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Piotr HEWELKE[1], Edyta HEWELKE[2], Sylwester CHOŁAST[3], Stanisław ŻAKOWICZ[1], Marcin LESAK[1]

[1]Department of Environmental Improvement, [2]Water Center – Laboratory
Warsaw University of Life Sciences – SGGW
[3]Masovian Landscape Park

Assessment of the possibility of applying selected pedotransfer functions for indicating the retention of forest soils in Poland
Ocena możliwości zastosowania wybranych funkcji pedotransfer do wyznaczania retencji gleb leśnych w Polsce

Key words: soil moisture content, matrix potential, water retention, forest soils, pedotransfer functions
Słowa kluczowe: wilgotność gleby, potencjał macierzysty, retencja wodna, gleby leśne, funkcja pedotransfer

Introduction

Soil retention capacity, that is the ability to retain and store water, is a functional relationship between the matrix potential and volumetric water content (pF curve). In agricultural ecosystems, it determines the choice of crops, crop yields, and the necessary agricultural infrastructure and farming technology. In forests, it influences the formation of a given forest habitat type, floristic species composition, and type and quality of the stand of trees. It is a soil property which affects the air-to-water ratios and susceptibility of soil to draught (Boczoń, Kowalska, Dudzińska & Wróbel, 2016; Liberacki, Kozaczyk, Stachowski, & Stasik, 2016). The retention of forest soils along with so-called landscape retention influence the water balance of a catchment and the course of flooding events to a large degree. A review of literature indicates that the retention capabilities of forest soils are much less known than the retention of land used for agriculture. Taking into consideration the key role of forests in absorbing carbon dioxide and compensating for the greenhouse effect, there is good reason to take up studies building on knowledge of the topic (Paschalis-Jakubowicz, 2010). An important argument is also the fact that the forestation index in Poland is 29.4%, with forests being one of the most important natural resources. A detailed understanding of the retention properties of a forest determines maintaining its various environmental benefits and is the basis for carrying out the rational management of water (Pierzgalski, 2008).

Due to the complicated and time-consuming process of directly measuring the pF curve, it is opportune to use indirect methods, which employ relationships between the physical properties of soil and their volumetric water content. These methods are referred to as pedotransfer functions, and their usefulness, especially for large-scale projects and pilot studies, has been indicated by, i.a., Pachepsky & Rawls (2004), and Vereecken et al. (2010). Studies on pedotransfer functions were carried out by, i.a., Brooks & Corey (1964), Trzecki (1974, 1976), Gupta & Larson (1979), van Genuchten (1980), Varallyay & Mironienko (1979), Varallyay, Rajkai, Pachepsky & Shcherbakov (1982), Rawls & Brakensiek (1982), Schaap, Leij & van Genuchten (2001), Carsel & Parrish (1988), Wösten, Lilly, Nemes & Le Bas (1999), Gnatowski, Szatyłowicz, Brandyk & Kechavarzi (2010), Rezaee, Shabanpour & Davatgar (2011), Skalova, Čistý & Bezák (2011), Hewelke, Gnatowski & Żakowicz (2013) and Hewelke, Gnatowski, Hewelke, Tyszka & Żakowicz (2015). A compilation of models describing pF curves has been presented, i.a., in the works of Walczak, Witkowska-Walczak & Sławiński (2004), Żakowicz, Hewelke & Gnatowski (2009), Guber & Pachepsky (2010), and Hewelke et al. (2015). The aim of the presented research is assessing the suitability of selected pedotransfer functions for indicating the retention abilities of forest soils.

