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Changes in the hydrophysical properties of peat soils under anthropogenic evolution**

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Abstract. The changes in the water characteristics of peat soils under anthropogenic evolution was investigated. It was stated that the transformation of organic formations as a result of drainage and agricultural utilization leads to changes in their physical properties, i.e., it causes the increase of bulk density and ash content and the decrease of total porosity as well as the quantity of macro- and micropores. Water retention of drained peat soils which have reached a more advanced stage of decomposition is lower and the loss of water with the increase of the water potential is smaller. Anthropogenic evolution does not cause significant changes of effective useful retention (EUR) in the investigated organic soils. Saturated hydraulic conductivity is higher for deeper peat layers which have a small degree of decomposition than for upper layers where the decomposition reaches a higher level. Anthropogenic evolution of peat soils leads to the considerable increase of unsaturated hydraulic conductivity at low soil water potentials or in the whole range of soil water potentials, only in the 25% of cases of the investigated organic soils is this relationship reversed.

Keywords: peat soils, anthropogenic evolution, water retention, hydraulic conductivity

INTRODUCTION

The natural evolution of the most ancient peat soils of Polish and Belarusan Polesye took place during the last post-glacial Holocene period. Anthropogenic evolution of the meliorated peat soils proceeds more rapidly, lasting no longer than 300 years. However, the biggest changes in peat soils have been observed during the last ten years [2,4,14, 20,27]. The drainage amelioration changes the natural direction of geochemical processes in peat soils, which are expressed in the destruction of soil organogenic layers. This is due to the mineralization and erosion processes, the decrease of humus content and the release of ash elements. The intensity of these processes depends on the peatland features, the composition of underlay rocks, the water regime and the kind of utilization. The kind of utilization especially is the reason that within such short period of time a complete destruction of the organic layer of the drained peat can be observed [1,3,4,9,12,26–28].

In the bioclimatic conditions of temperate climate zone the four stages of anthoropogenic evolution of the peat soils can be distinguished [1,2]. The first one lasts till only a peat horizon remains as isolated and the process of drying begins. Simultaneous with the qualitative transformation of organic matter, the decrease of its thickness can be observed as the result of mineralization processes and soil erosion. This stage is characterized by the gradual reduction of the peat layer due to subsidence and shrinkage as well as the irretrievable lost of peat. The evolution of the peat layer goes step by step according to the scheme: deep peat soils (peat depth more than 2 m), medium deep soils (peat depth – 1–2 m), shallow peat soils (peat depth – 0.5–1 m), peat gleysol soils (peat depth – 0.5–0.3 m), peaty gleysolic soils (peat depth less than 0.3 m).

The second stage of evolution begins together with the start of mixing of an arable peat layer with underlying mineral rocks. It causes the gradual enrichment of peat soils with mineral matter and a decrease in organic matter content. This way, the peat soil profile loses morphological properties which are characteristic for the peat horizon and this is the end of the meliorated peat stage.

The third stage of evolution occurs when the organic matter content in the organic-mineral soils derived from peat equals 15–30%.

The fourth stage of evolution begins when peat particles and peat-forming plant fragments are transformed in the

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plough layer so drastically that they cannot be visually observed even under a microscope or visually. The main part of deeply humified organic matter preserves its peat-mire genesis. This peculiarity differentiates the mineral residual peat soils from typically mineral soils. This kind of soil is formed as the result of the mixing and interaction of the peat with mineral bedrocks and contains less than 15% of organic matter [2,14].

A considerable part of peat soils in Polesye are shallow peat soils. About 90% of peat soils are bedded by sand sediments. The main feature of these soils is the fast destruction of their organic matter and the decrease of the water capacity of the peat layer. These two reasons lead to the transformation of peat soils in organic-mineral and after that in mineral residual peat soils. Due to the irregularity of mineral bottom and the difference in the depth of peat layer during the anthropogenic evolution the complicated soil complexes with non-uniform physical and hydrophysical properties and contrasting water regimes come into being instead of peat soils [3,14,28].

