrow pits (K1, K2, K3) in Tišice (Matula 1988; Kuráž 1989). The structure of PTFs calculations is schematically presented in Figure 1. The result of the calculations gives 8 sets, 4 equations each, that represent 32 own Continuous PTFs. The equations were developed for the data of all pits together and for each borrow pit locally (K1, K2, K3). The cor-

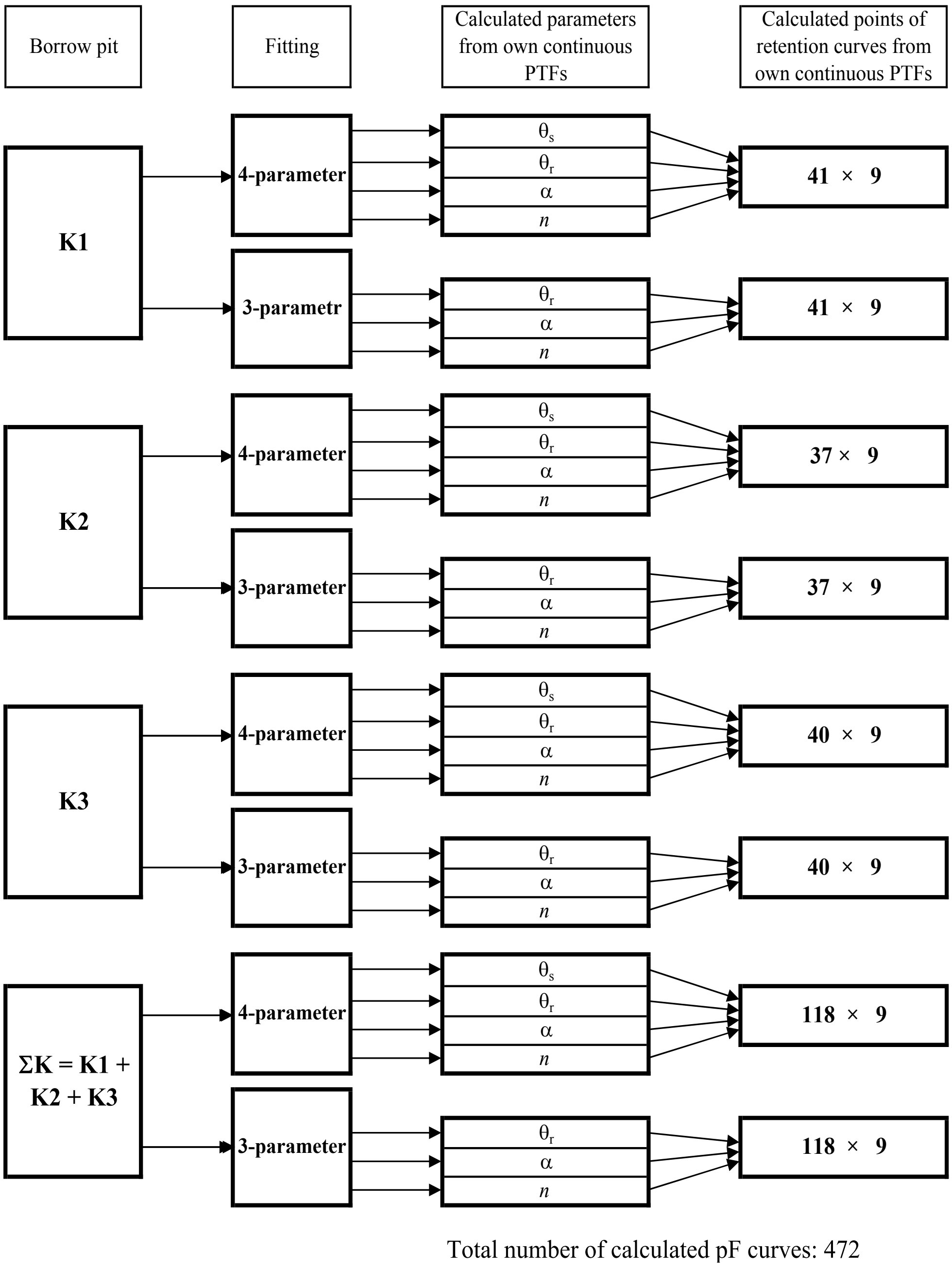


Figure 1. Scheme of own PTFs calculations

relation coefficients (R), mean residuals (MR), and root mean squared residuals ($RMSR$) were calculated. Based on MR, the systematic errors between the measured and estimated points of the PF curves were evaluated. The accuracy of the estimates was characterised by $RMSR$. The correlation coefficient is not powerful enough to represent the goodness of the fit, and thus all the curves measured and estimated were graphically compared. An example of the results obtained with K2 borrow pit is given in Figures 2–4. The accuracy of estimates represented by R, MR, and $RMSR$ is shown in Table 6.

