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Effect of aggregate size on water movement in soils

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A b s t r a c t. The effect of aggregate size on hydraulic conductivity coefficient of two tilled soils with different genesis and the same texture is presented. The distribution of values of the hydraulic conductivity coefficient of Haplic Phaeozem relative to the particular aggregate fractions displays a bimodal character similar to that of the pore size distribution. The values of hydraulic conductivity coefficient for fraction of <0.25 mm of Eutric Fluvisol are significantly higher than those for the remaining fractions. For the aggregate fraction of <0.25 mm of Eutric Fluvisol and for the aggregate fractions of <0.25 and 0.25-0.5 mm of Haplic Phaeozem the dominant mechanism of water flow is the inter-aggregate transport, while for the remaining (larger) aggregate fractions of both the soils the dominating flow mechanism is the intra-aggregate transport of water.

K e y w o r d s: soil, aggregation, water movement, hydraulic conductivity, relative conductivity

INTRODUCTION

The main soil properties exert an essential influence on the relationship between the components of water balance *ie* the water capacity and conductivity. The knowledge of these properties, the impact of various factors on them and the methods of their regulation allow to control water circulation processes in the biosphere. It is particularly important in areas used for agricultural production where adequate management of water resources leads to sustainable development, through the use of suitable land improvement and agrotechnical management, crop rotation (taking into account plant varieties which have a lower demand for water) and the creation of protection zones around arable fields, pastures and forest land. In agricultural areas the soil water capacity and conductivity may be changed by tillage through the modification of physical properties such as a density or structure of soil (Czyż and Dexter, 2009; Lal and Shukla, 2004; Lipiec *et al*., 2007; Witkowska-Walczak, 2000).

Soil structure, defined as mutual positioning of aggregate-forming mineral soil particles and organic matter within the soil matrix. Structural processes occur at a different scale (10^{-9} to a few cm), and vary in time and space, so soil structure is a dynamic property with numerous aspects, and is difficult to characterize (Kutilek, 2004). The skeleton structure of micro- and macroaggregates is important to maintaining size, stability, and continuity of pores within and between aggregates (Balashov *et al*., 2010; Horn and Smucker, 2005). The porosity is the functional entity of soil structure, and it can be characterized by pore size distribution, shape and space of pores, voids, channels, biochannels and biopores or macropores, cracks, fissures, fractures as well as vertical/horizontal continuity of pores. The desired size of aggregates is related with the soil function The smaller size of aggregates (dia <5 mm) is suitable for plant emergence and the soil with aggregates about 5 mm in diameter, with relatively low volume of inaccessible water – for the highest crop yield. The ideal seedbed agrees well with larger aggregates (dia about 15 mm) (Josa *et al*., 2010), because they enhance infiltration and/or provide depressions for water and thus allow more time for infiltration, delaying run-off generation. A coarser aggregate structure may also diminish the rate of evaporation and stimulate ion exchange processes. Recent studies revealed that organic matter associated with macroaggregates is better protected against mineralization and leaching than organic carbon not associated with mineral phase or present in small aggregates (Głąb *et al*., 2009; Kęsik *et al*., 2010). In tilled soils, stable soil surface aggregates provide a greater number of continuous and interconnected pores and have the potential to accelerate the flux i*e* preferential flow and affect unsaturated hydraulic conductivity and diffusivity (Kutilek, 2004). The preferential flow has been identified as the most important

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component of water movement in many soils, especially loams and clays (Kutilek *et al*., 2005). The preferential flow in aggregated soil influences transport of surface-applied agricultural chemicals in the soil and to surface and ground water (Richard *et al.*, 2001).

The water retention and transport depend on pore structure in soil, so the quantification of pore size distribution over a wide range of pore sizes is useful in practice and theoretical modelling (Durner and Fluhler, 1996; Gerke and Köhne, 2002). Relation of hydraulic conductivity coefficient to water potential or water content is a basic characteristic conditioning water movement in the environment, so these relationships are often modeling (Pachepsky and Rawls, 2004; Sławiński *et al.,* 2004). The description of pore size distribution depending on aggregate size and the determination of static hydrophysical properties were an aim of our previous investigations (Lipiec *et al.,* 2007).

The aim of this study was to quantify the effect of aggregate size on hydraulic conductivity coefficient of two tilled soils with different genesis and the same silty loam texture.

