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The application of pedotransfer functions in the estimation of water retention in alluvial soils in Żuławy Wiślane, northern Poland

Abstract: The aim of the studies was the assessment of the usefulness of selected pedotransfer function for calculating the water retention of alluvial soils in Żuławy Wiślane. Żuławy Wiślane are an important area, both as far as agricultural production and environmental values are concerned. The analysis accounted for three models, i.e.: van Genuchten-Wösten, Varellyay and Mironienko, Hewelke et al. Based on 122 dataset of alluvial soils from the Żuławy area, the statistical relationships between the measured values of total available water and values calculated for individual models were analysed. The studies carried out indicate that the analysed pedotransfer functions are characterized by different compatibilities with results obtained by means of direct measurement. The lowest average errors of fit were obtained for the Hewelke et al. and van Genuchten models.

Keywords: Soil water retention, water content of soils, matrix potential, total available water, multiple regression equations

INTRODUCTION

The water retention of soils is a functional relationship between the matrix potential and volumetric soil moisture content (pF curve). In agricultural ecosystems, it determines the choice of crops, crop yields and necessary farming infrastructure and agro-technology (e.g. Hewelke et al. 2013, Czyż 2000). Knowledge of soil water retention is essential to assessing the water balance, especially in short time frames as well as predicting soil droughts and the course of flooding in a catchment. Due to the complicated and time-consuming process of the direct measurement of the pF curve, indirect methods are proposed, using relationships between the physical properties of soils and their moisture content. These methods are referred to as pedotransfer functions and their suitability were demonstrated by (e.g. Pachepsky and Rawls 2004, Guber and Pachepsky 2010, Vereecken et al. 2010). Studies on pedotransfer functions have been carried out by many authors (e.g. Trzecki 1974, 1976; Varallyay and Mironienko 1979, Van Genuchten 1980, Rawls and Brakensiek 1982, Varallyay et al. 1982, Walczak 1984, Carsel and Parrish 1988, Wösten et al. 1999, Vereecken et al. 1989, 2010; Schaap et al. 2001, Pachepsky and Rawls 2004, Walczak et al. 2004, Dexter et al. 2008, Gnatowski et al. 2006, 2010; Guber and Pachepsky 2010, Skalova et al. 2011, Puhlmann and von Wilpert 2012, Hewelke et al. 2013, 2015, 2017; Brogowski and Kwasowski 2015,

Lamorski et al. 2017, Oleszczuk et al. 2018). Among the developed models, we can distinguish continuous functions, enabling the moisture content of soil (θ) to be calculated for any given matrix potential (h), as well as discontinuous functions, making it possible to indicate the $\theta(h)$ relationships for characteristic θ values. Extensive compilations and an analysis of the models describing function for estimating water retention curves of soils can be found in particular in Guber and Pachepsky (2010). Empirical material for the particular solutions covers a very diverse soil sample set (collection) reaching as many as a few thousand, e.g. Rawls and Brakensiek (1982) – 5320 samples, Wösten et al. (1999) – 4030 samples.

Żuławy Wiślane is an important area, both as far as agricultural production and the natural environment are concerned. Due to the share of polders (approx. 45 thousand ha) and areas around polders (approx. 72 thousand ha), they pose a particular challenge to water management (Nowicki and Liziński 2004). Alluvial soils make up over 90% of soils in Vistula River Delta; they are characterised by high diversity, from very light to very heavy textured soils. The peculiarity of Żuławy alluvial soils results from the course of alluvial processes. The accumulation of Vistula river sediments under high humidity conditions causes specific soil compaction and further accumulation of organic matter. The Żuławy area is considered one of the most valuable and most fertile in Poland (Orzechowski et al. 2004). The morphological

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and retention characteristics of these soils have been presented by Brandyk (1988) among others. Nearly 40% of Żuławy Wiślane is in a polder system, with each polder characterized by significant agro-hydrological integrity. Because of this fact, knowledge of soil water retention comprises important information for rational water management both in the area of a given polder as well as the entire Żuławy water system.

The aim of the studies presented in the article was the assessment of the suitability of selected pedotransfer functions for calculating the retention abilities of Żuławy Wiślane (Vistula River Delta) alluvial soils.