The problem of quality of new soils, formed at different stages of the anthropogenic evolution of soil layer in the meliorated peat soils is interesting from a scientific and practical point of view. The knowledge of the hydrophysical properties of such complicated soils complexes is very important for their rational management (protection and sustainable agricultural use).

The purpose of the work was to investigate the hydrophysical characteristics of soils formed in different stages of the anthropogenic evolution of peat soils.

MATERIALS AND METHODS

The soil material was taken from the central part of Polish Polesye. This territory was drained in the second part of the XXth century and is now situated in the Wieprz-Krzna Canal area where the drainage-drying program is realized. The studied peat soils represent the material at the different stages of organic matter transformation as well as mineral residual peat soil and mineral soil (Table 1). The choice of sample plots was also caused by the way of utilization. The samples were taken from different depths (5–10 and 30–45 cm) to have organic soils with the same genesis but with different stages of organic matter transformation. All investigated peat formations have a high value of ash content (more than 30%).

Site I (samples 1 and 2) is located in a floodplain. It is a deep organic soil, strongly drained, transformed, which is used as an opencast peat mine. Sample 1 (depth – 5–10 cm) is the proper moorsh derived from the reed-sedge peat with inclusions of iron [19]. Sample 2 (depth 30–35 cm) is the proper moorsh formed from the reed-sedge peat with inclusions of calcium and iron.

Sites II and III (samples 3, 4 and 5, 6) are shallow reclaimed peat soils. Both of them are used as the permanent grass. They have the same botanic composition, but differ in the degree of draining. Site II is heavy humified and site III is moderate humified meadow. Sample 3 (5–10 cm) is the peaty moorsh from a sedge peat and sample 4 (30–35 cm) is the medium decomposed sedge peat. Sample 5 (5–10 cm) is the humic moorsh and sample 6 (40–45 cm) is the sedge peat with a high degree of decomposition.

Site IV (samples 7 and 8) is an example of the final stage of anthropogenic evolution of the meliorated peat soil with a sand bedrock. In this site the full destruction of peat soil took place as a result of the drainage and agricultural cultivation with the field crop rotation. The mixture of arable peat layer (sample 7) with underlying sand bedrock (sample 8) led to the formation of the mineral soil which belongs to the residual peaty gleysolic soil according to Bambalov classification [1] or the humic mineral soil according to Okruszko classification [19]. It is used as an arable field.

The ash contents of the studied peat soils were determined by igniting the dried peat soil samples in a muffle furnace at about 550°C until their weight was constant [22]. The ash content was expressed in terms of the percentage of ignition residue from the quantity of dry material (34.1–92.7%). The determination of the humus content in sand and mineral residual peat soil were carried out using the Tiurin method. The specific surface area of soil samples (from 2 m^2g^{-1} for sample 8 to 254 m^2g^{-1} for sample 4) was evaluated from adsorption-desorption isotherms of water vapour

Table 1. Basic properties of the investigated soils

Sample	Layer (cm)	Ash content (%)	Humus (%)	Specific surface area (m^2g^{-1})	pH in		Fe (g kg^{-1}) of dry matter
					H_2O	KCl	
1.	5–10	43.4	–	197	7.0	6.7	13.7
2.	30–35	39.6	–	195	7.3	6.8	20.6
3.	5–10	42.6	–	207	5.2	4.6	10.0
4.	40–45	34.1	–	254	5.9	5.3	4.8
5.	5–10	46.5	–	177	6.8	6.2	5.0
6.	30–35	40.5	–	165	6.5	6.1	4.5
7.	5–10	92.7	6.40	27	6.8	6.4	6.7
8.	30–35	–	0.10	2	4.8	4.5	1.7

which were measured by gravimetric method using a vacuum chamber. The bulk densities of the investigated soils varied from 0.24 (sample 4) to 1.86 g cm^{-3} (sample 8) and the total porosity (determined at saturation) from 38 to 94%, respectively.

