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SOIL PHYSICS

Soil Water Retention Curve of Agrogray Soils: Influence of Anisotropy and the Scaling Factor

A. B. Umarova[a], E. V. Shein[a], and N. S. Kukharuk[b]

[a] *Faculty of Soil Science, Moscow State University, Leninskie gory 1, Moscow, 119991 Russia*
[b] *Belgorod State University, ul. Pobedy 85, Belgorod, 308015 Russia*
e-mail: a.umarova@gmail.com, evgeny.shein@gmail.com

Abstract—The soil water characteristic or soil water retention curve (WRC) of medium-loamy gray forest soil horizons was studied in cylinder-shaped samples of disturbed and undisturbed structure. The sample height varied within 2–4 cm and the diameter within 4.5–10 cm. The soil monoliths were sampled in three profiles: vertically, along the slope, and across the slope in accordance with the intrasoil paleorelief formed by the funnel-shaped surface of the second humus horizon. The experimental WRC were approximated with the van Genuchten equation. The statistical analysis of the WRc approximation parameters proved to differ significantly in filled soil samples and monoliths, and a number of parameters differ for samples of the maximal height and diameter. The reliable differences of the parameters were also noted for the different sampling directions, most often, for those across the paleorelief slope. The noted variation in the WRC approximation parameters may substantially influence the predictive estimation of the spring water reserve for example. This fact suggests the necessity to strictly indicate the sampling procedure, in particular, with respect to the soil profile, the asymmetry in the soil properties, and the sample sizes (scaling factor) used for analyzing the hydrological properties of structured soils.

Keywords: water retention curve, sampling, asymmetry, anisotropy in the soil properties, modeling, loose soil samples, soil monoliths

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INTRODUCTION

At the present stage of soil hydrology development, the influence of the water retention curve (WRC), i.e., the dependence between the capillary-adsorption water pressure and the volume soil water, appears to be one of the most important hydrological parameters of soils [2, 3, 5, 7, etc.]. This is because soil hydrology and the related sciences of practical application, such as reclamation, land use, agricultural technologies, etc., use at present physically substantiated mathematical models. These models are used for analyzing the hydrological situation, calculating the environmental risk, the structure and operation of soil constructions, draining and irrigation measures, etc., i.e., almost all the processes developing in soil that are related to the migration of water and solutions in the soil and soil cover. Since the migration of water and solutions in soils appears to be the basis for any soil process both under natural and human-modified conditions, the WRC occupies a central place in mathematical models of soil functioning with the former being an essential part in experimental soil models. The quality of deriving this dependence controls the adequacy of the model; the prediction quality and accuracy; and, respectively, making decisions and managing soil processes [5, 7, 13].

However, there is still no commonly accepted standardized experimental methods for obtaining this dependence, although a range of methods have been developed for determining the different water retention curves, and finally, for building practically the entire curve. The shape and position of the WRC vary significantly depending on such fundamental properties as the particle size distribution, mineral composition, density, organic content, and composition of exchangeable cations, as well as the dynamic properties such as the chemical composition of the soil solution, the structural composition, the direction of the hydrological processes, the drying or moistening (hysteresis phenomenon), and many other factors [7, 8, 16]. On the other hand, the WRC permits obtaining data on the pore space pattern, the quantitative parameters of the mobile and immobile water volumes, the available and unavailable water for plants, the ratios between the aerial and liquid phases upon different soil moisture, and many other soil parameters. This integrally representative and highly informative WRC permits us to apply it in practice for prediction and management of soil processes in landscapes using different models [13, 15]; however, it poses another problem, i.e., the necessity to determine the WRC on a large scale, which is very laborious, expensive, and almost impossible.