METHODOLOGY

Three models of pedotransfers were analyzed: van Genuchten-Wösten (van Genuchten 1980, Wösten et al. 1999), Varallyay and Mironienko (Varallyay and Mironienko 1979, Varallyay et al. 1982) and Hewelke et al. (2013).

Van Genuchten (1980) describes the $\theta(h)$ dependency in the form of a continuous function expressed by a non-linear regression formula:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha \cdot h|^n)^m}$$

where:

θ_s – saturated moisture content [$\text{cm}^3 \text{ cm}^{-3}$],

θ_r – residual moisture content [$\text{cm}^3 \text{ cm}^{-3}$],

h – soil matrix potential [cm],

$\alpha, n, m = 1 - 1/n$ – parameters of pF curve (cm^{-1}),
(–) respectively.

The values of θ_s as well as α and n can be calculated on the basis of empirical relationships provided by Wösten et al. (1999). Varallyay and Mironienko (Varallyay and Mironienko 1979, Varallyay et al. 1982) present the water retention characteristics of soil in the form of a discontinuous function expressed by the general formula:

$$\theta_{pF} = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_1 \cdot x_2 + b_4 \cdot x_1^2 + b_5 \cdot x_2^2$$

where:

θ_{pF} – soil moisture content for a respective value of the pF indicator,

$b_0, b_1, b_2, b_3, b_4, b_5$ – constant number coefficients for respective pF indicator and given soil texture classes, x_1, x_2 – variable coefficients indicating respective soil texture classes or bulk density.

The Varallyay and Mironienko's method allows for calculating soil moisture content for 9 characteristic values of the matrix potential on the basis of soil texture classes and bulk-density of soil for distinguished soil types.

The model described by Hewelke et al. (2013) comprises multiple regression equations and allows to define characteristic states of moisture content at 7 values of the matrix potential expressed by the pF indicator on the basis of a known content of selected particle fractions, bulk density and specific density of soil and organic matter content. For the value of the potential corresponding to pF=2.0 and pF=4.2 indicators, regression equations allowing for the moisture content of soil to be calculated take the form of:

$$\begin{aligned} \theta_{pF=2.0} = & (-18.7247 + 47.3855 \cdot \rho_b - 21.073 \cdot r_b^2 - \\ & 0.0855538 \cdot SPLAW + 0.000200187 \cdot SPLAW^2 \\ & - 0.00000689571 \cdot PIA^2 \cdot SPLAW + \\ & 0.0240447 \cdot \rho_p \cdot SPLAW)^2 \end{aligned}$$

$$\begin{aligned} \theta_{pF=4.2} = & (-3.87197 + 17.8961 \cdot \rho_b - 9.75799 \cdot \rho_b^2 - \\ & 0.000323457 \cdot SPLAW^2 + 0.00618455 \cdot \\ & \rho_b^2 \cdot PIA - 0.0000108911 \cdot PIA^2 \cdot SPLAW + \\ & 0.0433843 \cdot \rho_p \cdot SPLAW)^2 \end{aligned}$$

where:

r_b – bulk density, (Mg m^{-3}),

ρ_p – specific density (Mg m^{-3});

PIA – sand fraction contents for equivalent diameters 1–0.1 mm (%);

$SPLAW$ – content of particles smaller than 0.02 mm (%).

Assessment of the presented methods in terms of the possibility of applying them to calculate the water retention of alluvial soils in Żuławy Wiślane was carried out assuming the total amount of water available to plants as a criterion (total available water – TAW), comprising the difference between soil moisture content at values of pF=2.0 and pF=4.2. Based on the dataset of alluvial soils in the area of Żuławy, the statistical relationships between measured and calculated values for individual models were analysed. The studied dataset originates from 19 soil profiles of alluvial soils and covers 122 soil samples taken from various horizons. The undisturbed, standard (100 cm^3) soil samples were collected in three replicates for determination of soil water retention characteristic. Additionally the disturbed samples (bags) were collected for measure specific bulk density, particle size distributions and loss-on-ignition, which represents soil organic matter. The analyses of soil particle size distribution were conducted by Casagrande in Prószyński modification areometric method and the soil textural classes were classified according to the previous Polish Society of Soil Science (Polish Soil Classification, 1989) standard.