The measurements of static hydro-physical characteristics of the studied soils, i.e., relation between soil water potential and water content, were made within the range from 1 kJ m^{-3} (pF 1) to 100 kJ m^{-3} (pF 3) in the drying process according to the Richards procedure. The standard pressure chambers, manufactured by SOILMOISTURE Equipment, Santa Barbara, California USA, were used (Catalog Nos 1500 and 1600). It was assumed that effective useful retention (EUR) is defined as an amount of water which is bound in the soil with the potential ranging from 16 kJ m^{-3} (pF 2) to 50 kJ m^{-3} (pF 2.7) in the pores with a diameter between 6 and 30 mm. Water bound in pores smaller than 6 mm in diameter, is not easily accessible or totally inaccessible for plants. Water in the pores bigger than 30 mm in diameter is gravitational water [13,18].

Determination of the water conductivity coefficients was carried out through a method of instantaneous profiles based on the measurements of water content and water potential in the chosen layers of the soil sample by means of a TDR measuring set in the process of soil drying [17,23–25]. The measurements were carried out in cylinders filled with soil in which holes were drilled at heights of 1, 2.5 and 4 cm from the bottom and TDR water content measuring probes, together with micro-tensiometers measuring soil water potential, were installed. The soil samples were filled with water till saturation was reached and then left under a cover for 24 h in order to reach a state of thermodynamic equilibrium. Then the samples were uncovered, their water content and soil water potential were monitored during evaporation. The TDR gauge was linked to a PC which enabled automatic measurements, and the values of water content and water potential taken, to be recorded on the computer carrier. The measurements of the dynamics of soil water content and soil water potential profiles obtained, rendered possible the coefficient of unsaturated water conductivity, among other things. The use of micro-tensiometers makes it possible to measure the water potential within the range from 0 to 900 hPa (pF 1–pF 2.9). Furthermore, the hydraulic conductivity coefficient can be determined for the same range of the water potential. Because of the scatter of the results obtained using Eq. (3), the final stage of determination of unsaturated hydraulic conductivity by the instantaneous profiles method (IPM) is a procedure of smoothing, interpolation and extrapolation of the hydraulic conductivity results using the Mualem-Van Genuchten equation.

Assuming that the process of water movement is one-dimensional and takes place in isothermal conditions, the one-dimensional Darcy equation can be used for the calculation of the water conductivity coefficient [13] (z axis positive downwards):

$$q(z,t) = -k(\Theta)\left(\frac{\partial\Psi(z,t)}{\partial z} - 1\right), \tag{1}$$

and the equation that makes it possible to calculate the fluxes from the experimental data:

$$q(z,t) = -\int_0^z \frac{\partial\Theta(z,t)}{\partial t}\,dz\,. \tag{2}$$

Comparing the above equations, we arrive at a relation that makes the determination of water conductivity possible:

$$k(\Theta) = \frac{\int_0^z \frac{\partial\Theta(z,t)}{\partial t}\,dz}{\frac{\partial\Psi(z,t)}{\partial z} - 1} \tag{3}$$

where: $q(z,t)$ – water flux running in a given time through a selected surface of a soil sample (cm day^{-1}), $k(\Theta)$ – water conductivity coefficient (cm day^{-1}), $\Theta(z,t)$ – water content in the chosen layer of the soil sample in the selected time period (v/v); $\Psi(z,t)$ – soil water potential in a chosen layer of soil sample within a selected time period (cm H_2O).

For determination of water conductivity in the saturated zone (k_{sat}) the laboratory permeameter (Eijkelkamp – Agricultural Equipment, The Netherlands) has been used.

RESULTS AND DISCUSSION

During the anthropogenic evolution caused melioration processes and different utilization, the apparent changes of the structure and morphology of peat soils has taken place. The most significant changes can be observed in the upper layer of peat soils which undergo a stronger transformation depending on the mineralization and humification processes. It was noticed that the ash content of peat soils is higher (from 4 to 8%) at an advanced stage of decomposition than in less decomposed peats (Table 1). The transformation of a peat layer leads to changes of its density and porosity. The increase of upper layer peat bulk density was observed in the investigated Sites I, II and III. In Site IV the bulk density of sand (sample 8) is higher than upper mineral residual peat layer (sample 7). The increase of the surface layer peat bulk density simultaneously induced the decrease of total porosity. The changes of bulk density between upper and lower layers of peat soils, from 0.01 to 0.14 g cm^{-3} for Sites I, II and III, were the cause of the changes in their total porosity from 2 to 9% (Table 2).