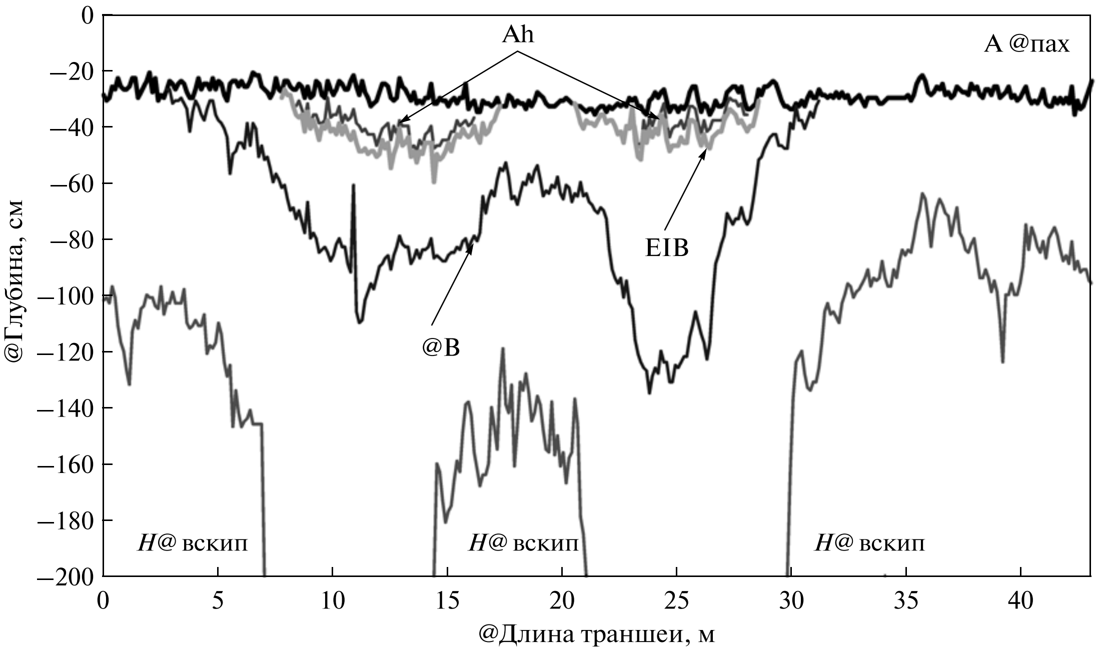

Fig. 1. Morphological structure of the trench in the year 2000. The designations: (Ah) the second humus horizon forming typical "microlows" in the paleorelief within the soil body; (*H* efferv) the effervescence depth upon treating the soil with a 10% HCl solution

In recent decades, the calculation approach has been used for obtaining various hydrophysical functions. It was suggested to calculate the so-called pedotransfer functions, i.e., the dependences between the WRC and the fundamental soil properties, which are known from soil surveys and are stored in databases [10, 12]. At present, pedotransfer functions are widely used both in regional soil hydrology and for compilation of hydrological maps of different scales. The particle-size distribution, organic substance content, and soil density are the main predictors in pedotransfer functions. The hydrological constants, such as the minimal water capacity and plant wilting water, which, as a rule, are correlated with the soil water pressure (–330 and –15 000 cm of a water column, respectively (two points on the water-retention curve)), are also often used [7, 12, 15]. However, the following questions arise at the present stage of using the WRC. (1) What other soil properties in addition to those traditionally accumulated in a database may exert an essential effect on the shape and position of the water-retention curve? (2) What influence does the scaling factor exert on the WRC determination? Most often, the WRC is determined experimentally in a laboratory using samples collected in the field. However, the sampling procedure (i.e., the sampling conditions, the size of the sample, etc.) for obtaining the water retention curve has been studied rather poorly. (3) How significant is the sampling factor for the subsequent analyses of the soil hydrological conditions using the prediction models (the sampling influence on the WRC)? The mentioned problems cover the main tasks of this work.

Proceeding from these tasks, this work was aimed at the study of the WRC dependence on the sampling conditions and methods in connection with the specifics of the evolution and modern morphology of agrogray soil.

