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Estimation of soil water retention curve using some agrophysical characteristics and Voronin's empirical dependence**

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A b s t r a c t. An original method to estimate the parameters of the soil water retention curve using (i) the standardized agrophysical characteristics (wilting point, hydroscopic property, particle density and bulk density) as an input dataset and (ii) an empirical dependence by Voronin is proposed. This method allows the creation of an alternative pedotransfer function.

K e y w o r d s: water retention curve, pedotransfer functions, method verification, approach comparison

INTRODUCTION

In connection with the wide use of dynamic models for agro-meteorological calculations and yield forecasting on the one hand, and a rather high cost of direct measurements of dependence between the volumetric soil water content (θ, cm^3 cm^{-3}) and the soil water (or matrix) potential (ψ, hPa) on the other, there is a real challenge to arrive at a reliable way to estimate parameters of the soil water retention curve (WRC). Efficiency of the WRC modelling in many respects is defined by the availability and informativeness of the initial data. Direct WRC measurements provide obtaining the most informative data, but often the results of such experimental investigations are not available. Therefore, methods of WRC modelling on the basis of some accessible soil characteristics are being developed quite intensively. Alongside with it, in many investigations it has been substantiated that effective WRC modelling is possible only by using a certain dataset of standardized soil characteristics (Ahuja *et al*., 1985; Rawls *et al*., 1991; Saxton *et al*., 1986; Williams *et al*., 1992). For example, WRC can be calculated using created databases on so-called pedotransfer functions (PTF) (Bouma, 1989; Cornelis *et al*., 2001). This would require soil organic matter content and bulk density information, and data on texture according to USDA soil particle size specification.

The data on soil organic matter content and bulk density are usually available. Nevertheless, often data on soil particle contents (soil particle size distribution) are not accessible enough. When data on both direct WRC measurements and texture are lacking, the most suitable method for WRC estimation might be an approach based on the use of other sufficiently available agrophysical characteristics.

The original method offered here allows estimation of WRC parameters from the data on such features of soil as the wilting point (θ_{WP}, cm^3 cm^{-3}), hydroscopic property (θ_{HP}, cm^3 cm^{-3}), particle density (ρ_p, g cm^3) and bulk density (ρ_b, g cm^3), employing an empirical dependence developed by Voronin (1986). In the case where no measured WRC points are accessible, the θ_{WP} value is considered as one of the agrophysical characteristics which can be defined by standardized experimental means.

Below there are submitted:
– the essence of the proposed method;
– the results of its verification on the basis of direct WRC measurements
– comparison with some advanced PTF approaches.

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METHOD

The Richards (1931) equation (RE) contains a factor representing the derivative of θ on ψ, being a function of water potential and referring to the differential (specific) moisture capacity of soil ($DMC = d\theta / d\psi$, cm^3 cm^{-3} hPa^{-1}). This factor substantially defines the results of soil water dynamics simulation within high and low ψ values *ie* for significant wet and dry soil conditions. Only a limited class of relations is suitable for the WRC description, while the use of some regression models can lead to physically absurd effect (Globus, 1987) resulting, as a consequence, in a significantly decreased RE solution accuracy. There are two basic approaches in the development of WRC models. The first one is based on revealing the physical essence of interaction between the liquid and solid phases of soil. Here some progress is possible by employing representations about the capillarity phenomenon and a log-normal size distribution of soil particles and pores (Chan and Govindaraju, 2004; D'Hollander, 1979; Haverkamp and Parlange, 1986; Kosugi, 1996, 1999;). For the second approach, it is common to use the following multiple linear regression dependences (Cornelis *et al*., 2001; Tomasella *et al*., 2003):

– between volumetric water contents and data on soil features such as bulk density, texture, and organic matter content for preset water potential values (Gupta and Larson, 1979; Mecke *et al*., 2002);
– between the same soil features and parameters of relations fitted to experimental WRC data (Tomasella *et al*., 2002; Porębska *et al*., 2006).