The soil water potential (pF)-water content characteristics for the investigated peat soils are presented in Fig. 1 in mass units and in Fig. 2 in volume units. It can be seen from Figs 1 and 2 that the shapes of these characteristics are similar and the water content values in the upper layers are lower than in the bottom layers for samples 1–6. In case of

T a b l e 2. Bulk density, porosity, distribution of pores and saturated water conductivity of the investigated soils

Sample	Bulk density (g cm^{-3})	Porosity (% m^3 m^{-3})	Amount of pores (% m^3 m^{-3})			k_{sat} (cm day^{-1})
			$\phi > 30$ µm	30 µm$< \phi < 6$ µm	$\phi < 6$ µm	
1.	0.42	80	26	10	44	1720
2.	0.41	83	15	9	57	360
3.	0.38	85	18	10	57	5
4.	0.24	94	23	16	55	393
5.	0.52	82	12	9	61	31
6.	0.41	84	14	9	61	265
7.	1.16	55	21	11	23	370
8.	1.86	38	31	2	5	1600

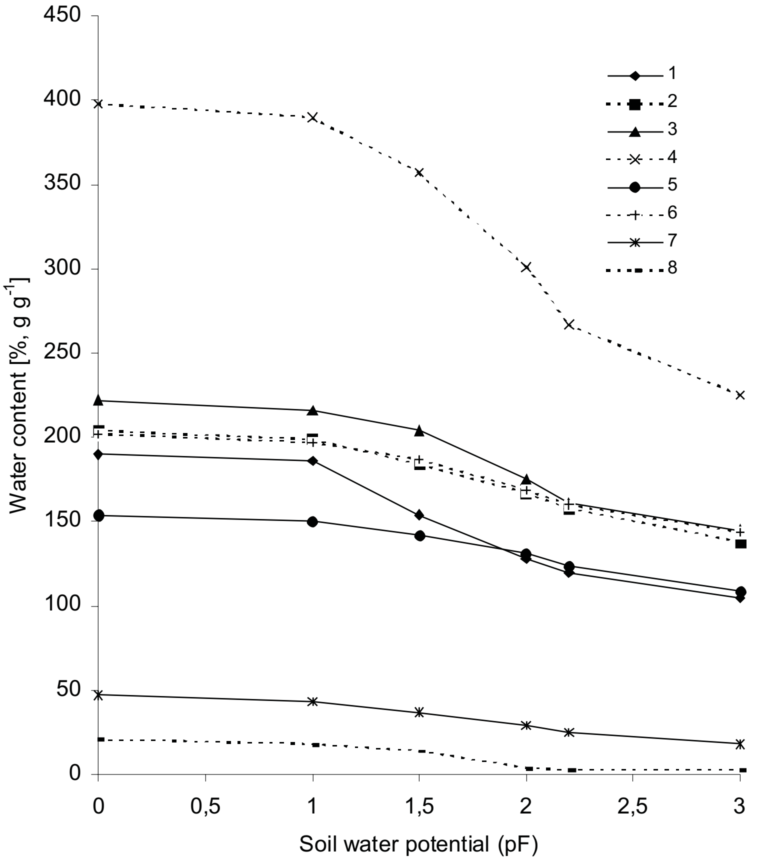

Fig. 1. Water retention curves for investigated soil samples (Nos 1–8), (water content in mass units (g g^{-1})).

