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Soil water retention and unsaturated hydraulic conductivity of heavy-textured Mollic Gleysol measured using the evaporation method

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Abstract

The knowledge of soil hydraulic properties is essential for describing and predicting water and solute transport processes in the soil. This study aimed to determine both the hydraulic conductivity function and the water retention characteristic for different layers of Mollic Gleysol using the evaporation method, with the goal of utilizing these findings for modelling water and solute transport. Measurements of soil water retention and unsaturated water conductivity by the evaporation method were performed for four characteristic layers of the heavy-textured Mollic Gleysol soil profile located in the south-western part of the Sępopol Lowland (Poland). Based on the data recorded in the experiment, the water retention and unsaturated hydraulic conductivity curves were measured. The parameters of the van Genuchten and van Genuchten-Mualem functions were determined using Microsoft Excel software. This involved simultaneous optimization of parameters related to soil water retention (θ_r, α, n) and unsaturated water conductivity (α, n, K_s, and L). Elaborated parameters of the van Genuchten equation, based on evaporation method measurements, reproduce the measured characteristics of the retention curves correctly. The optimised hydraulic conductivity characteristics also demonstrate the effectiveness of the van Genuchten-Mualem equation in describing unsaturated water conductivity. The provided methodology is suitable for determining the parameters of the van Genuchten and van Genuchten-Mualem functions for mathematical modelling of water and solute transport in heavy-textured Mollic Gleysols.

1. Introduction

The ability of soils to retain and conduct water is of considerable importance in water management issues in both agricultural and urban areas. The infiltration of water into the soil, the movement of water to plant roots, the inflow of water into drainage networks and wells, and the evaporation of water are just some of the important phenomena in which the rate of water movement plays a significant role. The soil water retention capacity determines the amount of water available to plants and mitigates the effects of droughts and excessive rainfall. The water retention and unsaturated hydraulic conductivity functions are essential for modeling water and solute transport in unsaturated soils using the Richards equation (Peters and Durner, 2008). The sandbox and pressure plate apparatus are common procedures for measuring water retention characteristics in many laboratories (Klute, 1986). For quantifying unsaturated hydraulic properties, different (steady and unsteady-state) field and laboratory methods are used (Klute and Dirksen, 1986). Steady-state methods include head control and flux control, whereas unsteady methods are represented by Bruce-Klute absorption, sorptivity, instantaneous profile, as well as inverse methods like one-step and multi-step outflow (Klute and Dirksen, 1986; Benson and Gribb, 1997; Szejba et al., 2013). Most of the mentioned methods are costly and time-consuming. One relatively simple method for determining both unsaturated hydraulic conductivity and soil water retention is the evaporation method (Šimůnek et al., 1998). This method is related to Wind's (1966) research, which enables the simultaneous calculation of unsaturated hydraulic conductivity and the water-retention function (Schindler et al., 2010). The evaporation method is based on measurements of water loss from the soil sample and simultaneous readings from the tensiometer. This type of experiment is conducted using different numbers of tensiometers at various heights (Halbertsma and Veerman, 1994; Wessolek et al., 1994; Šimůnek et al., 1998; Schindler and Müller, 2006).

The term 'heavy soil' refers to soil with a high clay content, characterised by highly cohesive properties and being difficult and power-consuming to cultivate. This kind of soil often has low drainable porosity, which in this case led to rapid waterlogging in the crop root zone when excess water was introduced. The productive value of the soil layer used by plant roots for crop production depends on how well optimum conditions for root growth have been achieved (Łachacz et al., 2017). The topsoil layer forms the matrix of the pore space through which roots penetrate, and through which water, air and nutrients are supplied to the roots. In addition, most heavy soils have a very low bearing capacity when wet, so mechanised agriculture is often impossible until the moisture content of the topsoil falls below field capacity. Knowledge of soil hydraulic properties is important for describing and predicting water and solute transport processes. The hydraulic conductivity function and the water retention characteristic, which are the two main soil hydraulic properties, are strongly influenced by soil structure and, with decreasing water content, increasingly influenced by soil texture (Douglas et al., 1980; Wendroth et al., 1993; Spoor and Leeds-Harrison, 1999; Kaźmierowski et al., 2006; Usowicz et al., 2024).

This study aimed to determine both the hydraulic conductivity function and the water retention characteristic for four different layers of Mollic Gleysol using the evaporation method, with the goal of utilizing these findings for modelling water and solute transport in future research.