The retention curves were measured in the laboratory using reference methods (Klute 1986). The moisture content values in the range from 0 to 2 were determined on a sand table, whereas the amounts of water at the pF: 2.7, 3.4 and 4.2 were measured in pressure chambers.

Assessment of the possibilities of applying the analysed models to indicate total available water was carried out using regression analysis. The model is the better fitted to the empirical data the smaller the differences between the observed and calculated values. Statistical measures comprising the coefficient of determination R^2 , root mean square error S , as well as the coefficient of random variation V were applied to assess the compatibility between the measured and calculated values (Kot et al. 2011).

Coefficient of determination R^2 is a dimensionless quantity of the goodness of model fit and, in its basic form, is defined by the formula:

$$R^2 = \frac{\sum_{i=1}^n (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^n (\hat{y}_i - \bar{y})^2}$$

where:

i – number of observation,

n – total number of observations,

y_i – measured value,

$\hat{y}_i$ – calculated value,

$\bar{y}$ – average value from sample.

The coefficient of determination indicates what part of the analysed phenomenon is explained by the estimated regression equation.

Root mean square error S is defined by the formula:

$$S = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n}}$$

where:

i – number of observation,

n – total number of observations,

y_i – measured value,

$\hat{y}_i$ – calculated value.

Root mean square error informs how much the actual measured values of the variable differ on average from theoretical values obtained using the considered model.

The coefficient of random variation V indicates what of the average level of the modelled phenomenon the root mean square error comprises and is expressed by the formula:

$$V = \frac{S}{\bar{y}}$$

In connection with the above, V specifies the average error made when calculating TAW in the analysed case using a model.

RESULTS

The summarised basic soil property statistic of the dataset have been presented in Table 1. The analysed series of Vistula alluvial soils is characterized by high diversity in terms of soil texture classes. It is represented by soils ranging from sands to clay soils. The following texture classes were distinguished: sands – 23.1%, silts – 12.1%, loams – 50.9% and clays – 14.0%. The content of individual fractions in the entire population is between 4 to 95% for sand (1.0–0.1 mm), silt (0.1–0.02 mm) from 2 to 84% and clay (≤ 0.02 mm) from 3 to 89%. Analysed soil bulk density ranged from 1.21 to 1.59 Mg m⁻³, specific density from 2.34 to 2.72 Mg m⁻³ and the content of organic matter from 0.2 to 11.1%.

The values of basic statistics characterizing the analysed soil water retention properties have been presented in Table 2. At the state close to soil saturation (pF=0.4), the average value of soil moisture content amounted to about 47.5% and gradually decreased reaching permanent wilting point value (pF=4.2) at about 18.4%. In the group of sands, the majority of water occurs in macropores, which is correlated with decreasing moisture content in the scope of total water available to plants. Along with an increase in the contents of silt and clay fractions, the amount of gravitational water and, at the same time, the value of field water capacity (pF=2) increases. The coefficients of variability of the moisture content were observed to have increased (from about 12.9% to 56%) along with an increase of the potential of the soil water.

TABLE. 1. Summary statistics of basic soil properties of the dataset ($n=122$)

Statistical measure	Content of particle [%]			Specific density [Mg m ⁻³]	Bulk density [Mg m ⁻³]	Organic matter [%]
	Sand	Silt	Clay			
Mean value	39.98	22.42	37.53	2.58	1.30	4.44
Standard deviation	26.57	13.79	23.97	0.11	0.14	2.88
Minimum value	4.00	2.00	3.00	2.13	1.12	0.20
Maximum value	95.00	84.00	89.00	2.72	1.59	11.10
Coefficient of variability, CV [%]	66.46	61.51	63.85	4.26	10.76	64.86

TABLE 2. Value of basic statistics of measured volumetric moisture content θ [vol. %] of the soils at predefined values of pF