CONCLUSIONS

The data set from the locality Tišice gave us the opportunity to evaluate two types of fitting (3- and

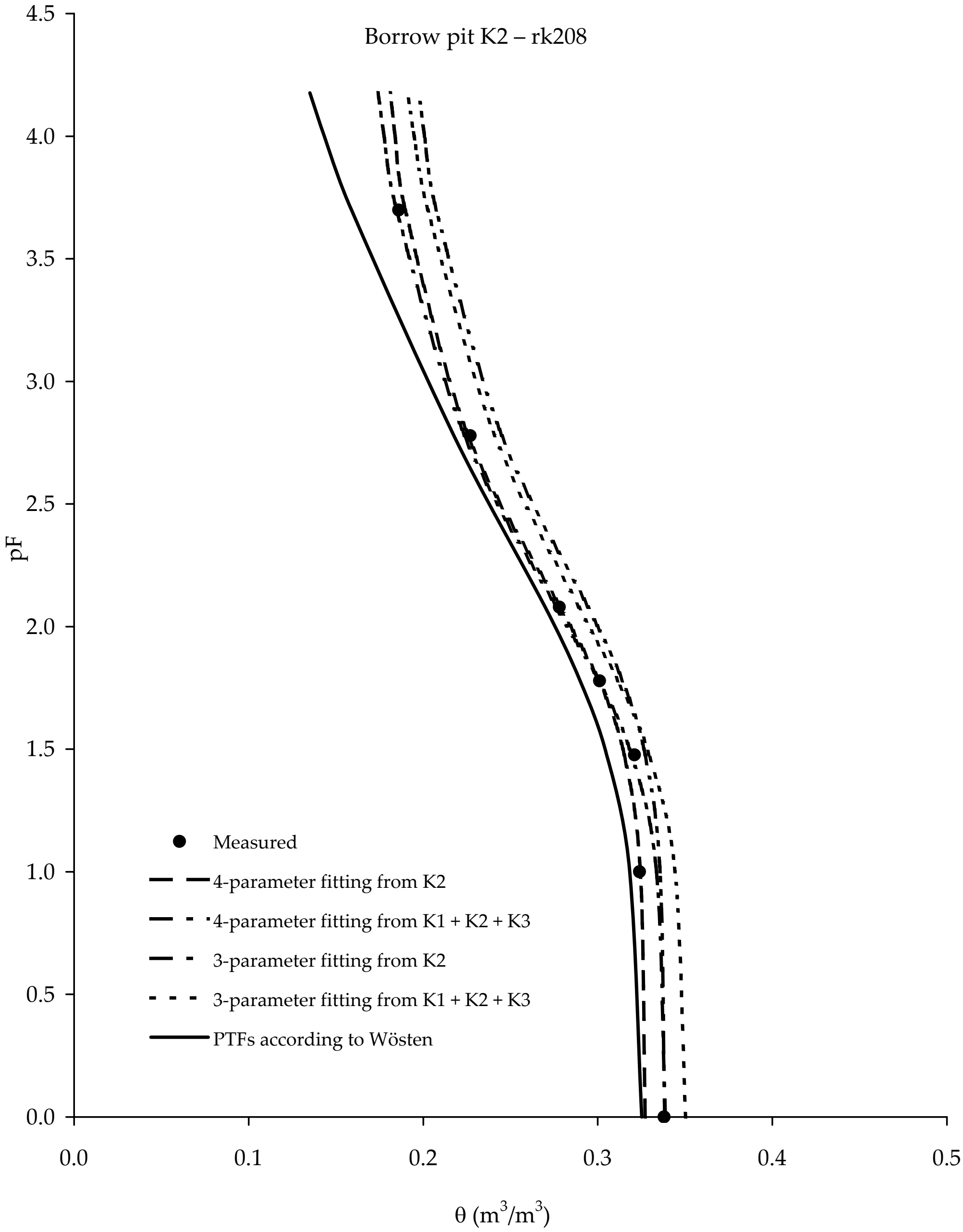
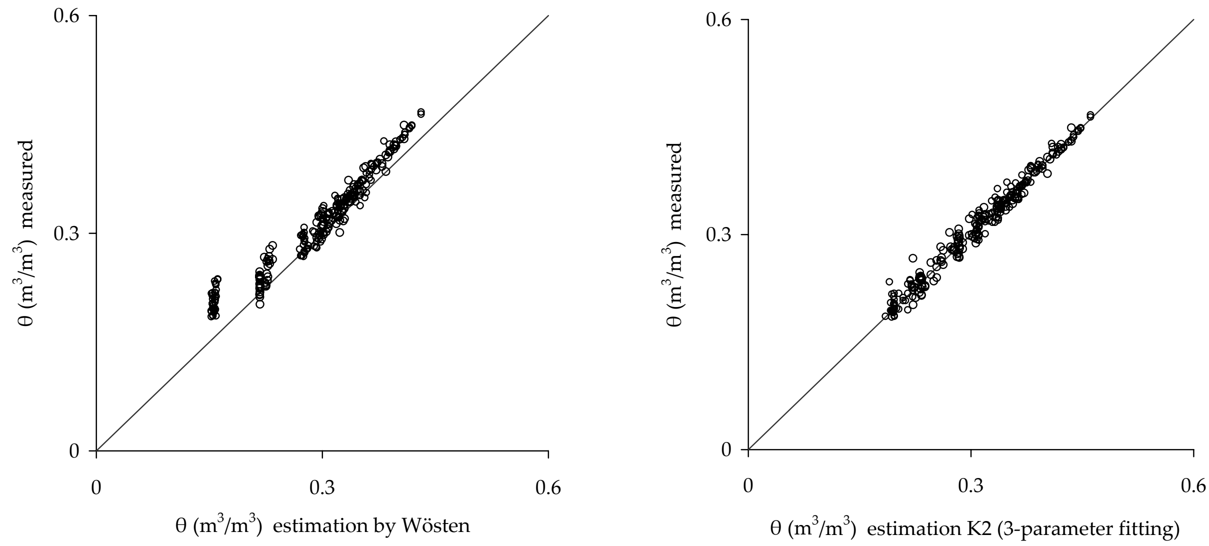