2. Materials and methods

Soil samples were collected from the soil profile in an experimental site located north of Lidzbark Warmiński (54°08’ N, 20°35’ E), Warmińsko-Mazurskie voivodeship, Poland (Fig. 1a). This site is located in the south-western part of the Sępopol Lowland (Solon et al., 2018). In the study region, the average annual air temperature is 7.1°C, and the average annual precipitation sum is 624 mm. The highest amount of rainfall is usually observed in July and August. The growing period lasts about 200 days. The snow cover occurs during 60–65 days (Nowicka et al., 1994). The studied area is characterized by slightly undulating land without signs of erosional processes (Fig. 1b), and the soils are drained by a tile drainage system with an average drain spacing of 21 m and a drain depth of 0.9 m (Szejba et al., 2009; Szejba et al., 2016). The surface soil materials were formed during the Pomeranian phase of Vistulian Glaciation, and represent areas of ice-dammed lake origin. In the site studied, glaciolimnic deposits, known as clay-loam sediments, prevail. These deposits are greasy, shiny, compacted, and of dark brown colour (Orzechowski et al., 2022). The main component of the deposits is illite mixed accompanied by illite-smectite clay minerals. The clay-loam sediments differ from typical Pomeranian glacial till and typical limnic material of the same age (Długosz et al., 2009). Soils developed from such sediments belong to the group with the highest clay content in Poland. The soils demonstrate low water permeability and stagnic and vertic properties (IUSS Working Group WRB, 2022). Due to their specific properties, these soils were primarily used for grazing; however, more and more areas are now being cultivated. Winter wheat (*Triticum* L.), winter oilseed rape (*Brassica napus* L. *var. oleifera* Metzger.), sugar beet (*Beta vulgaris* L. *var. sachariferea*) and maize (*Zea mays* L.) are grown on them (Orzechowski et al., 2020). The soil studied was classified in the Polish Soil Classification (Kabała et al., 2019) as typical stagnosol (drained) and within the WRB soil classification system (IUSS Working Group WRB, 2022) as a Mollic Gleysol (Loamic, Drainic, Protovertic).

Soil material was collected from four layers of a representative soil profile for laboratory tests (Fig. 1c). In the laboratory of the Department of Soil Science and Microbiology (UWM Olsztyn), the soil samples were air-dried and sieved through a 2 mm sieve. In the earth fractions (∅ smaller than 2 mm), the following analyses were carried out to determine general soil properties:

– texture by the pipette method with an Eijkelkamp pipette apparatus of NEN 5753 and ISO 11277 standards;

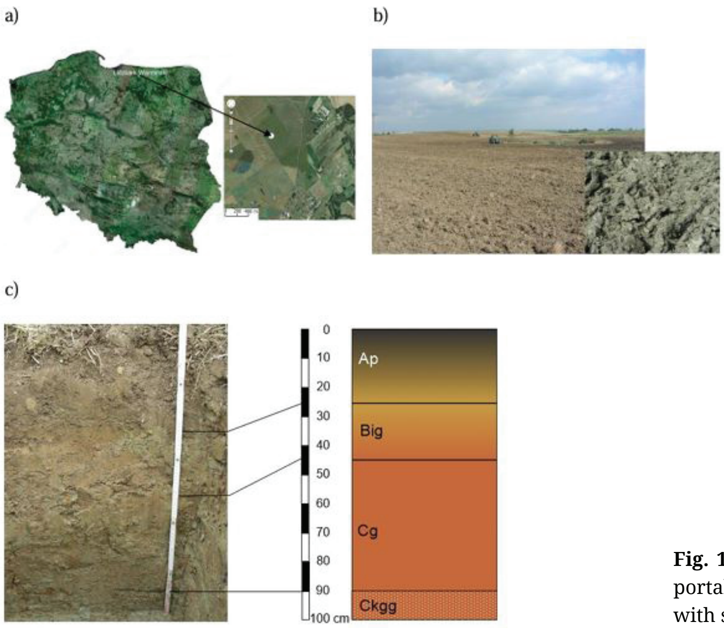

Fig. 1. Lidzbark Warmiński experimental site localization (https://mapy.geoportal.gov.pl; https://www.google.pl/maps) (a), the landscape of the study site with soil surface (b), profile of the examined soil (c)

- content of calcium carbonate by the Scheibler volumetric method (van Reeuwijk, 2002);
- soil reaction (pH) by the potentiometric method in 1 mol dm^{-3} KCl and distilled water (soil-to-solution ratio of 1:2.5);
- content of organic carbon and total nitrogen using a CN dry combustion analyser VarioMax Cube Elementar (Elementar Analysensysteme GmbH).

Laboratory measurements of soil moisture retention and unsaturated hydraulic conductivity were performed for four characteristic layers (10–20 cm, 30–40 cm, 70–80 cm, and 90–100 cm) of the soil profile. They were carried out in the Department of Environmental Development and Remote Sensing Laboratory (Warsaw University of Life Sciences). Undisturbed soil samples were collected into measuring cylinders with a diameter of 7.05 cm and a height of 4.4 cm. Then, using porous plates, they were saturated to full water capacity. Tensiometers were installed at two elevations: 1.1 cm and 3.3 cm, which were connected to transducers, enabling the measurement of the pressure head. When the samples reached equilibrium, they were placed on a scale with a measurement accuracy of 0.01 g (Fig. 2a). The readings of pressure head and water loss from the soil samples were made possible by connecting the scale and reading device to a computer. Tests were conducted until the pressure head at the upper tensiometer (1.1 cm) reached 700 cm. Laboratory measurements were conducted for a single representative sample for each depth.

The average pressure head value (calculated from a reading of two tensiometers) and volumetric moisture content (calculated from the measured mass of the soil sample) were determined for each time step according to the procedure described by Wendroth and Wypler (2008). This data was used to construct the soil water retention curve (pF curve), which was utilized to determine the soil moisture content at the upper and lower locations of the tensiometers at each time step. Assuming that the moisture content has a linear distribution along the depth of the soil column (Fig. 2b), the water flux density in the compartment between the two tensiometers can be calculated using the following formula:

$$q = \frac{q_1 + q_2}{2} \tag{1}$$

where:

q – the water flux density between the two tensiometers (cm h^{-1}),
q_1 – the water flux density across the 3.3 cm boundary equal to the change in soil water storage (ΔS_a) per unit area and time (t) at a depth between 3.3 and 4.4 (cm h^{-1}),
q_2 – the water flux density across the 1.1 cm boundary equal to the change in soil water storage ($\Delta S_a + \Delta S_b + \Delta S_c$) for a unit area in time (t) at a depth between 1.1 and 4.4 (cm h^{-1}).