The listed groups of WRC models relate to the pedotransfer functions. At present, the second basic approach is more promising. Its application is based on the use of the analytical equation (with 5 parameters) proposed by van Genuchten (1980):

$$\theta = \theta_R + \frac{\theta_S - \theta_R}{\left(1 + (\alpha|\psi|^{\eta})\right)^m}, \qquad (1)$$

where: θ_S – saturated soil water content (cm^3 cm^{-3}), θ_R – residual soil water content (cm^3 cm^{-3}), $m = 1 - 1/\eta$, α, and η, are empirical parameters governing the position and shape of WRC.

Equation (1) approximates the data on direct WRC measurements with sufficient precision. Along with it, there are also other WRC models which approximate the experimental data adequately. For example, the relation developed by Haverkamp *et al*. (1977) is such a WRC model. It is described as follows:

$$\theta = \theta_R + \frac{\tilde{b}\left(\theta_S - \theta_R\right)}{\tilde{b} + |\psi|^{\alpha}}, \qquad (2)$$

where: θ_S, θ_R, a, and $\tilde{b}$ are empirical parameters.

Equation (2) can be transformed as follows:

$$\theta = \theta_R + \frac{\theta_S - \theta_R}{1 + (b(-\psi))^a}, \qquad (3)$$

where: $b = \tilde{b}^{-1/a}$.

Equation (3) coincides with Eq. (1) in the absence of parameter m (formally, if $m = 1$). When calculating the parameters of Eq. (3), the following relations can be used:

$$\begin{cases} a = \lg\left(\dfrac{\left(\theta_S - \theta_{MC}\right)\left(\theta_{WP} - \theta_R\right)}{\left(\theta_{MC} - \theta_R\right)\left(\theta_S - \theta_{WP}\right)}\right)\lg^{-1}\left(\dfrac{-\psi_{MC}}{-\psi_{WP}}\right) \\ b = \left(\left(\theta_S - \theta_{MC}\right)/\left(\theta_{MC} - \theta_R\right)\right)^{1/a}\left(-\psi_{MC}\right)^{-1} \end{cases}, \qquad (4)$$

where: θ_{MC} – maximum capillary-sorption water capacity of soil (cm^3 cm^{-3}), ψ_{WP} – soil water potential (15 000 hPa) corresponding to θ_{WP} value, ψ_{MC} – soil water potential (hPa) corresponding to θ_{MC} value.

The residual soil water content and the saturated soil water content are estimated by means of the simple relations:

$$\begin{cases} \theta_R = \theta_{HP} \\ \theta_S = 1 - \rho_b / \rho_p \end{cases}. \qquad (5)$$

The soil water potential ψ_{MC} is calculated using the empirical dependence by Voronin (1986) that has been obtained as a result of analysing a representative volume of experimental WRC data from a wide variety of soils in Russia with respect to texture. This dependence is described as follows:

$$-\psi_{MC} = 10^{2.17 + \theta_{MC}/\rho_b}. \qquad (6)$$

For the estimation of the maximum capillary-sorption water capacity a fruitful enough idea is used. The main positions of this idea are:

– θ_{MC} value equals the soil water content that corresponds to point A (Fig. 1) where curve 1 and line 2 (for Eq. (3) and Eq. (6), respectively) are crossed;
– ψ_{MC} value equals the soil water potential at point B (Fig. 1) that corresponds to the maximum $DMC\left(\psi(\theta_i)\right)$ value within the $\theta_{WP} < \theta_i < \theta_S$ dataset (Fig. 1, curve 3):

$$\theta_{MC} = \arg\max\left(DMC\left(\psi(\theta_i)\right)\right), \qquad (7)$$

where:

$$DMC\left(\psi(\theta_i)\right) = \left.\frac{d\theta}{d\psi}\right|_{\psi(\theta_i)} = \frac{a_i b_i^{a_i}\left(-\psi(\theta_i)\right)^{a_i - 1}\left(\theta_S - \theta_R\right)}{\left(1 + \left(bi\left(-\psi(\theta_i)\right)\right)^{a_i}\right)^2}$$