Statistical measure	$\theta_{pF=0.4}$	$\theta_{pF=1.0}$	$\theta_{pF=1.5}$	$\theta_{pF=2.0}$	$\theta_{pF=2.7}$	$\theta_{pF=3.4}$	$\theta_{pF=4.2}$
Mean value	47.51	45.59	42.26	37.78	32.16	25.60	18.39
Standard deviation	6.14	6.81	6.97	11.94	12.67	11.88	10.29
Minimum value	35.91	31.01	15.03	6.01	3.54	2.05	1.05
Maximum value	57.51	55.02	52.53	50.01	45.02	38.81	33.00
Coefficient of variability, CV [%]	12.92	14.94	21.22	31.60	39.41	46.42	55.96

Water retention curves, identified directly and calculated according to the analysed models have been presented in Figure 1, also accounting for the course of the curve optimized according to the RETC programme (van Genuchten et al. 1991). The value of parameters for the van Genuchten formula were calculated using the Wösten's equation (Wösten et al. 1999) as well as the RETC programme (van Genuchten et al. 1991) optimizing the course of the pF curve determined empirically. The characteristics

of θ_s , α and n parameters for the analysed soil population have been presented in Table 3.

Total available water (TAW) identified empirically for the entire population ranged from 6 to 33% by mean value 20.6% and coefficient of variability 30.3%. The linear relationship between measured and calculated value of TAW for each of the models have been presented in Figure 2. Coefficient of regression β for analysed relationship amounted from 0.87 to 1.14.

FIGURE 1. Water retention curves determined directly and calculated using the analysed models for: a – sandy soil and b – clay soil

TABLE 3. Value of basic statistics of parameters θ_s , α and n for van Genuchten's formula

Statistical measures	Parameter θ_s		Parameter α		Parameter n	
	Acc. to Wösten	Acc. to RETC	Acc. to Wösten	Acc. to RETC	Acc. to Wösten	Acc. to RETC
Mean value	45.43	47.50	0.0566	0.0420	1.3271	1.2555
Standard deviation	4.89	4.69	0.0091	0.0977	0.1798	0.2247
Minimum value	34.54	36.88	0.0265	0.0015	1.1515	1.0819
Maximum value	53.86	56.55	0.0757	0.9475	1.9065	2.4381
Coefficient of variability, CV [%]	10.76	9.87	16.15	237.79	13.55	17.89

FIGURE 2. Relationship between measured and calculated (by analysed models) values of total available water (TAW)

DISCUSSION

The analysis of the soil texture classes, soil bulk and specific density and content of organic matter confirm that the studied population of soil samples is characterized by significant variation of physical properties. These properties decide about the abilities of the soil to retain water and are usually applied as explanatory variables in pedotransfer functions (e.g. Trzecki 1974, 1976; Walczak 1984, Vereecken et al. 1989, Wösten et al. 1999). Significant variation in retention capacity is confirmed by the laboratory results of soil water desorption curves. In the analysed soils, the amount of water available to plants ranged

from 6% for sands to 33% for clays. The obtained results of the soil retention capacities are generally in accordance with those provided in literature regarding alluvial soils of the Vistula River Delta and indicate their significant morphological and spatial diversity (e.g. Brandyk 1988).

The courses of $\theta(h)$ functions approximate the measured course in various degrees calculated on the basis of the analysed models. Approximation of the measured curve is rather in agreement for sandy soils for all of the analyzed models. For heavier soils, these differences may be significant (Fig. 1). Comparing the α parameters (Table 3) indicates significant differences between the values calculated

TABLE 4. Statistical measures of assessing the compatibility of calculated and measured TAW values for analysed models

Statistical measure of assessment	Van Genuchten – Wösten	Varallyay – Mironienko	Hewelke et al.	Van Genuchten – RETC
Coefficient of regression (β)	1.0154	0.8695	1.1427	0.994
Coefficient of determination (R^2)	0.425	0.229	0.645	0.884
Root mean square error (S)	5.30	7.61	4.29	2.85
Coefficient of random variation (V)	0.27	0.39	0.22	0.15

according to Wösten's formula and were obtained according to the RETC programme on the basis of the measured pF curve. Based on the whole population, it can be concluded that variability of the α parameter calculated according to Wösten's formula is low and characterized by a coefficient of variability $CV=16.2\%$, while α obtained on the basis of the measured pF curve is characterized by a coefficient of variation of as much as 237.8% (Table 3). This means that the values of the $\theta(h)$ function calculated using Wösten's formula may differ significantly from values obtained on the basis of measurement. The observed situation is characteristic for empirical models, where fit to actual values is determined by the parameters of the model.