The average change of water storage in a compartment with thickness Δz = 1.1 cm was computed from the water content change ($\Delta\theta$) during a time step (Δt) (i.e., between two successive collections of tensiometer readings and corresponding column weights) according to the formula:

$$\Delta S = \Delta\theta \, \Delta z \tag{2}$$

The values of soil moisture content changes at depths of 1.1 and 3.3 cm were determined based on the measurement of the pressure head and the estimated moisture retention curve. Soil moisture content change values were linearly interpolated for calculating ΔS_b and ΔS_c and extrapolated ΔS_a (Fig. 2b). The water flux density was calculated using the following formula (Wendroth et al., 1993):

$$q = \frac{\Delta S_a + (\Delta S_a + \Delta S_b + \Delta S_c)}{2\Delta t} = \frac{(3.5\Delta\theta_{3.3} + 0.5\Delta\theta_{1.1})\Delta z}{2\Delta t} \tag{3}$$

a) b)

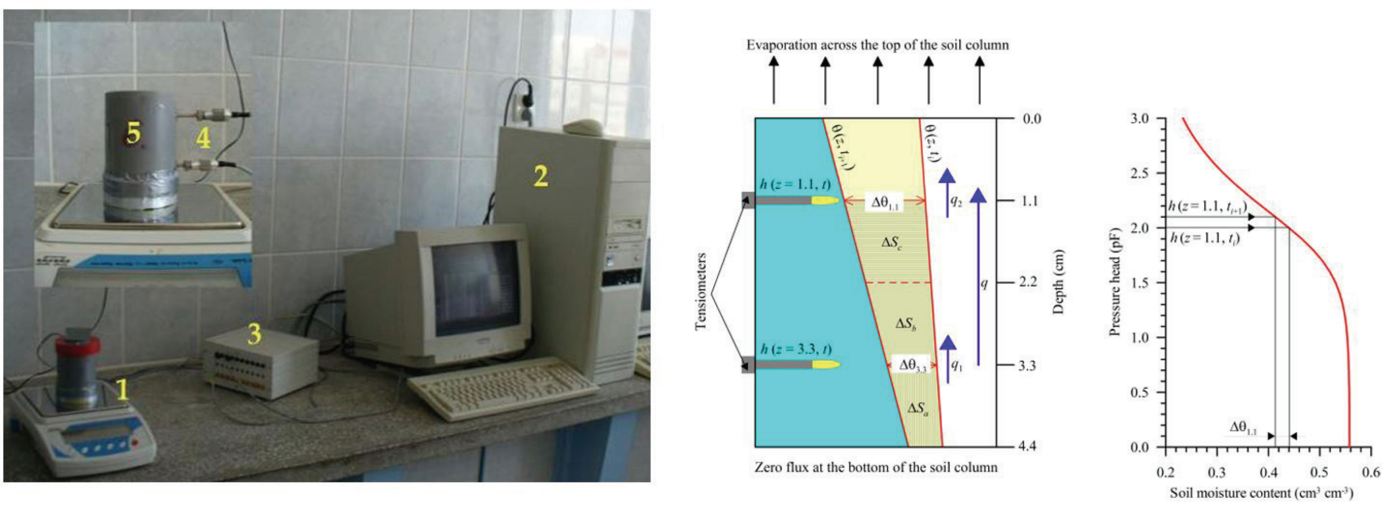

Fig. 2. Laboratory experimental setup for the measurement of soil water retention curve and unsaturated hydraulic conductivity (a, where: 1 – scale, 2 – computer, 3 – pressure head recorder, 4 – two tensiometers, 5 – soil core), and water flux calculation scheme for evaporation method (b, explanation of symbols in the text)

Once the water flux density and hydraulic gradient (arithmetically averaged for each particular time interval) were determined, the value of unsaturated water conductivity was calculated from the formula:

$$K(h_{av}) = -\frac{q}{\left.\frac{dh}{dz}\right|_{3.3}^{1.1} + 1} \quad (4)$$

where:
K – hydraulic conductivity (cm h^{-1}),
q – the water flux density between the two tensiometers (cm h^{-1}),
h – pressure head (cm),
z – depth coordinate (cm).

Corresponding h_{av} values for the $K(h_{av})$ relationship were calculated from:

$$h_{av} = \frac{h_{i,-1.1} + h_{i+1,-1.1} + h_{i,-3.3} + h_{i+1,-3,3}}{4} \quad (5)$$

where $h_{i,z}$ denote the measured pressure head at time i and depth z.

Based on the measurements of soil water retention and hydraulic conductivity curves, the van Genuchten-Mualem function parameters were estimated (van Genuchten, 1980). The description of the soil water retention function is as follows:

$$\theta = \theta_r + (\theta_s - \theta_r)(1 + |\alpha h|^n)^{-m} \quad (6)$$

where:
θ_r – residual soil water content (cm^3 cm^{-3}),
θ_s – saturated soil water content (cm^3 cm^{-3}),
α – parameter (cm^{-1}),
n, m – dimensionless parameters, where $m = 1-1/n$,
h – pressure head (cm).