(according to Eq. (3)):

$$a_i = \lg\left(\frac{\left(\theta_S - \theta_i\right)\left(\theta_{WP} - \theta_R\right)}{\left(\theta_i - \theta_R\right)\left(\theta_S - \theta_{WP}\right)}\right)\lg^{-1}\left(\frac{-\psi(\theta_i)}{-\psi_{WP}}\right);$$

$$b_i = \left(\left(\theta_S - \theta_i\right)/\left(\theta_i - \theta_R\right)\right)^{1/a_i}\left(-\psi(\theta_i)\right)^{-1};$$

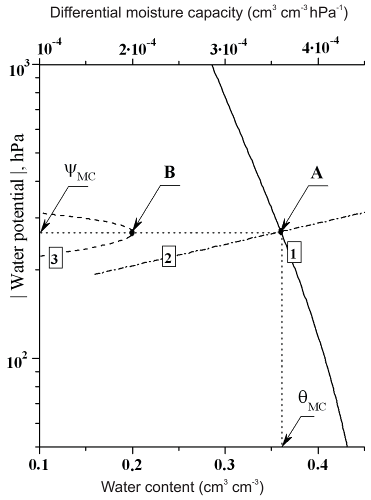

Fig. 1. Estimation of value for soil sample selected in Eichenhof, horizon 4Bt, silty loam (Table 1); 1 – WRC calculated using Equation (3); 2 – Voronin's empirical dependence according to Equation (6); 3 – *DMC*.

$$-\psi\left(\theta_i\right) = 10^{2.17+\theta_i/\rho_b};\ \theta_i = \theta_{WP} + i\left(\theta_S - \theta_{WP}\right) / \left(\widetilde{N} - 1\right);$$

$$i = 1,2,\ldots,\widetilde{N} - 2; \widetilde{N} \leq 100.$$

The set of Eqs (3)-(7) and the proposed approach allow creating an alternative PTF method that makes it possible to estimate WRC parameters from wilting point, hydroscopic property, particle density, and bulk density with the use of the empirical dependence by Voronin. Besides, θ_{MC}, value is an adequate assessment of such an important soil hydrological constant as field capacity (Shein, 2005).

RESULTS

The investigation was carried out using soil samples selected from different arable sites within the Federal State of Brandenburg (Germany), that differ with respect to their texture, bulk density, and organic matter content (Table 1). For these four soil samples Fig. 2 demonstrates the results of WRC modelling with respect to six different PTF approaches and the dataset of some accessible soil characteristics. We compared WRC modelling accuracy of these methods listed in Table 2. The first approach allows estimating the parameters of Eq. (1) with (Fig. 2, dash curve 1) by means of PTF database developed using WRC data on soil samples taken from the different sites within the territory of East Germany (Schindler *et al*., 2004). The second method permits the calculation of the parameters of Eq. (1) with $m \neq 1$ (Fig. 2, dot curve 2) employing PTF developed by Vereecken *et al*. (1989). The third approach uses PTF database developed by Schaap and Leij (1998) for calculating the parameters of Eq. (1) with $m \neq 1$ (Fig. 2, dash-dot curve 3). The fourth method for estimating parameters of Eq. (1) with m=1 is based on PTF developed by Gupta and Larson (1979) (see Fig. 2, dash-dot-dot curve 4). The fifth approach uses PTF developed by Cosby *et al*. (1984) to calculate parameters θ_S, c, and ψ_S (Fig. 2, short-dash curve 5) and it is described by the following equation:

$$\theta = \theta_S \left(|\psi| / \psi_S\right)^{-1/c}. \quad (8)$$

The sixth method (submitted by the authors of this paper) is based on Eqs (3)-(7) and the assumption that $\rho_p = 2.65\,\mathrm{g\ cm^{-3}}$ ($\widetilde{N} = 80$). The results of this method are shown in Fig. 2 (solid curve 6).