OBJECTS AND METHODS

The agrogray forest soils in Vladimir opolie was the object of our study. These soils have been investigated comprehensively in the course of long-term field works executed at the Department of the Physics and Reclamation of Soils of the Soil Science Faculty of Moscow State University, and the experimental results were published in papers and monographs [1, 6, 8]. The soil cover in Vladimir opolie is markedly contrasting due to the paleorelief; it is composed of gray forest soils of different podzolization degrees and gray forest soils with a second humus horizon (Ah). This horizon is known to be specified by its crumb–blocky structure, and it is surrounded by a podzolic horizon, which also manifests a markedly pronounced structure with horizontal stratification, which should be reflected in the hydrophysical functions of soil samples collected from the Ah, E1B, and AhE1 horizons. As an example, Fig. 1 shows a scheme of the soil cover studied using a trench method [1, 6, 8]. The trench 200 cm deep and 42 m long distinctly reveals the second humus horizon (Ah) forming *microlows* with a typical paleorelief within the soil body. The slopes of these intrasoil *microlows* can be seen. Therefore, samples for the hydrophysical studies may be taken from the Ap, Ah,

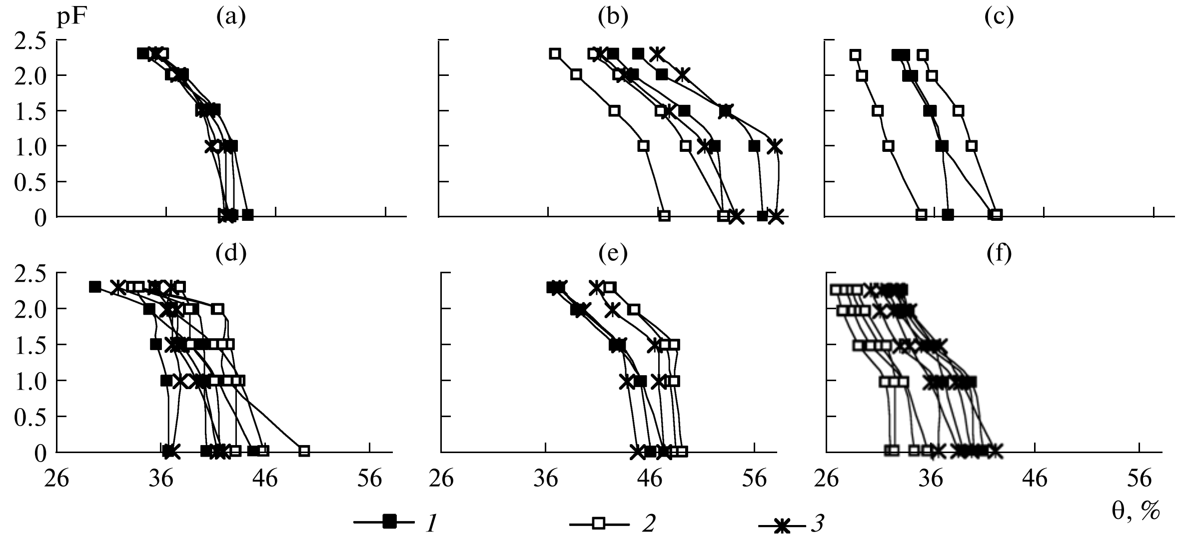

Fig. 2. WRCs of soil monoliths collected from the gray forest soil horizons and transitional layers. The designations: (A) Ap; (B) Ah; (C) EB; (D) Ap–EB; (E) Ap–Ah; (F) AhE; (*1*) samples of undisturbed structure collected vertically; (*2*) samples collected along the slope formed by the second humus horizon; (*3*) samples collected across the slope within the soil.

E1B, Ap–E1B, Ap–Ah, and AhE1 horizons both along and across this slope.

In these directions, the samples with both disturbed and undisturbed structures were collected from the main genetic soil horizons. In the further discussion, they are referred to as the samples of undisturbed structure sampled vertically along the intrasoil slope formed by the second humus horizon, as well as those sampled across the intrasoil slope.