The following relationship expresses the parametric description of the water conductivity curve (Mualem, 1978):

$$K(h) = K_s \frac{\{[1 + |\alpha h|^n]^m - |\alpha h|^{n-1}\}^2}{[1 + |\alpha h|^n]^{m(L+2)}} \quad (7)$$

where:
K_s – saturated hydraulic conductivity (cm d^{-1}),
L – dimensionless parameter.

Parameters of functions (6) and (7) were determined using Microsoft Excel software. This involved simultaneous optimisation of parameters related to water retention (θ_r, α, n) and unsaturated water conductivity (K_s, L). The optimisation was performed according to the objective function expressed as follows:

$$O(b) = \sum_{i=1}^{N_1} \{w_i[\theta_o(h_i) - \theta_c(b, h_i)]\}^2 + \sum_{i=N_1+1}^{N_2} \{w_i W_1 W_2 [K_o(h_i) - K_c(b, h_i)]\}^2 \rightarrow min \quad (8)$$

where:
b – vector of optimal parameter values: $b = (\theta_r, \alpha, n, K_s, L)$,
θ_o, θ_c – observed and calculated values of soil moisture content (cm^3 cm^{-3}),
K_o, K_c – observed and calculated values of total water outflow from the sample (cm d^{-1}),
w_i, W_1, W_2 – weight coefficients,
N_1, N_2 – number of measurements of moisture content and hydraulic conductivity, respectively.

As proposed by van Genuchten et al. (1991), the value of (w_i) is usually equal to 1 due to the lack of sufficiently detailed information on the impact of a single observation on the optimisation results of the parameter vector (b). The value of the W_1 weight coefficient included in equation (8) provides additional flexibility in assigning weights to the water content data compared to the water conductivity data. This weight ranges from 0.1 to 1.0 (Wösten and van Genuchten, 1988), indicating a reduction in the influence of water conductivity data on the optimization results of the vector parameters (b). The value of the W_2 parameter serves as a proportionality coefficient between two different sets of data used in the optimisation procedure and can be expressed as:

$$W_2 = \frac{(N_2 - N_1)\sum_{i=1}^{N_1} w_i \theta_i}{N_1 \sum_{i=N_{1+1}}^{N_2} w_i K_o(h)} \quad (9)$$

where symbols are as in the equation (8).

3. Results and discussion

The results of measurements of the physical and chemical properties of the characteristic soil horizons are shown in Tables 1 and 2, respectively. The distinct soil horizons differ in their granulometric composition. The Big horizon is characterised by the highest clay fraction content (over 56%), while the clay fraction in horizon Cgg does not exceed 40%, and in horizons Ap and Cg is slightly less than 30%. According to the PTG classification (2009), soil material in the Big horizon can be classified as very heavy, while soils from the other horizons are classified as heavy soils. The soil is characterised by a high organic carbon content, particularly the Ap horizon, where the content exceeds 21 g kg^{-1}. All soil horizons (except Ckgg) are characterised by slightly acidic pH. The Ckgg horizon is slightly alkaline due to the presence of $CaCO_3$.

Results of measured pressure heads as a function of time for the analysed layers of the soil profile are shown in Fig. 3. The values of matrix potentials at a depth of 1.1 cm are characterized by quite high dynamics of changes over time (Fig. 3a). In a soil material from a layer of 90–100 cm (CL), a pressure value of 700 cm of water column was recorded after approximately 16 hours. At a depth of 3.3 cm, the measured values of pressure head did not generally exceed 200 cm, except in the case of 30–40 cm layer (C), where after 16 hours a sharp increase in the value of the matrix potential was observed (Fig. 3b). This is probably due to the fact that during the experiments, cracks were formed

Table 1
Particle-size distribution of the examined soil horizons

Depth	Soil horizon*	Percentage of particle size (mm)				Texture class**
cm		>2.0	2.0–0.05	0.05–0.002	<0.002	
0–26	Ap	0.0	39.0	34.0	27.0	L – loam
26–45	Big	0.0	13.9	29.6	56.5	C – clay
45–90	Cg	0.0	45.0	25,7	29.3	SCL – sandy clay loam
90–150	Ckgg	0.0	38.6	22.2	39.2	CL – clay loam

* – according to Polish Soil Classification (2019)
** – according to USDA (Glossary of Soil Science Terms, 1997)

Table 2
Selected chemical properties of the examined soil horizons

Depth	Soil horizon	pH		$CaCO_3$	$C_{org.}$	N_t	C:N
cm		H_2O	KCl	(%)	(g kg^{-1})	(g kg^{-1})	
0–26	Ap	6.2	5.4	0.0	21.3	2.20	9.7
26–45	Big	5.2	4.0	0.0	5.6	0.70	8.3
45–90	Cg	5.6	4.0	0.0	2.2	0.30	7.3
90–150	Ckgg	8.0	6.5	1.3	2.2	0.35	6.3

on the surface of the soil sample and one of them reached a depth of 3.3 cm. This could result in increased access to soil air at the measurement plane where the lower tensiometer was installed. The water flux density data used to determine the unsaturated hydraulic conductivity are shown in Fig. 3c. Temporal changes in the water flux density value are characterized by quite a large scatter around the average value in layers 10–20 (L) and 30–40 cm (C). For the lower-lying soil materials, the flow measures are homogeneous and close to the average value, which is approximately 1.3 mm d^{-1}. For the soil samples taken from the 30–40 cm layer (C), in the final phase of the experiment (t > 16 h), a clear increase in the water flux density is observed. This is likely due to the formation of cracks, which are clearly visible in the pressure head time distribution (Fig. 3b).