T a b l e 1. Soil and site characteristics of soil samples used for model-experiment comparison

Sites	District of Brandenburg (Germany)	FAO soil	Parent material	Annual precipitation (mm)	Land use type	Horizon	Top depth (cm)	Bottom depth (cm)
Seelow	Maerkisch- Oderland	Fluvic Gleysol	Alluvium	470	Arable	1Ap	0	30
						2Bg1	30	50
						3Bg2	50	65
						4BgCr	65	80
Eichenhof	Maerkisch- Oderland	Fluvic Gleysol	Alluvium	440	Arable	4Bt	30	45
Bölkendorf (field 9)	Uckermark	Calcic Luvisol	Diluvium	550	Arable	1Ap	0	30
						2Bt	30	65
						3Bt	65	95
Bölkendorf (field 6)	Uckermark	Eutric Cambisol	Diluvium	550	Arable	2Bw	30	50

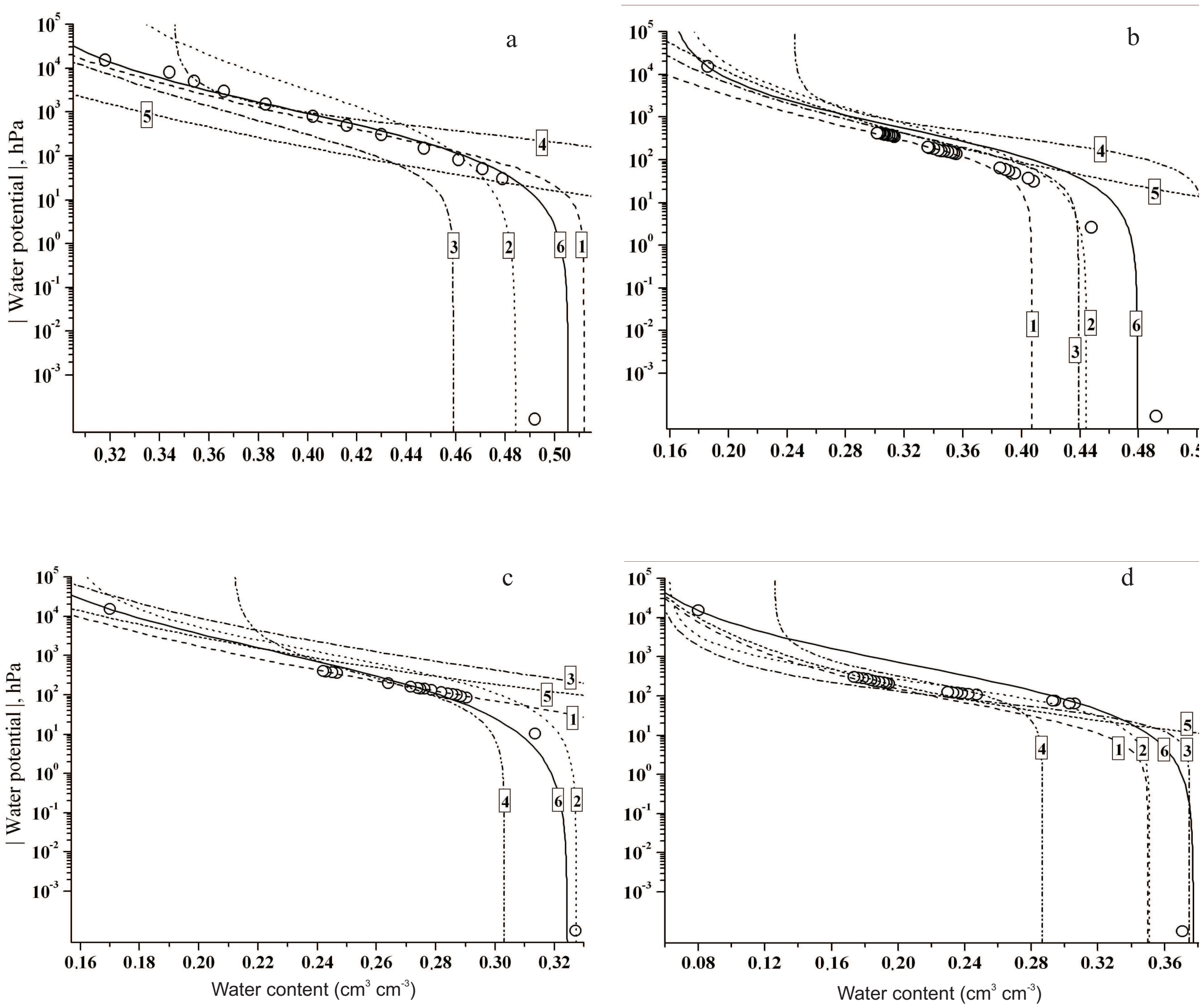

Fig. 2. Comparison of WRC modelling results by different approaches: 1 – Schindler *et al*. (2004); 2 – Vereecken *et al*. (1989); 3 – Schaap and Leij (1998); 4 – Gupta and Larson (1979); 5 – Cosby *et al*. (1984); 6 – Terleev *et al*. (this paper) with measured data on 4 soil texture classes (○): a – Seelow, horizon 1Ap, clay; b – Eichenhof, horizon 4Bt, silty loam; c – Bölkendorf (field 9), horizon 3Bt, loam; d – Bölkendorf (field 6), horizon 2Bw, sand.

DISCUSSION

The soil water retention curves calculated on the basis of the new approach proposed in this paper (see the last method in Table 2) are compared both with data measured directly (Fig. 3) and with curves calculated on the basis of five different WRC parameters estimation methods taken from literature (Table 2). The first of the compared methods is based on PTF database developed with the direct WRC measurements from East German soils, as well as with the information about characteristics of those soils. Obviously, this method has higher accuracy because in this case WRC parameters of the same region were estimated, whereas all the other methods were developed using data on soil characteristics from different areas of the world. The first method is presented to show the extent of accuracy with which WRC parameters can be estimated when all soil characteristics necessary for PTF modelling are available. The comparison shows that all approaches have approximately the same accuracy for all different soil texture classes used. To estimate WRC parameters, all methods except the last one use initial information on contents of sand, silt, clay, and organic matter in soil as well as on the bulk density of soil. The sixth approach proposed by the authors' estimates WRC parameters according to Eq. (3) with the use of other input datasets. The results of our investigations suggest the validity of this method for WRC parameter estimation: *DMC* reaches its maximum and the Voronin's empirical dependence crosses the WRC at the same value for the soil water potential ψ_{MC}. It proves indirectly that the WRC model according to Eq. (3) could be produced using physical basis which is not revealed completely up till today.