samples 7–8 (mineral residual peat soil) the relation is opposite. The values of water content in both cases (mass and volume units) show that less transformed peat soils (samples 2, 4, 6) have a higher moisture than those more transformed (samples 1,3,5). For less transformed peat soils the moisture at saturation varies from 202 to 398% and at pF 3 – from 138 to 224% in mass units (Fig. 1) and from 83–94% at saturation to 44–59% at pF 3 in volume units (Fig. 2). The mineral residual peat soil (samples 7–8) retains a significantly lower amount of water, i.e., at saturation – 20 to 47% and at pF 3 – 3 to 18% in mass units, and in volume units at saturation – 38 to 55% and 5 to 20% at pF 3. Water content in the investigated soils between saturation and pF 1 is nearly the same which is an indicator of the absence of very large pores (diameters bigger than 300 mm). The sharp decrease of water content between pF 1 and pF 2–2.2 shows the significant amount of large pores (diameters between 300 and 30–18.5 µm). The differences in water content between pF 2

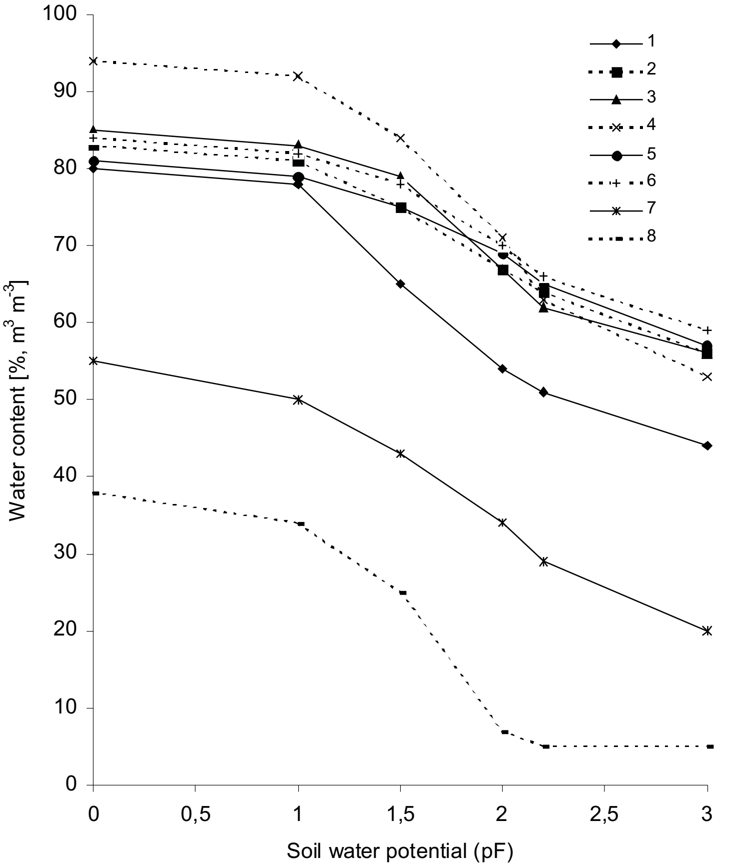

Fig. 2. Water retention curves for investigated soil samples (Nos 1–8) (water content in volume units (m^3 m^{-3})).

and pF 3 are significantly lower than between pF 1 and 2 which is expressed by the smaller inclination of water retention curve to pF axis. The amount of small pores (diameters smaller than 6 μm), which bind the water not easily accessible or inaccessible, is significantly higher in less transformed peat soils and changes from 44 to 61% m^3 m^{-3} whereas in peat soil with a higher degree of transformation – 5–23% m^3 m^{-3}.

The effective useful retention (EUR), defined as an amount of water held in the soil between pF 2 and 2.7, is one of the most important properties of soils for efficient use of water, because it directly influences the growth of plants and their yield [20]. It was noticed that values of EUR for sites I and III were nearly the same (9–10%), for site II the transformation caused a EUR decrease (6%), but for site IV – its increase (9%). It means that the upper layer of mineral residual peat soil is characterized by a similar EUR value as organic soils and creates more favourable conditions for agrophytocenozis.

Under natural conditions the water retention of peat soils is very high. Peat soils are characterized by a high amount of small pores (Table 2) and a very heterogeneous pore structure formed from plant residues in different stages of decomposition [15]. In the peat, different pore categories have been identified: large multiple and simply connected open pores, dead-end pores, completely isolated pores and pores in cell structures [18].