Measured and fitted using the van Genuchten formula (6), the soil water retention characteristics are presented in Fig. 4, and the values of the equation parameters are listed in Table 3. As shown in Fig. 4, the values of the determination coefficients (r^2), which measure the quality of fit between the calculated and measured data, are close to 1. This, therefore, confirms the predictive ability of the van Genuchten function to describe the pF curve. The measured and fitted relationships between the pressure head and unsaturated hydraulic conductivity of the analysed soil layers, as shown in Fig. 5, were used to fit equation (7). The values of the equation parameters are listed in Table 3.

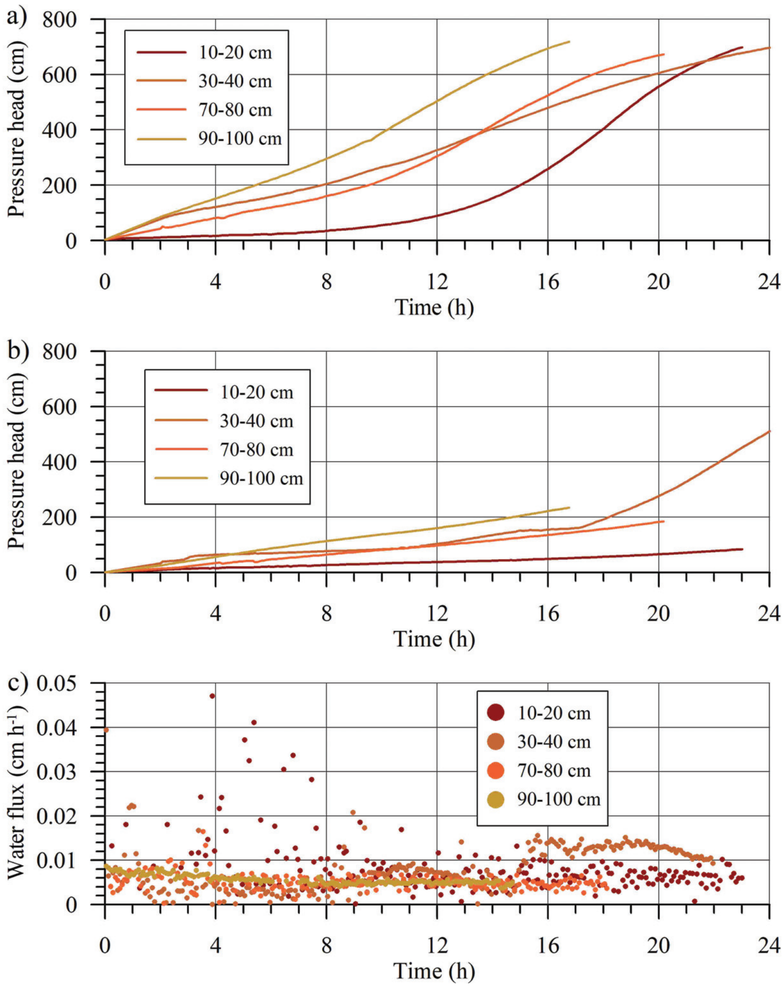

Fig. 3. Values of measured pressure heads for the analyzed soil layers: at the depth of 1.1 cm (a); at the depth of 3.3 cm (b) and the water flux density at the depth of 2.2 cm (c)