T a b l e 2. Results of WRC modelling using the different approaches

Sites	Seelow				Eichenhof	Bölkendorf			
						field 9			field 6
Soil horizons	1Ap	2Bg1	3Bg2	4BgCr	4Bt	1Ap	2Bt	3Bt	2Bw
Physical properties (input data)									
Sand	17	6	4	3	17	44	49	45	67
Silt	38	28	33	37	58	36	32	31	25
Clay	45	66	63	60	25	20	19	24	8
Organic matter	4.86	1.93	2.52	2.87	1.8	2.1	1.6	1.4	0.5
Bulk density	1.31	1.2	1.17	1.09	1.38	1.48	1.78	1.79	1.65
Wilting point	0.318	0.375	0.361	0.414	0.186	0.180	0.144	0.170	0.080
Hydroscopic property	0.277	0.326	0.314	0.360	0.159	0.135	0.108	0.123	0.0343
Schindler *et al*. (2004) Curve 1, Eq. (1), $m \neq 1$									
θ_S	0.512	0.543	0.543	0.543	0.407	0.375	0.375	0.375	0.35
θ_R	0.154	0.249	0.249	0.249	0	0	0	0	0.016
α (hPa^{-1})	0.0163	0.0181	0.0181	0.0181	0.0087	0.068	0.068	0.068	0.0567
n	1.15	1.18	1.18	1.18	1.21	1.13	1.13	1.13	1.27
RMSD_j^*	0.0312	0.0845	0.117	0.140	0.0565	0.0799	0.0249	0.0274	0.112
RMSD^{**}=0.0792									
Vereecken *et al*. (1989) Curve 2, Eq. (1), $m = 1$									
θ_S	0.484	0.536	0.542	0.562	0.445	0.411	0.325	0.327	0.351
θ_R	0.381	0.372	0.365	0.355	0.165	0.144	0.132	0.155	0.062
α (hPa^{-1})	0.00027	0.00047	0.00042	0.00048	0.00103	0.00157	0.00099	0.00083	0.00413
n	0.526	0.426	0.450	0.471	0.683	0.732	0.760	0.698	1.02
RMSD_j^*	0.0736	0.0487	0.0706	0.0601	0.102	0.140	0.0523	0.0407	0.0938
RMSD^{**}=0.0850									
Schaap and Leij (1998) Curve 3, Eq. (1), $m \neq 1$									
θ_S	0.459	0.459	0.459	0.459	0.439	0.399	0.399	0.399	0.375
θ_R	0.098	0.098	0.098	0.098	0.065	0.061	0.061	0.061	0.053
α (hPa^{-1})	0.0161	0.0161	0.0161	0.0161	0.010	0.0142	0.0142	0.0142	0.0234
n	1.10	1.10	1.10	1.10	1.25	1.18	1.18	1.18	1.65
RMSD_j^*	0.0679	0.208	0.233	0.258	0.0586	0.136	0.230	0.236	0.156
RMSD^{**}=0.183									
Gupta and Larson (1979) Curve 4, Eq. (1), $m = 1$									
θ_S	0.575	0.624	0.644	0.676	0.525	0.421	0.295	0.303	0.287
θ_R	0.346	0.446	0.435	0.421	0.245	0.197	0.185	0.212	0.126
α (hPa^{-1})	0.0027	0.00256	0.00252	0.0025	0.00274	0.00297	0.00341	0.00337	0.00352
n	1.21	1.14	1.18	1.22	1.39	1.28	0.988	0.898	1.25
RMSD_j^*	0.116	0.114	0.117	0.122	0.273	0.185	0.0964	0.0674	0.179
RMSD^{**}=0.166									

T a b l e 2. Continuation

Sites	Seelow				Eichenhof	Bölkendorf			
						field 9			field 6
Soil horizons	1Ap	2Bg1	3Bg2	4BgCr	4Bt	1Ap	2Bt	3Bt	2Bw
				Cosby *et al*. (1984) Curve 5, Eq. (8)					
θ_S	0.481	0.497	0.499	0.501	0.481	0.443	0.435	0.441	0.410
ψ_S (hPa^{-1})	23.9	30.4	31.8	32.5	23.9	13.2	11.9	13.0	8.01
c	10.2	13.5	13.0	12.5	7.03	6.24	6.08	6.87	4.36
RMSD_j^*	0.142	0.174	0.202	0.232	0.110	0.122	0.0969	0.150	0.0839
				RMSD**=0.141					
				Terleev *et al*. (this paper) Curve 6, Eq. (3)					
θ_S	0.506	0.547	0.559	0.589	0.479	0.442	0.328	0.325	0.377
θ_R	0.277	0.326	0.314	0.360	0.159	0.135	0.108	0.123	0.0343
b (hPa^{-1})	0.00083	0.00058	0.0007	0.00049	0.0018	0.00123	0.00118	0.00074	0.00154
a	0.599	0.580	0.608	0.590	0.724	0.599	0.564	0.495	0.597
RMSD_j^*	0.0172	0.0441	0.0878	0.0346	0.101	0.196	0.0359	0.0229	0.274
				RMSD**=0.132					