All the samples (loose and monoliths) were placed in plastic rings of different sizes: (1) 4.5 cm in diameter and height; (2) 4.5 cm in diameter and 2 cm in height; (3) 10 cm in diameter and 4.5 cm in height.

Before the experiment, the samples were stored in a refrigerator in a hermetic package in order to preserve the natural water and to restrict the biological activity.

The WRC was determined by the method of water adsorption above a saturated salt solution (for the upper portion of the curve) and by the tensiostatic method in loose samples and soil monoliths [5] under a drying regime (for the lower portion of the curve). The middle portion of the water retention curve was calculated according to Voronin [2, 16].

RESULTS AND DISCUSSION

Let us consider the effect of the soil sampling direction on the shape and position of the WRC curve for different horizons of the investigated soil. Figure 2 shows the lower portions of the water-retention curve obtained tensiostatically for the soil horizons sampled in different directions.

The curves for the Ap horizon (Fig. 2a) are found to be very densely located with the minimal scattering of the water values. This horizon is the most homogenous; it does not show the WrC anisotropy. The Ah horizon (Fig. 2b) stands out, which manifests a higher water retention capacity as compared to the plow horizon, and simultaneously shows the differentiation in the WRC curves depending on the soil monolith sampling direction. The horizontal monoliths sampled along the paleorelief are specified by the lower water contents with their curves being located to the left of the others.

The anisotropy in the WRC is still more markedly pronounced in the lower part of the Ah horizon (Fig. 2e) along with the sharp decrease in the water-retaining capacity as compared to the overlying horizon. This horizon is also clearly distinguished by the anisotropy in the water-retention function. Monoliths taken along the paleorelief slope manifest the highest coefficient of water retention in wet soil, and it decreases sharply with the lowering water.

The experimental data on the dependence between the soil water and the soil water pressure was approximated by the van Genuchten equation, in which Θs, Θr, α, and n are the main parameters (provided m is taken equal to $m = 1 - \frac{1}{n}$) [5, 14, 17].

It is assumed that the approximation parameters according to van Genuchten are physically substantiated. The Θs parameter is close to the volume water of complete soil saturation, although, in the bulk of cases, upon the mathematical description of the WRC curve, it takes lesser values than the soil porosity. The α parameter is the one inverse proportional to the pressure of the air entering the soil, i.e., the barbotage pressure, and the parameter n characterizes the sloping angle of the WRC curve.

Table 1. Approximation parameters of the soil SWC curves and their statistical comparative analysis

No.	Samples	Sample sizes: height–diameter, cm	Θs, cm^3/cm^3	α, cm^{-1}	n
		Ah horizon, gray forest soil, 15–17 cm			
1	Loose	4.5–4.5	$0.372^{(2,3,4)}$	$0.016^{(2,3,4)}$	$1.259^{(2,3,4)}$
2	Monoliths	2–4.5	$0.340^{(1)}$	$0.007^{(1,4)}$	$1.326^{(1,4)}$
3	Monoliths	4.5–4.5	$0.324^{(1)}$	$0.006^{(1,4)}$	$1.333^{(1,4)}$
4	Monoliths	4.5–10	$0.341^{(1)}$	$0.002^{(1,2,3)}$	$1.391^{(1,2,3)}$
		B horizon, gray forest soil, 40–45 cm			
5	Loose	4–4.5	$0.427^{(7,8)}$	$0.051^{(7,8)}$	$1.210^{(7,8)}$
6	Monoliths	2–4.5	$0.440^{(7,8)}$	$0.021^{(7,8)}$	$1.262^{(7,8)}$
7	Monoliths	4–4.5	$0.367^{(4,5)}$	$0.009^{(5,6)}$	$1.366^{(4,5)}$
8	Monoliths	4–10	$0.323^{(4,5)}$	$0.013^{(5,6)}$	$1.212^{(4,5)}$