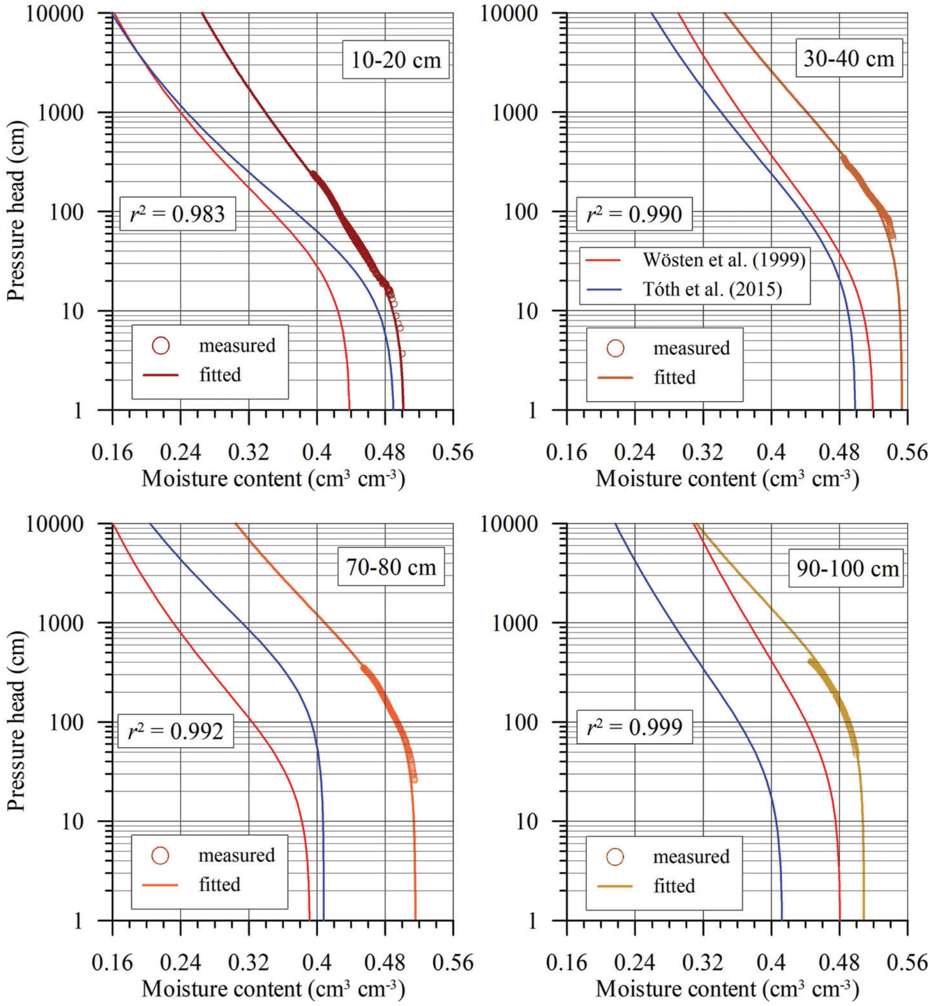

Fig. 4. The measured and optimized soil water retention characteristics for analyzed soil layers together with characteristics of the water retention of soils developed as class pedotransfer functions by Wöstenet al. (1999) and Tóth et al. (2015)

Table 3
The water retention and conductivity functions parameters of the examined soil layers

Layer	Texture class	Parameters of van Genuchten-Mualem functions (6–7)					
		θ_s	θ_r	α	*n*	*L*	K_s
cm		(cm³ cm⁻³)	(cm³ cm⁻³)	(cm⁻¹)	(-)	(-)	(cm d⁻¹)
10–20	L	0.5027	0.0	0.0376	1.1079	9.86	38.170
30–40	C	0.5532	0.0	0.0068	1.1150	6.32	0.674
70–80	SCL	0.5155	0.0	0.0048	1.1355	4.49	0.210
90–100	CL	0.5087	0.0	0.0039	1.1330	2.80	0.185

The optimised hydraulic conductivity characteristics also indicate the usefulness of the van Genuchten-Mualem concept for describing unsaturated water conductivity using equation (7). However, the values of the determination coefficients between the measured and calculated unsaturated hydraulic conductivity values are lower than in the case of pF curves. The lowest r^2 value of 0,138 was determined for the data from the layer of 30–40 cm. This may be due to the formation of quite large cracks during measurements of unsaturated water conductivity in this layer, caused by high clay content.

Analysing the data presented in Table 3, it can be concluded that the soils studied are characterised by very high values of moisture at saturation (θ_s), which exceed 0.5 cm³ cm⁻³ whereas residual moisture content (θ_r) is equal to 0 cm³ cm⁻³. The value of the parameter α, which is approximately equal to the inverse of the pressure head at the inflection point of the water retention