Material and methods

The work analyzed three models of pedotransfer functions. The first model, described by Hewelke et al. (2015), was designed for podzolic and brown soils found in Poland beneath pine and spruce stands. The prepared multiple regression equations make it possible to predict the characteristic states of volumetric water content with seven values of the matric potential expressed by the pF indicator, on the basis of known predefined bulk density of soil, specific density, and contents of organic matter and selected particle fractions. For values of potential pF = 2 and pF = 4.2, regression equations which make it possible to calculate the water content (θ) of soil take the form of:

$$\theta_{pF=2.0} = -87.9967 + 122.001 \cdot \rho_b - 213.517 \cdot \log(\rho_b) + 1.63628 \cdot \log(\rho_b) \cdot S_{pl} \quad (1)$$

$$\theta_{pF=4.2} = 9.55007 - 0.0551704 \cdot S_a \cdot \rho_b + 0.26058 \cdot S_i \cdot \rho_b - 0.180619 \cdot S_i \cdot \rho_p + 0.0149768 \cdot S_i \cdot C_{org} \quad (2)$$

where:

ρ_b – bulk density [g·cm^{-3}];

S_{pl} – content of particles smaller than 0.02 mm [%];

S_a – sand fraction content for equivalent diameters from 1 to 0.1 mm [%];

S_i – silt fraction content for equivalent diameters from 0.1 to 0.02 mm [%];

ρ_p – specific density [g·cm^{-3}];

C_{org} – organic matter content [%];

The second analyzed model, also a point pedotransfer function, was designed by Varallyay and Mironienko (1979). The prediction of volumetric water content for nine values of the matrix potential of soil expressed by the pF indicator requires familiarity with the granulometric composition and bulk density of soil. Water content (θ) for a specified value of the pF indicator is determined using the following general formula:

$$\theta_{pF} = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_1 \cdot x_2 + b_4 \cdot x_1^2 + b_5 \cdot x_2^2 \quad (3)$$

where:
b_0, b_1, b_2, b_3, b_4, b_5 – constant number coefficients for each group of soil and value of pF;
x_1, x_2 – variable coefficients, indicating respective properties of soil (soil texture classes and bulk density).

Three characteristic groups of soils are distinguished in this method. The group is identified by comparing the calculated porosity values with the actual value (Żakowicz et al., 2009).

Van Genuchten (1980) proposes a continuous pedotransfer function in the form of a non-linear regression equation:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha \cdot h|^n)^m} \quad (4)$$

where:
h – soil water pressure [cm];
θ_r – residual water content [cm^3 cm^{-3}];
θ_s – volumetric water content in a state of full saturation [cm^3 cm^{-3}],
α, n, $m = 1 - 1 / n$ – shape parameters of the pF curve respectively [cm^{-1}], [-], [-].

Empirical relationships facilitating the assessment of θs values as well as the parameters of the shape of the pF curve, α and n, were developed by Wösten et al. (1999). The authors assumed that the parameters of the van Genuchten's function (4) are statistically dependant on the content of ø < 50 μm fraction, as well as organic matter content (Żakowicz et al., 2009).

The assessment of the methods was carried out accepting the total amount of water available to plants (total available water – TAW), which is the difference between the volumetric water content of the soil at values of pF = 2.0 and pF = 4.2, as the criterion. In order to indicate retention curves, standard methodology of sand boxes and pressure chambers was applied (Klute, 1986). Statistical relationships between the measured values and those calculated according to the individual models were analyzed.

Results and discussion

Forest soils comprising the population used to develop the regression model (Hewelke et al., 2015) are characterized by statistical measures presented in Table 1. The obtained values of the spread, that is of the differences between maximal and minimal values, as well as the values of the coefficient of variation characterizing dispersion, indicate the diversity of the analyzed soils in terms of their retention properties. For verification of the regression equations, the TAW values were determined using the direct method as well as calculated according to the model. Linear regression analysis (Fig. 1)

TABLE 1. Basic statistics for measured volumetric moisture content of soil at predefined values of pF
TABELA 1. Wartości podstawowych miar statystycznych dla pomierzonych wartości wilgotności gleby przy zadanych wartościach pF