With the known approximation parameters and their statistics (mean square errors of the parameters), we may compare the studied objects qualitatively [10]. For the corresponding approximation parameters (e.g., α' and α'') in various samplings, we may calculate the t-criterion by the following equation:

$$t = \frac{|\alpha' - \alpha''|}{\sqrt{(S_{\alpha'})^2 + (S_{\alpha''})^2}},$$

where $S_{\alpha'}$ and $S_{\alpha''}$ are the standard deviations of the α' and α'' parameters. In the case when the t-criterion turns out to exceed the table value for the given freedom degree and the significance level (traditionally taken as 0.5), the parameters of two samplings differ significantly. In this case, we may confirm the reliability of the difference in the respective characteristics of the process.

Table 1 lists the results of the WrC approximation for soil samples of various sizes collected from the humus Ap horizon and the mineral B horizon of the gray forest soil, which analyzed in three replicates, as well as the statistical comparison of the main approximation parameters. The loose samples and monoliths of standard sizes (4.5 cm in height and diameters) used in the tensiostatistic method procedure participated in the comparison. In addition, the monoliths of the same diameter but of shorter height (2 cm), as well as monoliths of the same height (4.5 cm) and a wider diameter (10 cm), were used. The figures in the index designate that this parameter differs significantly ($P = 0.05$) from the corresponding parameters of this number. For example, $0.372^{(2)}$ means that the Θs value for the loose sample from the A horizon differs from the Θs parameter of the undisturbed sample in the A horizon of height 2 cm and diameter 5 cm numbered as 2.

Judging by the Θs parameter, the loose soil sample from the Ap horizon contains the maximal amount of water, whereas the monoliths of various size differ insignificantly from each other. In the mineral B horizon, the values of the full saturation water in loose soil samples and the smallest monoliths (2 cm in height) are close, being equal to 0.427 and 0.440 cm^3/cm^3, respectively.

Note that the α parameter decreases in the sequence from the loose soil sample to the large-size monolith, which physically means an increase in the barbotage pressure with the growing structural order and the enlarging size of the soil monoliths.

Let us statistically compare the obtained approximation parameters according to Student's criterion. The analysis of the results shown in Table 1 reveals that, in the Ap horizons, the Θs values significantly differ from the loose samples and monoliths, whereas the monoliths of the different sizes are close to each other in this parameter. For this horizon, a difference is registered in the α parameter values between the loose soil samples and the monoliths 10 cm in diameter. The α and n values also reliably differ for the monoliths of the maximal height. It is worth noting that a significant difference in the WRC parameters is typical for all the values of the loose samples (with disturbed structure); this reliably points to the substantial difference in the WRC of the loose soil samples and monoliths. These results testify to the necessity to determine the SWC only in soil samples with undisturbed structure.

As for the sample size, only the widest samples (10 cm in diameter) are distinguished by the α and n parameters. Their area is equal to 78.5 versus 15.9 cm^2 of all the other monoliths and loose soil samples. Therefore, the occurrence of various pores (by their diameter and weaving degree) in a greater soil volume is highly probable. The influence of the cylinder walls on the water retention capacity (which may be of double trend) is less pronounced in these samples. On the one hand, the additional porosity due to the near-wall spacing (becoming more pronounced with the sample drying) may raise the water content in the lower part of the WRC curve. On the other hand, the limited monolith size leads to more frequent cases of weaving pores interruption; to cutting capillaries; and, as a result, to decreasing water retention, which becomes more noticeable in a smaller volume of soil monolith.

In the B horizon, the loose soil samples and the smallest monoliths are indistinguishable in any WRC parameters. The B horizon has a blocky-prismatic structure, which is well preserved in the disturbed sample. The monoliths 2 cm high are the closest to the size of the aggregates, so they manifest the closest hydrological regime to that of loose soil samples. A twofold increase in the monolith height and, the more so, a fivefold additional increase in their area (large monoliths) increases the contribution of the soil texture to the soil water-retention capacity.