The degree of transformation of organic matter in peat soils under drainage changes with depth. This feature was found to be the most evident for the sedge peat soil (site II, samples 3, 4). Two major hydrologic zones exist within this peat soil. An upper aerated zone of fluctuating water conditions and an underlying anaerobic zone of a constant waterlogged state. Thus, the peat layer at the depth of 30–35 cm (sample 4) is the sedge peat, medium decomposed in anaerobic conditions. Figs 1 and 2 show that of all the peat studied, sample 4 contains the greatest quantity of water at saturation – about 400 % g g^{-1} or 94% m^3 m^{-3} and has a large macropore content – 23 %. But at the same time this peat soil gives up its water more readily with increasing soil water potential (pF) which is shown by a sharp change of shape of the water retention curve. Water retention curves for both layers of site III (samples 5, 6) have the same character, but they are more smooth than the water retention curves for site II. The 30–35 cm peat layer retains more water at all pF values as compared with 5–10 cm surface layer. The strongly transformed reed sedge peat soil profile (site I) revealed the same regularity in water retention characteristics as the above organic soil profiles. The topsoil layer (sample 1) holds more water at any pF as compared with the deeper soil layer (sample 2), but the differences in water content for these layers from saturation to pF 1 did not exceed a few percent and they increase with the increase of pF values. In the case of peats which have reached a more advanced stage of decomposition (samples 1, 3, 5), the water content at saturation was lower and the decrease of water content with the increasing pF were also smaller. Results of a similar kind have been obtained previously for peat soils [7,10,18]. The mineral residual peat soil (site IV, sample 7) has been characterized by a significantly smaller water retention under all the soil water potentials as compared with the aforementioned organic soils (samples 1–6). The difference in water content between them reached 100% g g^{-1} and more than 20% m^3m^{-3}. The high water retention of an upper layer of residual peat soil is probably stipulated by organic content (7%). The water retention of the underlying sandy layer (sample 8) is the lowest among all the investigated soils. This sandy layer characterizes the highest content of macropores (31%) and the lowest content of mezo- and micropores (7%).

The saturated hydraulic conductivity characterizes the movement of water in the soil when all the soil pores are filled with water. The values of saturated hydraulic conductivity for the investigated soils are presented in Table 2. It can be seen that for Site I the value of saturated hydraulic conductivity is considerably higher for the sample 1–1720 cm day^{-1} than for the sample 2–360 cm day^{-1}, whereas for the Sites II, III and IV the values are lower for upper layers (samples 3, 5 and 7 – 5, 32 and 370 cm day^{-1}, respectively) than for deeper layers (the samples 4, 6 and 8 – 393, 265 and 1600 cm day^{-1}, respectively). This may be due to the fact that Site I is strongly decomposed peat (proper moorsh) and it is characterized by a large content of large macropores (26%) in the top layer (sample 1) and the Fe content in sample 2 is very high – 20.6 g kg^{-1}. The saturated hydraulic conductivity of organic materials changes with their state of decomposition [13,16,25]. The drainage leads to an increase in peat density and speeds up the decomposition. It means that saturated hydraulic conductivity is higher for deeper peat layers which have a small degree of decomposition (samples 4, 6 and 8) than for upper layers where the decomposition reaches a higher level (samples 3, 5 and 7).

The results of investigations of unsaturated hydraulic conductivity carried out with the use of the instantaneous profile method and smoothed using Mualem-van Genuchten's model as a function of water potential are given in Fig. 3. It is known that the unsaturated water conductivity of peat soils depends on the nature of peat, decomposition degree, ash