Statistics measures Miary statystyczne	Measured volumetric moisture contents at predefined values of pF Wartości pomierzone charakterystycznych stanów uwilgotnienia krzywej pF						
	θ_pF = 0.4	θ_pF = 1.0	θ_pF = 1.5	θ_pF = 2.0	θ_pF = 2.7	θ_pF = 3.4	θ_pF = 4.2
x_s [%]	45.47	40.85	35.52	18.57	12.59	8.39	3.02
σ [%]	6.86	7.18	8.03	11.39	10.28	6.83	2.09
min [%]	33.50	26.40	16.21	4.61	1.00	0.71	0.40
max [%]	62.20	56.80	51.70	42.41	35.42	23.50	8.10
CV [%]	15.09	17.58	22.61	61.34	81.65	81.41	69.21

x_s – average value, wartość średnia; σ – standard deviation, odchylenie standardowe; min – minimum value, wartość minimalna; max – maximum value, wartość maksymalna; *CV* – coefficient of variability, współczynnik zmienności.

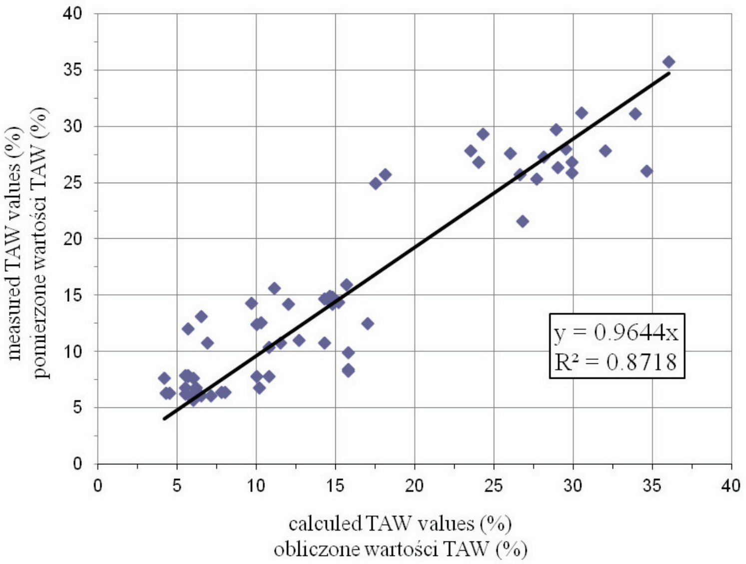

FIGURE 1. Measured and calculated values of total available water (TAW)
RYSUNEK 1. Pomierzone i obliczone wartości potencjalnej retencji użytecznej (TAW)

indicated that the coefficient of the slope of the linear relationship between the calculated and measured TAW values was 0.964. The coefficient of determination (R^2) for the prepared dependency was 0.872.

The goodness of the fit is quantified by many authors (Donatelli, Wösten & Belocchi, 2004; Dexter, Czyż, Richard & Reszkowska, 2008; Vereecken et al., 2010) in terms of the mean error and the root mean squared error. The mean error (*ME*) is defined as:

$$ME = \frac{1}{N}\sum_{i=1}^{i=N}\left|E_i - M_i\right| \quad (5)$$

where:
N – the number of differences between E_i and M_i;
E_i – the estimated value;
M_i – the measured value.

The root mean squared error (*RMSE*) is defined as:

$$RMSE = \sqrt{\frac{1}{N}(E_i - M_i)^2} \quad (6)$$

In the analyzed case, the values of *ME* and *RMSE* are 2.31 and 2.68 mm, respectively. Such an accuracy is fully acceptable for pilot studies and large-scale projects.

The usefulness of the analyzed regression equations was also assessed using an independent population of data, covering 41 forest soils with the mechanical composition of loose sand, slightly loamy sand, slightly loamy silty sand, heavy loamy sand and light loam, from other locations (Masovian Landscape Park Complex). The values of the basic statistical measures for the measured values of volumetric water content of soil at predefined values of pF for the independent population have been provided in Table 2. Spread analysis and variation coefficients indicate more variation in the retention properties of the independent series. Dependencies between the calculated and measured values of potential useful retention for this series have been shown in Figure 2. The obtained slope coefficient of the linear relationship between measured and calculated values was 1.075, while the coefficient of determination R^2 = 0.853. The significance of the intercept (1.4109) analyzed using Student's t-test was not confirmed. The results obtained for the independent series indicate the possibility of applying the developed formulas for determining the retention of forest soils characterized by properties similar to those of the analyzed soils.