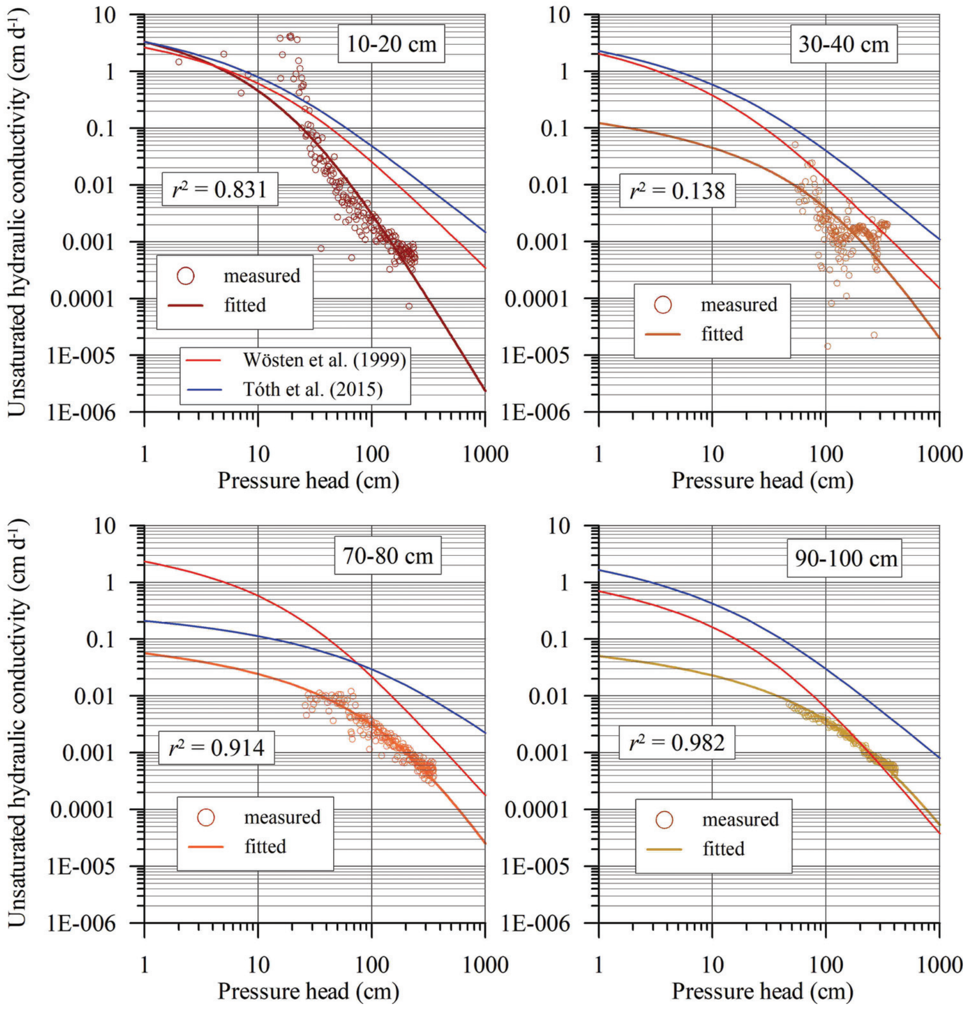

Fig. 5. The measured and optimized relationships between pressure head and unsaturated hydraulic conductivity of the analysed soil layers together with characteristics of the unsaturated hydraulic conductivity of soils developed as class pedotransfer functions by Wöstenet al. (1999) and Tóthet al. (2015)

curve, is generally low, except for layers 10–20 cm (L), which have the highest α values. The low values of the dimensionless parameter *n*, which reflect the steepness of the moisture retention curve and determine the rate at which the S-shaped curve turns toward the ordinate for large negative values of pressure head, are observed in all examined soil layers. Fitted saturated hydraulic conductivity values (K_s) decrease with the depth of the soil profile, and the conductivity values are very low and do not exceed 1 cm d^{-1}, with the exception of layer 10–20 cm (L), where K_s is equal to 38.17 cm d^{-1}. The values of the *L* parameter, which accounts for pore continuity and tortuosity, were positive for all examined soils.

The results of the determination of soil water retention and hydraulic conductivity functions were compared with those published in the literature by Wösten et al. (1999) and Tóth et al. (2015), who presented the so-called class pedotransfer functions for European soils. The assessed parameters of the van Genuchten-Mulalem function for the examined soils using the class pedotransfer were presented in Table 4, and the courses of the soil water retention curves and the unsaturated hydraulic function were shown in Fig. 4 and Fig. 5, respectively.

Comparing the van Genuchten-Mualem parameters obtained during this study with the values published in the literature, it can be noticed that the values of the measured saturated soil moisture (θ_s) content are higher than those published in the literature, especially for the SCL soil layer, where the maximum difference is equal to 0.123 cm^3 cm^{-3}. In case of residual soil moisture content (θ_r) the determined values during this study are comparable with the literature values. The values of the shape parameter *n* appearing in the van Genuchten equation (6) determined in the study are comparable to those presented by Wösten et al. (1999) and Tóth et al. (2015). The values of the shape parameter α are by one order of magnitude lower than the literature values, with the exception of the L (10–20 cm) layer, where the values are comparable.

The result of good compliance of the shape parameters is a similar course of the soil water retention curve, which is particularly evident in the case of 30–40 cm (L) and 70–80 cm (SCL) layers (Fig. 4). The values of saturated hydraulic conductivity (K_S) in the Mualem equation (7) determined in the study are significantly lower than the literature values, with the exception of the 10–20 cm soil layer (L), whose determined value of K_S is

Table 4
The water retention and conductivity functions parameters of the examined soil layers developed as class pedotransfer functions by Wösten et al. (1999) and Tóth et al. (2015)

Texture class	Author	Parameters of van Genuchten-Mualem functions (6–7)					
		θ_s	θ_r	α	*n*	*L*	K_s
		(cm³ cm⁻³)	(cm³ cm⁻³)	(cm⁻¹)	(-)	(-)	(cm d⁻¹)
L	Wösten et al. (1999)	0.439	0.01	0.0314	1.1804	–2.3420	12.061
	Tóth et al. (2015)	0.491	0.00	0.0347	1.1931	–4.3000	14.17
C	Wösten et al. (1999)	0.520	0.01	0.0367	1.1012	–1.9722	24.8
	Tóth et al. (2015)	0.499	0.00	0.0234	1.1200	–5.0000	17.07
SCL	Wösten et al. (1999)	0.392	0.01	0.0249	1.1689	–0.7437	10.755
	Tóth et al. (2015)	0.413	0.00	0.0227	1.1191	–5.0000	12.35
CL	Wösten et al. (1999)	0.481	0.01	0.0198	1.0861	–3.7124	8.5
	Tóth et al. (2015)	0.408	0.00	0.0032	1.1993	–5.0000	0.45

considerably higher, probably due to the better soil structure. The specified positive value of the parameter *L* associated with the distribution of soil pores in the Mualem equation differs significantly from the literature data, where the value of this parameter is typically negative for all soils. The data presented in Fig. 5 shows that the unsaturated water conductivity value of the investigated soils is, in most cases, significantly lower than the literature values. In the case of the 10–20 cm layer, the measured water conductivity was comparable to literature values under conditions close to full soil saturation (up to a suction pressure of 30 cm), while at higher suction pressures (1000 cm), the measured values are two orders of magnitude lower than literature values. In the 30–40 cm and 90–100 cm layers, the results of measurements in the 70–100 cm suction pressure range are comparable to those of Wösten et al. (1999).