Reliable differences in all the WRC parameters are observed between the loose soil samples and the small monoliths versus the large soil samples (monoliths 4 cm in height with a diameter of 4.5 cm, as well as the monoliths 4 cm in height and 10 cm in diameter).

Thus, a significant (reliable) difference in the shape and position of the WRC curve may be obtained upon using soil samples of different preparation modes (loose samples and monoliths) and different sizes. The following question arises: How significant are these differences? What discrepancies in predicting the mathematical models will arise from using the WRC values obtained for soil samples of different sizes and structures?

We performed the following experimental calculation: we calculated the seasonal water reserve in the 0- to 20-cm-thick soil layer after the spring snow thawing and gravitational water runoff. Under the conditions of the Vladimir opolie (in Suzdal district), the snow thaws approximately on April 8–12. The period between the snow melting and the physical maturity condition reached by the soil (soft-plastic state) is approximately 8–10 days. During the next 20–22 days, the water reserve necessary for the first seeds germination is formed. This process was simulated by the physically grounded HYDRUS model using the WRC parameters listed in Table 1 with the other conditions (the initial and boundary conditions, filtration coefficient, etc.) being the same for all the experimental options. Let us consider these options: loose samples (option 1), samples 2 cm high and 4.6 cm in diameter usually used for WRC determination (option 2), samples 4 cm high and 4.6 cm in diameter (option 3), and samples 4 cm high and 10 cm in diameter (option 4).

To predict the spring reserve of productive water in the layer of 0–20 cm to the germination time of the first spring crop seeds, we used the average perennial scenario for the Vladimir opolie conditions: the meteorological conditions were taken on the upper soil boundary, and the condition of free water runoff was assumed for the lower soil boundary (a depth of 60 cm). Thus, only the WRC parameters varied (due to the different sizes of the samples) in this predictive experiment; all the other conditions of the water migration (the conditions on the upper and lower soil boundaries, filtration coefficients, etc.) were absolutely the same for all the options.

The calculation of the spring reserve of productive water proved that the application of the WRC obtained for the samples of different sizes leads to substantially different results in agronomic practice: option 1 gives 4.3 cm of the water layer (which fits the most favorable and optimal conditions); option 2 suggests 3.2 cm (favorable conditions); option 3 results in 2.9 cm (satisfactory conditions); and option 4, 4.0 cm (favorable conditions) (cited after [4]). That is, in the case of using loose soil sample, we may overestimate the predictive results concerning the spring water reserve, and we may underestimate them upon using the standard size monoliths. It is interesting that, if we take the option with the largest soil-monolith size as the most adequate prediction of the spring water reserve, it turns out to be the closest to the case with the loose soil option.

As proceeds from the predictive experimental calculation, the assessment of the productive water ranges widely (from optimal to satisfactory) depending on the soil sample structure (monolith or loose sample) and the sample size used upon the WRC determination for prediction models. The optimal, i.e., the highest and probably overestimated values, are obtained from the experiments with loose soil samples, and the lowest values are obtained for the monoliths 4 cm in height and 5 cm in diameter. The further experimental task is to find the range of the sample sizes within which the stability and validity of the revealed trend may be proved. At present, only one point is clear: qualitatively different results may be obtained for the prediction of the spring water reserves depending on the condition and size of the samples used for the WRC determination.

The study of the shape and position of the WRC curve depending on the various directions of sampling, i.e., the study of the influence of the anisotropy in the texturally heterogeneous soil properties on the hydrophysical characteristics of the soils, was the next research task. The choice of Vladimir opolie soils for the investigation of the effect of the WRC anisotropy on its approximation parameters, as well as its effect on the prediction of the soil hydrological regime, is not by chance. According to previous studies [1, 6, 9], the soils in Vladimir opolie function in accordance with the ancient paleorelief, which, in turn, preserve the complex soil cover pattern.