The statistical measures of assessing the compatibility between measured and calculate TAW value (Fig. 2) have been given in Table 4. The presented measures show that the highest value of R^2 for relationships between the measured and calculated TAW values were obtained for the Hewelke et al. model (2013) i.e., $R^2 = 0.645$ at $\beta = 1.143$. Van Genuchten's model with Wösten's coefficients is characterized by slightly worse fit, $R^2 = 0.425$ at $\alpha = 1.015$. If parameters identified on the basis of the measured retention curve (RETC programme) are used for the van Genuchten formula, the obtained compatibility between measured and calculated TAW values is very high, $R^2 = 0.884$ at $\beta = 0.994$. This observation is significant from the point of view of the need to discretize the retention curve in numerical solutions of flow equations in an unsaturated soil medium. Significantly poorer fit was obtained for the Varallyay model, resulting in $R^2 = 0.229$ at $\beta = 0.248$. A similar hierarchy of models is indicated by the root mean square error and coefficient of random variation. The obtained root mean square error for the Hewelke et al. as well as Genuchten-Wösten models were $S = 4.25$ and $S = 5.30$ respectively. This means that the average error of fit for these models is $V = 0.22$ and $V = 0.27$ of the average TAW value respectively. For the Varallyay model, this is significantly higher and amounts to 0.39 . The studies carried out confirm the local nature of pedotransfer function, which stems also from the influence of various factors other than

the explanatory variables accounted for in the models. Many authors (Domżał 1979, Walczak 1984, Watts and Dexter 1997, Czyż et al. 2003) highlight the significant influence of the soil management on their retention abilities. Witkowska-Walczak (2000) and Dexter et al. (2008) indicate the aggregate structure as a factor affecting retention. The amount of water available to plants may also be shaped by the contents of specified minerals and chemical properties of soils connected with them (Kabała and Muszyfaga 2015).

CONCLUSIONS

1. The analysed soils from the Delta Vistula River area (Żuławy Wiślane) comprise alluvial soils of highly diversified physical and water retention properties. The total available water content measured according to the standard laboratory methodology ranged from 6% for sands to 33% for clays.
2. The smallest error of fit for the assessment of total available water (TAW) was obtained for the Hewelke et al. model. This amounts to $V = 0.22$ with a coefficient of determination of $R^2 = 0.645$ and regression coefficient of $\beta = 1.143$.
3. An especially good fit ($R^2 = 0.994$, $\beta = 1.015$) was observed for the van Genuchten model under the condition of applying parameters identified on the basis of the measured $\theta(h)$ function (RETC model).
4. Applying pedotransfer functions may significantly limit the time and financial outlays for the assessment of total available water. On the other hand, it should be born in mind that they have a local nature, as a result of which differences in precision of retention assessment may be significant. There is a good basis for applying these functions in practice, especially at the level of research work and large-scale projects.

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Zastosowanie wybranych funkcji pedotransfer do wyznaczania retencji wodnej mad

Streszczenie: Celem badań była ocena przydatności wybranych funkcji pedotransfer do obliczania retencji wodnej mad na Żułach Wiślanych. Żuławy Wiślane stanowią ważny obszar zarówno dla produkcji rolnej, jak i z uwagi na bogactwo środowiska przyrodniczego. W analizie uwzględniono trzy modele: van Genuchtena-Wösten, Varellyaya i Mieronenki oraz Hewelke i in. Na podstawie 122 próbek glebowych pochodzących z 19 profili mad z obszaru Żuław analizowano związki statystyczne pomiędzy pomierzonymi wartościami potencjalnej retencji użytecznej a wartościami obliczonymi dla poszczególnych modeli. Przeprowadzone badania wykazały, że analizowane funkcje pedotransfer charakteryzują się różnym dopasowaniem do wyników uzyskiwanych na drodze pomiaru bezpośredniego. Najmniejsze średnie błędy dopasowania uzyskano dla modeli Hewelke i in. i van Genuchtena.

Słowa kluczowe: retencja wodna gleby, wilgotność gleby, potencjał macierzysty, całkowita woda dostępna, równanie regresji wielokrotnej