The low water conductivity of the investigated soil results in a poor infiltration capacity, which causes surface runoff that can lead to water erosion in undulating terrain conditions. The poor water conductivity of the soils also limits the height and intensity of capillary rise, making it difficult for the capillary rise to supply the root zone of the plants, leading to the drying out of the root zone of the plants, which in the case of swelling and shrinking soils leads to the formation of cracks and fissures. This is confirmed by field observation, which is documented in Fig. 6.

4. Conclusions

Elaborated parameters of the van Genuchten equation, based on evaporation method measurements, reproduce the measured characteristics of the soil water retention curves correctly. The values of the determination coefficients are close to 1.

The optimised hydraulic conductivity characteristics also demonstrate the effectiveness of the van Genuchten-Mualem equation in describing unsaturated soil water conductivity. However, the determination coefficient values for the measured and calculated hydraulic conductivity are lower than for the water retention curves.

The parameters of van Genuchten functions for the investigated soil horizons are generally comparable to those presented

a) b)

Fig. 6. Field observation: surface run-off (a), the formation of cracks and fissures (b)

by Tóth et al. (2015) and Wösten et al. (1999) (except for the *L* parameter, which accounts for pore continuity and tortuosity). The specified positive value of the parameter *L* associated with the distribution of soil pores in the Mualem equation differs significantly from the literature data, where the value of this parameter is consistently negative for all soils.

The saturated water content values are several percent higher than values presented by Tóth et al. (2015) and Wösten et al. (1999) and they exceed $50\%_{vol.}$. Thus, it can be stated that the heavy-textured Mollic Glaysols of south-western Sępopol Lowland have a higher soil water capacity than European heavy-textured soils.

The fitted saturated hydraulic conductivity values (K_s) decrease with depth within the soil profile. The values are very low, never exceeding 1 cm d^{-1}, except for the 10–20 cm loam layer, where K_s is 38.17 cm d^{-1}. The values of saturated hydraulic conductivity determined in the study using the Mualem equation are significantly lower than those in the literature, with the exception of the 10–20 cm soil layer, for which the determined K_s value is considerably higher, probably due to the better soil structure.

In summary, the provided methodology is appropriate for determining the parameters of the van Genuchten and van Genuchten-Mualem functions for the mathematical modelling of water and solute transport in heavy-textured Mollic Gleysols.

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Conflict of interest

The authors declare that they have no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Daniel Szejba – Conceptualization, Data curation, Funding acquisition, Supervision, Validation, Visualization, Writing – original draft. **Tomasz Gnatowski** – Investigation, Methodology, Visualization, Writing – review & editing. **Jan Szatyłowicz** – Supervision, Validation, Visualization, Writing – review & editing. **Andrzej Łachacz** – Data curation, Investigation, Methodology, Writing – review & editing. All authors read and approved the final manuscript.

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Ocena właściwości retencyjnych i hydraulicznych gleby opadowo-glejowej typowej (Mollic Gleysol) na podstawie pomiarów metodą ewaporacyjną

Słowa kluczowe:

Właściwości fizyczne gleb
Utwory glacilimniczne
Model van Genuchtena-Mualema
Procedura optymalizacyjna

Streszczenie

Znajomość właściwości hydraulicznych gleby jest niezbędna do opisu i prognozowania procesów transportu wody i substancji rozpuszczonych w glebie. Celem pracy było określenie funkcji przewodności hydraulicznej oraz retencyjności wodnej dla różnych warstw gleby zaklasyfikowanej w Systematyce gleb Polski (2019) jako opadowo-glejowa typowa (odwodniona), a w ramach klasyfikacji WRB (2022) jako Mollic Gleysol, metodą ewaporacyjną. Pomiary właściwości retencyjnych i hydraulicznych wykonano dla czterech charakterystycznych warstw profilu glebowego położonego na Równinie Sępopolskiej w okolicach Lidzbarka Warmińskiego. Na podstawie danych uzyskanych w trakcie pomiaru wyznaczono krzywe retencyjności wodnej oraz przewodnictwa hydraulicznego w stanie niepełnego nasycenia. Parametry funkcji van Genuchtena i van Genuchtena-Mualema wyznaczono za pomocą programu Microsoft Excel. Wiązało się to z jednoczesną optymalizacją parametrów dotyczących właściwości retencyjnych (θ_r, α, n) i przewodności hydraulicznej (α, n, K_s i L). Opracowane na podstawie pomiaru metodą ewaporacyjną parametry równania van Genuchtena prawidłowo opisują pomierzone krzywe retencyjności wodnej gleby. Zoptymalizowane charakterystyki przewodnictwa hydraulicznego również wykazują efektywność równania van Genuchtena-Mualema w opisywaniu nienasyconej przewodności wodnej. Przedstawiona metodyka jest odpowiednia do określania parametrów funkcji van Genuchtena i van Genuchtena-Mualema do matematycznego modelowania transportu wody i substancji rozpuszczonych w glebach ciężkich i bardzo ciężkich (Mollic Gleysols).