In order to assess the possibility of applying van Genuchten's and Varallayay's models for calculating the retention capacity of forest soils, an independ-

TABLE 2. Basic statistics for measured volumetric moisture content of soil at predefined values of pF for independent population
TABELA 2. Wartości podstawowych miar statystycznych dla pomierzonych wartości wilgotności gleby przy zadanych wartościach pF dla serii niezależnej

Statistics measures Miary statystyczne	Measured volumetric moisture contents at predefined values of pF Wartości pomierzone charakterystycznych stanów uwilgotnienia krzywej pF						
	θ_pF = 0.4	θ_pF = 1.0	θ_pF = 1.5	θ_pF = 2.0	θ_pF = 2.7	θ_pF = 3.4	θ_pF = 4.2
x_s [%]	40.16	37.37	27.12	17.67	13.07	9.97	7.37
σ [%]	7.92	8.38	13.53	15.48	14.11	11.09	7.78
min [%]	27.59	26.63	9.34	1.69	0.97	0.66	0.35
max [%]	57.50	55.00	52.00	48.20	42.00	34.00	24.50
CV [%]	19.71	22.41	48.88	87.62	107.91	111.25	106.00

x_s – average value, wartość średnia; σ – standard deviation, odchylenie standardowe; min – minimum value, wartość minimalna; max – maximum value, wartość maksymalna; *CV* – coefficient of variability, współczynnik zmienności.

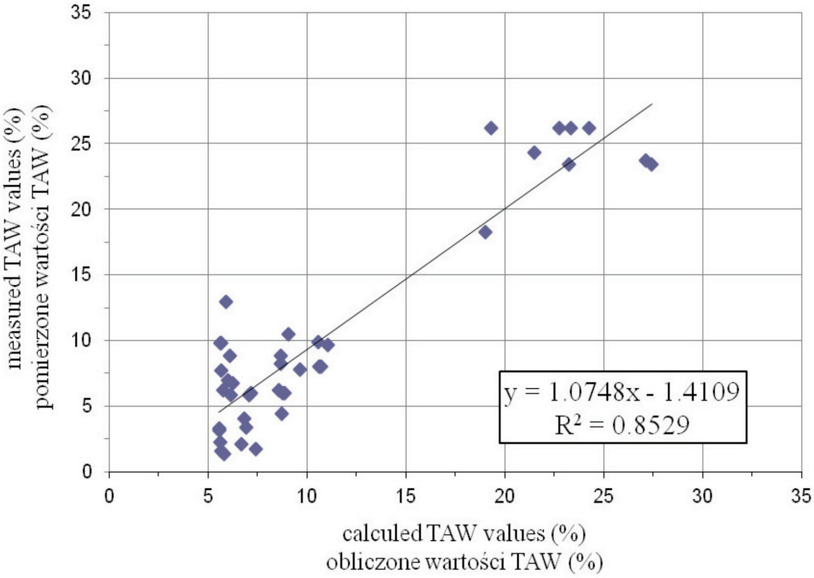

FIGURE 2. Measured and calculated values of total available water (TAW) for independent population

RYSUNEK 2. Pomierzone i obliczone wartości potencjalnej retencji użytecznej (TAW) dla populacji niezależnej