*$\text{RMSD}_j = \sqrt{(1/N_j \sum_{i=1}^{N_j} \left(1-\hat{\theta}_{ij}/\theta_{ij}\right)^2}$, **$\text{RMSD} = \sqrt{\sum_{j=1}^{K} N_j RMSD_j^2 / \sum_{j=1}^{K} N_j}$, $\hat{\theta}_{ij}$ and θ_{ij} – simulated and measured soil water content, accordingly, N_j – quantity of measured WRC points for soil sample j, K – quantity of soil samples (K= 9).

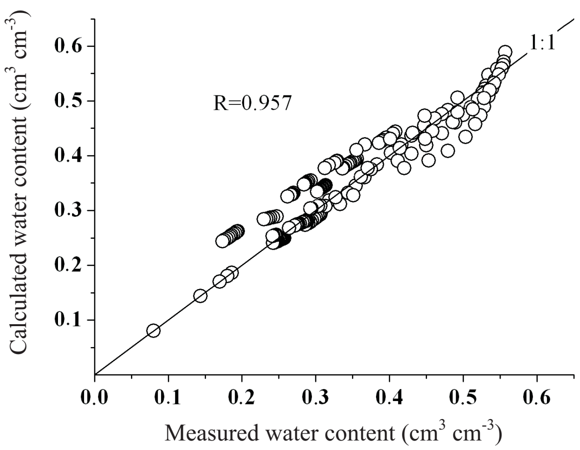

Fig. 3. Comparison of WRC modelling results by Terleev *et al.* (this paper) method with measured data on all selected soil samples.

CONCLUSIONS

1. In practical calculations, use of models describing soil water dynamics encounters significant difficulties due to initial data being absent or incomplete. The same problems raise when attempts are made to apply complex agro-ecosystem models for estimating plant vegetation phases, formulating agro-meteorological prognoses, and making yield forecasts. In reality, knowledge is often limited to the type of soil, its texture class, bulk density, and also some hydrological constants (wilting point and/or hydroscopic property of soil). The results of this study allow considerable expansion of the applicability of WRC models because of the possibility to estimate data necessary for WRC modelling from the available soil characteristics.

2. Verification of the results obtained with the use of the proposed method shows that this approach possesses accuracy sufficient for practical agrometeorological calculations and yield forecasting.

3. It is necessary to point out that in the PTF methods selected for comparison, the standard dataset necessary for calculation of WRC parameters is used. The most important aspect of this paper is the demonstration of the approach for estimation of WRC parameters when directly measured WRC data or the initial information necessary for applying PTF methods developed earlier are not available. The proposed approach does not use these data. Instead, it relies on more accessible data, that are typical in some countries of Eastern Europe and Russia, yet delivers results of acceptable accuracy.

REFERENCES

Ahuja L., Naney J., and Williams R., 1985. Estimating soil water characteristics from simpler properties or limited data. Soil Sci. Soc. Am., 49, 1100-1105.

Bouma J., 1989. Using soil survey data for quantitative land evaluation. Adv. Soil Sci., 9, 177-213.

Chan T.P. and Govindaraju R.S., 2004. Estimating soil water retention curve from particle size distribution data based on polydisperse sphere system. Vadose Zone J., 3, 1443-1454.

Cornelis W.M., Ronsyn J., van Meirvenne M., and Hartmann R., 2001. Evaluation of pedotransfer functions for predicting the soil moisture retention curve. Soil Sci. Soc. Am. J., 65, 638-648.

Cosby B.J., Hornberger G.M., Clapp R.B., and Ginn T.R., 1984. A statistical exploration of soil moisture characteristics to the physical properties of soils. Water Resour. Res., 20, 682-690.

D'Hollander E.H., 1979. Estimation of the pore size distribution from the moisture characteristic. Water Resour. Res., 15, 107-112.