In the present work, we used samples of gray forest soil and gray forest soil with a second humus horizon collected vertically along the ancient paleorelief slope and at a right angle to the slope. The sample sizes, the conditions of the sample storage, and the analytic methods were similar for all the variants. The tests were repeated in 3–7 replicates.

The data obtained (Table 2) proved that reliable differences are registered mainly for the Θs parameter upon vertical sampling or horizontal sampling along the soil paleoslope. Most often, this effect is observed upon sampling soil monoliths across the slope. Probably, the pore space is modified most significantly in this case, which leads to the WRC transformation.

Let us compare the predictive reserves of productive water using various WRCs only depending on the

Table 2. Approximation parameters of the WRC curves (according to van Genuchten) of the soil samples collected in different directions (different sampling)

No.	Samples	Horizon, sampling depth, cm	Θs, cm^3/cm^3	α, cm^{-1}	n
		Gray forest soil with a second humus horizon			
1	Vertical	Ap, 9–14	0.441$^{(3)}$	0.062$^{(3)}$	1.090
2	Horizontal along the slope		0.410	0.027	1.094
3	Horizontal across the slope		0.410$^{(1)}$	0.015$^{(1)}$	1.102
4	Vertical	Ah, 28–32	0.487$^{(6)}$	0.047	1.097
5	Horizontal along the slope		0.485	0.008	1.125
6	Horizontal across the slope		0.458$^{(4)}$	0.015	1.104
7	Vertical	Ah, 36–40	0.538	0.045	1.093
8	Horizontal along the slope		0.494	0.144	1.070
9	Horizontal across the slope		0.548	0.060	1.091
10	Vertical	AhAEl, 43–47	0.410$^{(11)}$	0.155	1.045
11	Horizontal along the slope		0.338$^{(10)}$	0.203	1.045
12	Horizontal across the slope		0.387	0.203	1.059
13	Vertical	B, 70–74	0.384	0.044	1.070
14	Horizontal along the slope		0.378	0.085	1.063
		Gray forest soil			
15	Vertical	Ap–ElB, 28–32	0.455$^{(17)}$	0.132$^{(17)}$	1.070
16	Horizontal along the slope		0.460$^{(17)}$	0.112	1.079
17	Horizontal across the slope		0.401$^{(15,16)}$	0.010$^{(15)}$	1.088
18	Vertical	ElB, 36–40	0.433	0.062	1.078
19	Horizontal across the slope		0.432	0.114	1.072

direction of sampling the soil monoliths. Let us leave all the other conditions the same for all the options (i.e., on the upper meteorological boundary, on the lower boundary at the 60 cm deep, the filtration coefficients, etc.). The predicted results for the productive water reserves are listed in Table 3.

As is seen, this model experiment also results in reliably different productive water reserves upon using samples of the same size and structure but collected in different directions with respect to the inner soil cover relief. This points to the necessity to standardize the procedures of the sampling, storing, and preparation of the samples for deriving hydrophysical information and to the necessity of taking into account the soil paleorelief specifics in texturally and structurally anisotropic soils. It is necessary to make allowance for the anisotropy of the water-retention curve at hydrological and predictive agronomic calculations of the water reserves.

Table 3. Predictive estimation of the productive water reserve in the layer of 0–20 cm with the WRC obtained from the soil sampled in different directions with the consideration of the paleorelief within the soil body

Sampling conditions	Productive water reserves in the layer of 0–20 cm, cm of the water layer	After Medvedev and Plisko [4]
Vertical	2.6	Satisfactory
Horizontal along the slope	1.6	Unfavorable
across the slope	3.75	Favorable

CONCLUSIONS

The soil water characteristic now appears to be the principal constituent in predictive and optimization calculations of water transfer and retention by soils. However, its experimental determination is extremely laborious, whereas the calculation methods are reduced to the compilation of the WRC curve on the basis of a limited number of predictors. As a rule, these are such indices as the particle-size distribution, density, and the organic content in the soil. At the same time, the sampling procedure is not adequately justified for the WRC analysis in a laboratory. In particular, this is true for the sampling conditions (using disturbed or undisturbed soil samples, the direction of the soil monolith sampling, the anisotropy of the soil horizons), as well as for the preliminary preparation of the samples. It is shown that, for the soils with a strong structure and a texturally differentiated profile, the sampling procedure should be obligatorily taken into account upon determining the WRC and deriving the pedotransfer functions. The underestimation of the soil profile structure specifics and anisotropy in the soil properties and sample sizes (the scaling factor) may result in significant errors in the calculations up to changes in the qualitative estimation of the soil water reserves.