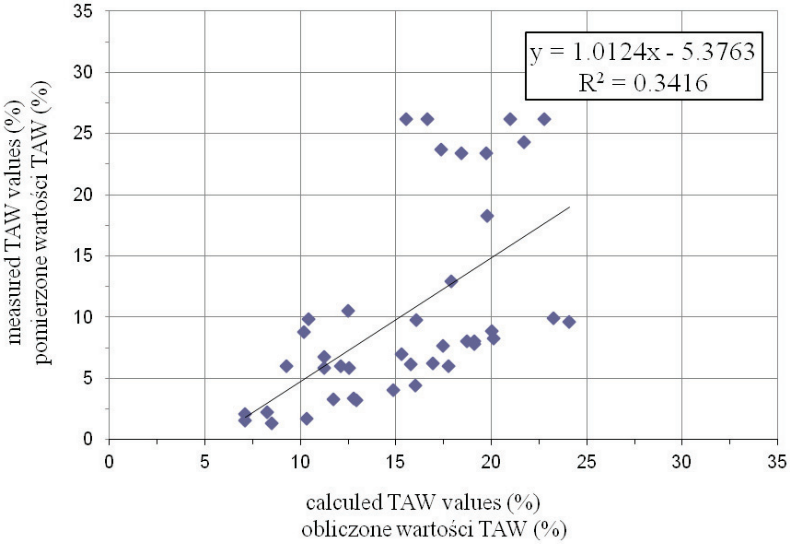

FIGURE 3. Measured and calculated values TAW for analysed forest soils by van Genuchten's model

RYSUNEK 3. Obliczone i pomierzone wartości TAW dla analizowanych gleb leśnych według modelu van Genuchtena ent measurement series identical to that of the regression model (Hewelke et al., 2015) was used. For the linear dependency between the measured values of TAW and those calculated according to van Genuchten's model (Fig. 3), the determination coefficient of R^2 = 0.3416 was obtained, as well as a stastically significant intercept equal to –5.3763. In the case of Varallyay's and Mironienko's model (Fig. 4), a higher value of the determination coefficient was obtained, i.e. R^2 = 0.7004, whereas the intercept reached the value of as much as –20.872, accompanied by a very high slope coefficient of the analyzed linear relationship, equal to 1.9482. The obtained results indicate that the analyzed models devised for soils used for agricultural purposes do not appropriately describe the retention properties of the analyzed forest soils. The specific properties of forest soils as compared to soils used for agricultural purposes have been pointed out many authors, who emphasize their lower density, higher stability of aggregates and macroporosity, as well as higher hydraulic conductivity (i.a. Fisher & Binkley, 2000). Wahren, Feger, Schwärzel & Münch (2009) observed higher field capacity of soils adjecent to forests than in comparable soils used for agricultural surfaces. Hydraulic conductivity in the saturated zone and at field capacity in soils of forest habitats was up to four times higher than in the case of agricultural soils. Nussbaum, Papritz, Zimmermann & Walthert (2016) indicate a significant role of organic matter content in shaping volumetric density of forest soils. The necessity of accounting for the specifics of forest soils in pedotransfer functions has been indicated by Vereecken, Maes, Feyen & Darius (1989), Teepe,

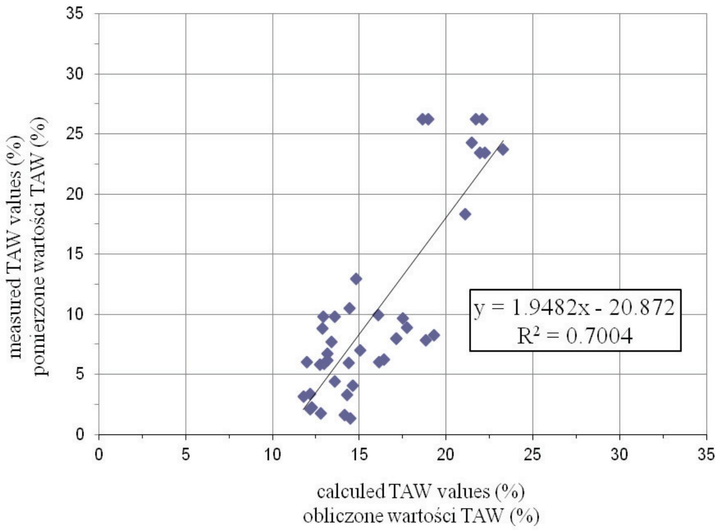

FIGURE 4. Measured and calculated values TAW for analysed forest soils by Varallyay's and Mironienko's model
RYSUNEK 4. Obliczone i pomierzone wartości TAW dla analizowanych gleb leśnych według modelu Varallyaya i Mironienki

Dilling & Beese (2003), and Puhlman & von Wilpert (2012).