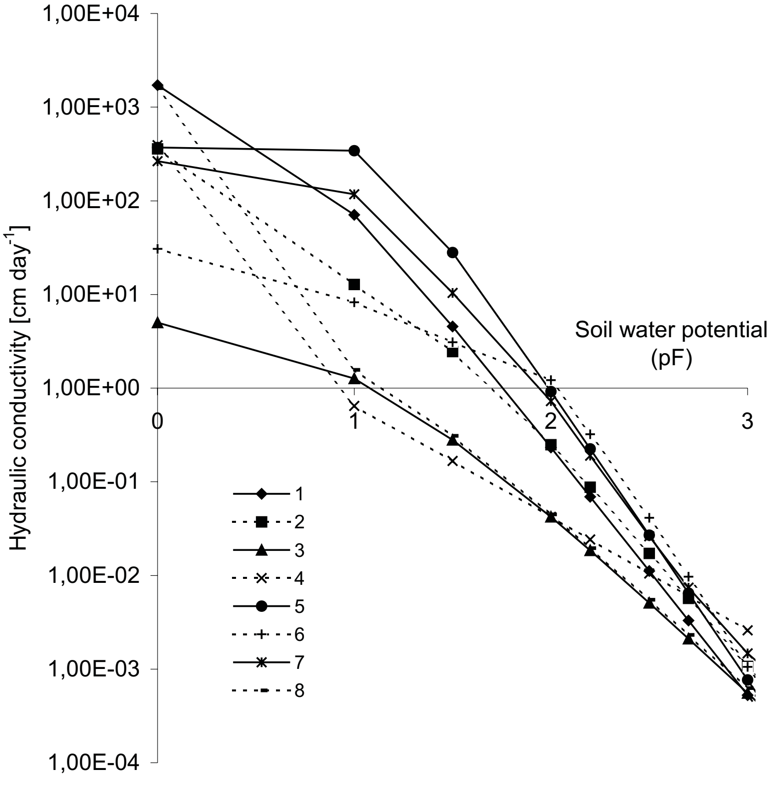

Fig. 3. Hydraulic conductivity at chosen soil water potentials for investigated soil samples (Nos 1–8).

content, bulk density (consolidation) and flux direction [5,6,8, 11,16,21,25], so it is clear that the drainage and agricultural utilization, i.e., anthropogenic influence, lead to the changes of physical properties of peat soils and at the same time they change the unsaturated hydraulic conductivity.

Through analysis of the courses of curves presented in Fig. 3 it can be stated that at low soil water potentials in the Sites I and III and at all the investigated potentials in the Site IV (except pF<0.2) the values of unsaturated hydraulic conductivity (k_{unsat}) are lower in the deeper layers of peat soils whereas in the Site II the values of k_{unsat} reversed. For example at pF 1 the k_{unsat} for sample 1 equals 71 cm day^{-1}, sample 2 – 12.8 cm day^{-1}, sample 6 – 8.3 cm day^{-1}, sample 7 – $1.2 \cdot 10^2$ cm day^{-1} and for sample 8 – 1.6 cm day^{-1}. In the case of samples 3 and 4 the values of k_{unsat} at pF 1 are nearly the same – 1.2 and 0.7 cm day^{-1}. For the samples 1 and 2 at pF 1.7 and for the samples 3 and 4 at pF 2 the values k_{unsat} are the same. Further on, up to pF 3 they decrease then reaching $6.3 \cdot 10^{-4}$ and $1 \cdot 10^{-3}$ cm day^{-1}, respectively. It can be stated that the anthropogenic evolution of peat soils leads to the considerable increase of k_{unsat} values at low soil water potentials (Sites I and III) or in all ranges of soil water potentials (Site IV). Only in the case of the Site II (heavy humified shallow reclaimed peat soil) is this relationship reversed.

CONCLUSIONS

1. Transformation of organic formations as the result of drainage and agricultural utilization leads to changes of their physical properties, i.e., it causes the increase of bulk density and ash content and the decrease of total porosity as well as the quantity of macro- and micropores.
2. Water retention of the drained peat soils which have reached a more advanced stage of decomposition is lower and the loss of water with the increase of the water potential is smaller.
3. Anthropogenic evolution does not cause significant changes in effective useful retention (EUR) in the investigated organic soils.
4. Saturated hydraulic conductivity is higher for deeper peat layers which have a small degree of decomposition than for upper layers where the decomposition reaches the higher level.
5. Anthropogenic evolution of peat soils leads to the considerable increase of unsaturated hydraulic conductivity at low soil water potentials or in the whole range of soil water potentials, only in 25% of cases of the investigated organic soils is this relationship reversed.

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