Figure 2. Example of typical comparison of measured and estimated pF curves by using different types of own fittings, Wösten's fitting and measured SWRC data (rk208 = No. of sample)



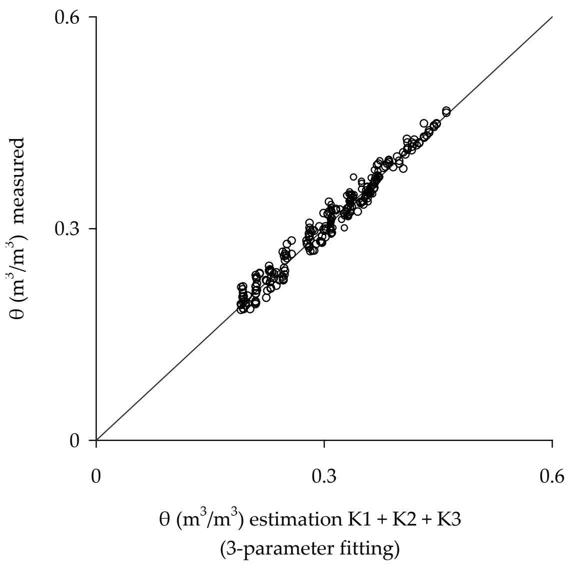


Figure 3. Example of the results of comparison of 3-parameter fittings in the selected borrow pit K2