Giménez D., Rawls W.J., Pachepsky Y., and Watt J.P.C., 2001. Prediction of a pore distribution factor from soil textural and mechanical parameters. Soil Sci., 166(2), 79-88.

Globus A.M., 1987. Soil-hydrophysical Supporting of the Agro-Ecological Mathematical Models (in Russian). Hydrometeoizdat Press, Leningrad, Russia.

Gupta S. and Larson W., 1979. Estimating soil water characteristics from particle size distribution, organic matter percent, and bulk density. Water Resour. Res., 15, 1633-1635.

Haverkamp R. and Parlange J.-Y., 1986. Predicting the water-retention curve from particle size distribution: 1. Sandy soils without organic matter. Soil Sci., 142, 325-339.

Haverkamp R., Vauclin M., Touma J., Wierenga P.J., and Vachaud G., 1977. A comparison of numerical simulation model for one-dimensional infiltration. Soil Sci. Soc. Am. J., 41, 284-294.

Kosugi K., 1996. Lognormal distribution model for unsaturated soil hydraulic properties. Water Resour. Res., 32, 2697-2703.

Kosugi K., 1999. General model for unsaturated hydraulic conductivity for soil with lognormal pore-size distribution. Soil Sci. Soc. Am. J., 63, 270-277.

Mecke M., Westman C.J., and Ilvesniemi H., 2002. Water retention capacity in coarse podzol profiles predicted from measured soil properties. Soil Sci. Soc. Am. J., 66, 1-11.

Porębska D., Sławiński C., and Lamorski K., 2006. Relationship between van Genuchten's parameters of the retention curve equation and physical properties of soil solid phase. Int. Agrophysics, 20, 153-159.

Rawls W.J., Gish T.J., and Brakensiek D.L., 1991. Estimating soil water retention from soil physical properties and characteristics. Adv. Soil Sci., 16, 213-234.

Richards L.A., 1931. Capillary conduction of liquids through porous media. Physics, 1, 95-112.

Saxton K.E., Rawls W.J., Romberger J.S., and Papendick R.I., 1986. Estimating generalized soil water characteristics from texture. Soil Sci. Soc. Amer. J., 50, 1031-1036.

Schaap M.G. and Leij F.J., 1998. Database-related accuracy and uncertainty of pedotransfer functions. Soil Sci., 163, 765-779.

Schindler U., Thiere J., Steidl J., and Müller L., 2004. Bodenhydrologische Kennwerte heterogener Flächeneinheiten - Methodik der Ableitung und Anwendungsbeispiel für Nordostdeutschland. Fachbeitrag des Landesumweltamtes, 87 (Bodenschutz 2), 56.

Shein E.V., 2005. Soil Physics (in Russian). Moscow St. Univ. Press, Moscow, Russia.

Terleev V.V., 2000. Modelling the water-retention ability of capillary soil-pores (in Russian). St.-Petersburg, St. Univ. Press, St.-Petersburg, Russia.

Tomasella J., Hodnett M.G., and Rossato L., 2002. Pedotransfer functions for the estimation of soil water retention in Brazilian soils. Soil Sci. Soc. Am. J., 64, 327-338.

Tomasella J., Pachepsky Y., Grestana S., and Rawls W.J., 2003. Comparison of two techniques to develop pedotransfer functions for water retention. Soil Sci. Soc. Am. J., 67, 1085-1092.

Van Genuchten M.Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44, 892-989.

Vereecken H., Maes J., Feyen J., and Darius P., 1989. Estimating the soil moisture retention characteristic from texture, bulk density and carbon content. Soil Sci., 148, 389-403.

Voronin A.D., 1986. Principium of Soil Physics (in Russian). Moscow St. Univ. Press, Moscow, Russia.

Williams R., Ahuja L., and Naney J., 1992. Comparison of methods to estimate soil water characteristics from soil texture, bulk density, and limited data. Soil Sci., 153, 172-184.