MATERIAL AND METHODS

The soils used were Haplic Phaeozem (HP) and Eutric Fluvisol (EF) under long-term conventional tillage system (SE Poland). Steppe plants, providing large amounts of organic matter and fluvial outwash, were the main soil-forming factors of these soils. The basic properties of soils in natural state were as follows: HP was built from silt (67%), clay (22%) and sand (11%), whereas EF from silt (62%), clay (25%) and sand (13%), respectively. The bulk densities were 1.15 and 1.32 g cm^{-3}, C_{org} – 3.0 and 2.3% and pH_{KCl} – 6.8 and 7.4 for HP and EF, respectively. Soil samples were taken after harvesting from the arable layer (0-15 cm) close to field water capacity (about water potential – 150 hPa) in the natural (undisturbed) (125 cm^3 cylinders) and disturbed form. To determine aggregate size distribution and separation of size ranges of aggregates, the soil samples were taken into rigid containers and transported to the laboratory. Following drying up the soil in the laboratory to the air-dry state. The aggregate size distribution was determined by the standard sieve method using sieves of 10, 5, 3, 1, 0.5 and 0.25 mm mesh. The obtained results for the particular fractions were as follows: <0.25 mm – 11 and 3%, 0.25-0.5 – 15 and 2%, 0.5-1 – 15 and 17%, 1-3 – 23 and 28%, 3-5 – 14 and 11%, 5-10 mm – 15 and 27% and >10 mm – 7 and 28% (w/w) for HP and EF, respectively.

The pore size distribution of soil samples was obtained from their water retention curves (Lipiec *et al*., 2007). To determine the soil water retention curves, cylinders were filled with aggregates of the particular fractions: <0.25; 0.25-0.5; 0.5-1; 1-3; 3-5 and 5-10 mm. Then the cores were subjected to vibration and 3 successive wetting-drying cycles to get uniform density (Shiel *et al*., 1988, Witkowska-Walczak, 2000). It was stated in our earlier investigations that the amount of water stable aggregates was between 88-97% and the percentage were greater for beds of smaller than larger aggregates (Lipiec *et al*. 2007). The same size cores were used to determine water retention curves of undisturbed soil. The retention curves of the aggregate beds and undisturbed soil were determined using standard Richards chambers (SoilMoisture Equipment, Santa Barbara, CA, USA) in the drying process (5 replicates). To obtain whole continuous pore size distribution from the soil water retention curves the procedure described by Kutilek *et al*. (2005) was used. The standard soil water retention curves, θ(h), in this procedure are transformed into the parametric forms $S(h)$, where S is the relative saturation and h is the pressure head plotted as logarithm. Then the derivative curves $dS(ln(h))/d\ ln(h)$ are calculated and used for computation of pore size ditribution with the equation r =1490/h where r is the equivalent pore radius (μm) and h is the pressure head (cm).

Measurement of the hydraulic conductivity coefficient in a saturated zone, K_s (m day^{-1}), was carried out using a laboratory permeameter (Eijkelkamp-Agrisearch Equipment, Giesbeek, The Netherlands) with a constant head method as a standard (5 replicates).

The hydraulic conductivity coefficient in a unsaturated zone of the soil was determined by the instantaneous profiles method (IPM) with the application of TDR (Time Domain Reflectometry) meter that enables the simultaneous measurement volumetric water content and water potential in the soil cores (Malicki and Skierucha, 1989; Sławiński *et al.*, 2002; Walczak *et al*., 1993). It was possible to install 3 pairs of sensors to measure water content and the soil water potential at 1, 2.5, and 4 cm from the bottom. The absolute measurement error of soil hydraulic conductivity coefficient by instantaneous profiles method originates mainly from the reflectometric water content measurements. In the soil water potential range from saturation to field capacity (water potential about 150 hPa) the maximum relative error of soil water conductivity coefficient does not exceed 10%. For the soil water potential close to the 850 hPa point the maximum relative measurement error is about 50% (Sławiński *et al*., 2006). The IPM procedure makes it possible to determine of hydraulic conductivity coefficient from 1 to about 850 hPa. The relative hydraulic conductivity coefficients were calculated according Mualem equation: $K_r = K_x/K_s$, where K_s in our case was equal K at 1 hPa.

RESULTS AND DISCUSSION

As it was shown in our earlier paper (Lipiec *et al*., 2007) the derivative presentations of pore size distribution curves demonstrate that the pore structure of the aggregate beds and undisturbed soils is organized hierarchically, with matrix domain and secondary domain consisting of two subdomains in many cases. The minima separating the structural pores from the matrix pores varied from 2 to 4 μm in HP and EF, depending on the size range of the aggregates. The range of the minima is similar to that reported by Kutilek *et al*. (2005)