Conclusions

1. The analysis of relationships between the measured values of total available water of forest soils carried out both for the inside series (R^2 = 0.872 and slope coefficient 0.904), as well as the independent series (R^2 = 0.853 and slope 1.075) confirms good fit of the model.

2. The hypothesis regarding the possibility of applying van Genuchten's and Wösten's as well as Varallyay's and Mironienko's models intended for arable soils for determining the retention of forest soils, verified on the basis of a series number n = 41 has been not confirmed statistically.

3. The carried out studies confirm the local nature of pedotransfer functions and indicate the need for their further development, especially regards to soils from forested areas.

Summary

Assessment of the possibility of applying selected pedotransfer functions for indicating the retention of forest soils in Poland. Landscape retention influences the water balance of a catchment and the course of flooding events. The degree of retention capabilities of forest soils are much less known than the retention of land used for agriculture. Soil retention capacity influences the formation of a given forest habitat type, floristic species composition, as well as the type and quality of the stand of trees. The analysis was carried out for a regression model dedicated to selected forest soils within the area of Poland, as well as van Genuchten's and Wösten's, and Varallyay's and Mironienko's models. In order to assess the fit of the models, an independent series of forest soils were used. The models prepared for soils used for agricultural purposes do not result in statistically acceptable fit when it comes to the analyzed forest soils. The analysis of measured and calculated values of total available water indicate good fit of the regression model developed for the analyzed group of podzolic and brown forest soils.

Streszczenie

Ocena możliwości zastosowania wybranych funkcji pedotransfer do wyznaczania retencji gleb leśnych w Polsce. Retencja gleb leśnych w znacznym stopniu decyduje o bilansie wodnym zlewni i przebiegu zjawisk hydrologicznych, wpływa na kształtowanie się określonego typu siedliska lasu, skład florystyczny i jakość drzewostanu. Zdolności retencyjne gleb leśnych są znacznie mniej rozpoznane niż retencja gleb użytkowanych rolniczo. Retencja może być wyznaczona zarówno metodą bezpośrednią, jak i pośrednio za pomocą tzw. funkcji pedotransfer opisującej jej związek z określonymi właściwościami fizycznymi gleby. Analizę prowadzono dla modelu regresyjnego opracowanego dla wybranych gleb leśnych z obszaru Polski oraz dla modeli van Genuchtena i Wöstena oraz Varallyaya i Mironienki. Do oceny dopasowania modeli zastosowano niezależną serię gleb leśnych. Analiza pomierzonych i obliczonych wartości potencjalnej retencji użytecznej wskazuje na dobre dopasowanie modelu regresyjnego opracowanego dla badanej grupy gleb leśnych bielicowych i brunatnych. Modele opracowane dla gleb użytkowanych rolniczo nie dają akceptowalnego statystycznie dopasowania dla analizowanych gleb leśnych. Przeprowadzone badania potwierdzają lokalny charakter funkcji pedotransfer.

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Author's addresses:
Piotr Hewelke, Edyta Hewelke,
Stanisław Żakowicz, Marcin Lesak
Szkoła Główna Gospodarstwa Wiejskiego
Wydział Budownictwa i Inżynierii Środowiska
Katedra Kształtowania Środowiska
ul. Nowoursynowska 159, 02-787 Warszawa
Poland
e-mail: piotr_hewelke@sggw.pl
edyta_hewelke@sggw.pl
stanislaw_zakowicz@sggw.pl

Sylwester Chołast
Mazowiecki Park Krajobrazowy
ul. Sułkowskiego 11, 05-400 Otwock
Poland