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REFERENCES

1 1. T. A. Arkhangel'skaya, "Thermal diffusivity of gray forest soils in the Vladimir opolie region," Eur. Soil Sci. **37** (3), 332–342 (2004).

2. A. D. Voronin, *Fundamentals of Soil Physics* (Izd. Mosk. Gos. Univ., Moscow, 1986) [in Russian].

3. A. M. Globus, *Soil-Geographical Supply of Agroecological Mathematical Models*, (Gidrometeoizdat, Leningrad, 1987).

4. V. V. Medvedev and I. V. Plisko, *Bonitation and Qualitative Evaluation of Ukrainian Lands* (13-ya Tipografiya, Kharkov, 2006) [in Russian].

5. *Theory and Methods of Soil Physics,* Ed. by E. V. Shein and L. O.. Karpachevskii (Grif i K, Moscow, 2007) [in Russian].

6. A. B. Umarova, *Preferential Water Flows in Soils: Regularities of the Formation and the Role in Soil Functioning* (GEOS, Moscow, 2011) [in Russian].

7. E. V. Shein, *A Course of Soil Physics* (Izd. Mosk. Gos. Univ., Moscow, 2005) [in Russian].

8. E. V. Shein, "Soil hydrology: stages of development, current state, and nearest prospects," Eur. Soil Sci. **43** (2), 158–167 (2010).

2 9. E. V. Shein, A. L. Ivanov, M. A. Butylkina, and M. A. Mazirov, "Spatial and temporal variability of agrophysical properties of gray forest soils under intensive agricultural use," Eur. Soil Sci. **34** (5), 512–517 (2001).

10. E. V. Shein and T. A. Arkhangel'skaya, "Pedotransfer 1
functions: state of the art, problems, and outlooks," Eur. Soil Sci. **39** (10), 1089–1099 (2006).

11. E. V. Shein, A. M. Rusanov, E. Yu. Milanovskii, D. D. Khaidapova, E. I. Nikolaeva, "Mathematical models of some soil characteristics: substantiation, analysis, and using features of model parameters," Eur. Soil Sci. **46** (5), 541–547 (2013).

12. *Developments in Soil Science*, Ed. by Ya. A. Pachepsky and W. J. Rawls (Elsevier, Amsterdam, 2004).

13. K. Ranatunda, E. R. Nation, and D. G. Barrat, "Review of soil water models and their applications in Australia," Environ. Model. Software **23**, 1182–1206 (2008).

14. M. G. Schaap and M. Th. van Genuchten, "A modified 3
Mualem-Van Genuchten formulation for improved description of the hydraulic conductivity near saturation," Vadose Zone J. **5**, 27–34 (2006).

15. J. Simunek, M. Th. van Genuchten, and M. Sejna, "Development and applications of HYDRUS and STANMOD software packages and related codes," Vadose Zone J. **7** (2), 587–600 (2008).

16. V. V. Terleev, W. Mirshel, U. Schindler, and K.-O. Wenkel, "Estimation of soil water retention curve using some agrophysical characteristics and Voronin's empirical dependence," Int. Agrophys. **24**, 381–387 (2010).

17. M. Th. van Genuchten, "A closed-form equation for predicting the hydraulic," conductivity of unsaturated soils, Soil Sci. Soc. Am. J. **44**, 892–898 (1980).

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SPELL: 1. Arkhangel'skaya, 2. Butylkina, 3. Schaap