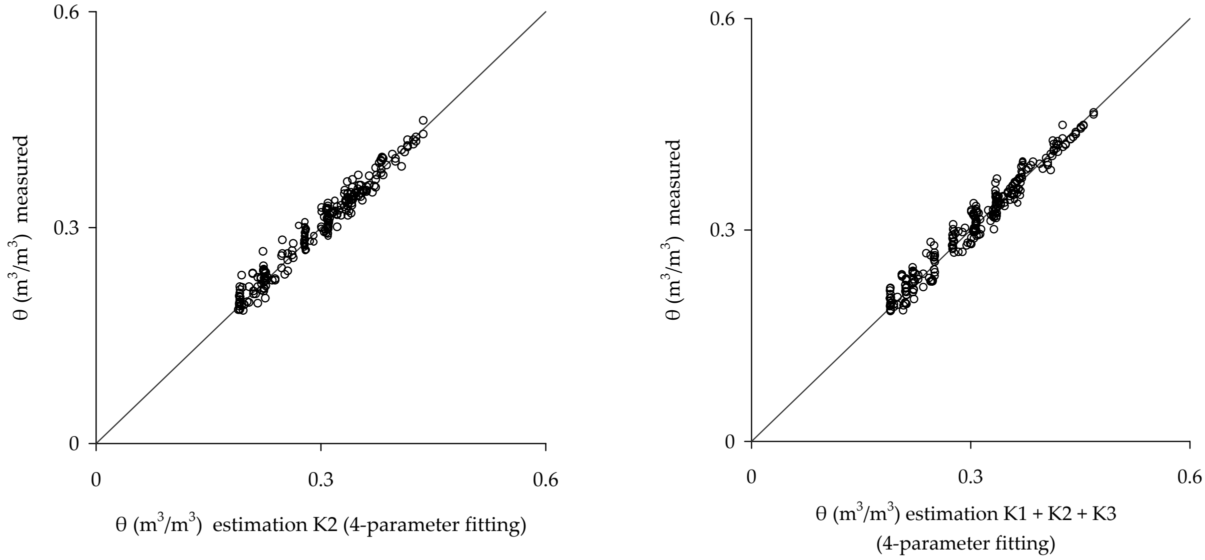


Figure 4. Example of results of comparison of 4-parameter fittings for selected borrow pit K2

Table 6. Evaluation of the goodness of fit, *R*, *MR*, *RMSR* values

Source data to derive parameters of PTFs	Type of comparison	*R*		*MR*		*RMSR*	
		3-parametr fitting*	4-parametr fitting	3-parametr fitting*	4-parametr fitting	3-parametr fitting*	4-parametr fitting
K1	measured vs. Wösten	0.9663	na	0.0007	na	0.0265	na
	measured vs. own fitted K1	0.9820	0.9794	0.0029	0.0030	0.0540	0.0544
	measured vs. own fitted K1 + K2 + K3	0.9841	0.9818	0.0002	0.0002	0.0139	0.0145
K2	measured vs. Wösten	0.9727	na	0.0012	na	0.0343	na
	measured vs. own fitted K2	0.9885	0.9866	0.0008	0.0009	0.0287	0.0297
	measured vs. own fitted K1 + K2 + K3	0.9857	0.9822	0.0008	0.0009	0.0284	0.0293
K3	measured vs. Wösten	0.9598	na	0.0012	na	0.0353	na
	measured vs. own fitted K3	0.9745	0.9748	0.0006	0.0006	0.0245	0.0250
	measured vs. own fitted K1 + K2 + K3	0.9774	0.9775	0.0006	0.0006	0.0245	0.0242

*There are two types of 3-parameter fitting: in Wösten's comparison θ_s, α, *n* were fitted, θ_r was equal 0.01, while for the own PTFs parameters θr, α, n were fitted and θs was taken from the measurement

na – not applicable, only three parameters are fitted in Wösten's PTFs

4-parameter fittings). A relatively large data set (121 carefully measured retention curves) and precisely and well measured basic soil physical properties were available. All data were collected during the same time period, using identical methodology performed by a single team of researchers. This offered us a reliable data set, which is unique with respect to both a sufficient volume and homogeneity. The soil type, Chernozem, is well known for its good soil physical behaviour. Based on the results presented above, we can formulate the following conclusions:

– Continuous PTFs of Wösten *et al.* (1998) provide quite acceptable estimates for the selected locality Tišice, in spite of the use of Wösten's parameters derived for a different set of the soil data. In addition, a fixed value for the residual water content (θ_r), 0.01, was used if no measured data were available.

– The Own Continuous PTFs gave good estimates of the retention curves. This is documented by very high correlation coefficients, and low *RMSR* values (see Table 6).

– The comparison of 3- and 4-parameter fittings showed clearly in a majority of cases better results in 3-parameter fitting if the measured θ_s was introduced into the calculation as the fixed parameter. This θ_s is quite often available from the basic physical properties determination in common soil survey.

– The authors realise that the above stated conclusions are based only on one soil type with a very good soil physical behaviour.

The application of the PTFs on the localities with no retention curve data measured is possible, but the estimates can be expressively improved if some retention curves are additionally measured.

The estimates may be sufficiently accurate for many purposes, such as hydrological models, landscape and watershed management, etc.

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