for variously textured and compressed soils (2.5-10.9 μm). However, the minima had similar radius (approximately 6 μm) when various tillage systems were applied to the same soil. The minima separating the structural and macropore subdomains in our study occur mostly in beds of aggregates >1 mm and undisturbed soils, corresponding to approximately 20-60 μm. Irrespective of the soil type, the porous system of the aggregate beds <0.25, 0.25-0.5 and 0.5-1 mm tends to be bimodal with textural and structural domains, and trimodal with an additional macropore domain in the case of beds of aggregates of 1-3, 3-5 and 5-10 mm. In the second group of aggregate beds (1-10 mm) the peaks are more close together in EF than in HP. The peaks associated with the textural pore system in all aggregate beds of both soils correspond to a pore radius of approximately 0.42 μm. In general, the peaks were of greater magnitude in beds of aggregates <0.25 mm than in beds of larger aggregates. These differences are much more pronounced in EF than in HP due to greater magnitude of the textural peak in the former. The structural domains in the beds of aggregates from HP display a narrow peak corresponding to a pore radius of approximately 3.7 μm for aggregates <0.25 mm and a less narrow peak of 18.7 μm for aggregates of 0.25-0.5 mm. However, in the case of the aggregate beds >0.5 mm the structural peaks range within the pore radius of 3.7-35 μm and are more distinct in beds of aggregates of 0.5-1 mm than of larger aggregates of 1-10 mm. In EF, compared to HP, the structural peaks are less pronounced in aggregate beds within <0.25 mm. The peaks associated with macropore domain in HP are poorly defined for aggregates of 0.25-1 mm and for aggregate beds of 1-3, 3-5 and 5-10 mm are well pronounced with pore radius of up to approximately 700 μm. However, in EF the macropore peaks in all aggregate beds from 0.25 to 10 mm correspond to similar pore radius of approximately 60 μm. A substantially greater pore radius of the macropore peak in beds of aggregates of 1-10 mm of Haplic Pheaozem than of EF can be, in part, a result of fewer disturbances of the aggregates in the former by the wetting-drying cycles preceding determination of the water retention curve. This can be partly attributed to greater water stability of HP than EF. Additionally, this macropore peak can be associated with a greater soil water content at saturation in the former (59-62% vol.) than in the latter (52-55% vol.) that could be easily drained at low pressure heads while determining water retention curves. As to undisturbed samples, the pore size distribution in both soils display trimodality that is more defined in HP than in EF.

The hydraulic conductivity coefficients at 1 hPa (saturated conductivity) for HP were shown in Table 1. It can be stated that these values were changed over 13 times for HP and over 15 times for EF to the increase of aggregate sizes.

The values of hydraulic conductivity coefficient for HP and EF particular aggregates fractions are shown in Figs 1 and 2.

Analyzing the changes in the values of the hydraulic conductivity coefficient in relation to the values of the soil water potential it can be noted that high values of the hydraulic conductivity coefficient for HP within the full range of variability of soil water potential values were observed for aggregates <0.25, 0.25-0.5 and 0.5-1 mm. Those were: 30, 200 and 96 cm day^{-1} for 2.5 hPa and 8.5 10^{-3}, 7.5 10^{-3} and 9.2 10^{-4} cm day^{-1} for 850 hPa, respectively. Whereas, for aggregates of the fractions of 1-3, 3-5 and 5-10 mm the values of the hydraulic conductivity coefficient were significantly lower throughout the range of soil water potential values studied, *ie* from 3.5 to 2 10^{-6}, 1.6 -1.2 10^{-6} and 1-1 10^{-6} cm day^{-1} at 2.5 and 850 hPa, respectively. Analyzing the distribution of soil pores by their diameters in our previous investigations, it was observed that for aggregates of <0.25, 0.25-0.5 and 0.5-1 mm the pore distributions display similar bimodal runs. The first maximum for both distributions coinciding with pore radius of *ca.* 0.7 μm, while the second maximum for aggregates of 0.25-0.5 and 0.5-1 mm is shifted towards higher pore radius values with relation to aggregates of <0.25 mm. The higher values of hydraulic conductivity for aggregates with diameters of <0.25, 0.25-0.5 and 0.5-1 mm relative to pores with diameters of 1-10 μm may indicate that the dominant factor causing water movement is the gradient of the capillary component of soil water potential. This may also be indicated by the similar runs of pore distributions by diameters for aggregates within that range of variability. The relatively small changes in the hydraulic conductivity coefficients within the range of low values of soil water potential (2.5-31 hPa) for fractions of <0.25; 0.25-0.5 and 0.5-1 mm, compared to the other fractions, result from the low share of large pores (100-1000 μm) which, within that size range, release water. Above soil water potential values corresponding to 31 hPa, the slope of the curves is similar for all aggregate fractions. A similar run is also observed for the pore distributions for equivalent diameters of <1 μm (Lipiec *et al.,* 2007).

The highest values of the hydraulic conductivity coefficient were recorded for EF aggregates with diameters of <0.25 mm – 4.9 cm day^{-1} at 2.5 hPa and 6.3 10^{-3} cm day^{-1} at

T a b l e 1. Values of saturated conductivity coefficients for different aggregates fractions (mm) and natural state

Soil	Conductivity coefficient (cm day^{-1})						
	<0.25	0.25-0.5	0.5-1	1-3	3-5	5-10	Natural state
HP	50	330	340	640	690	680	370
EF	40	210	500	780	650	620	320

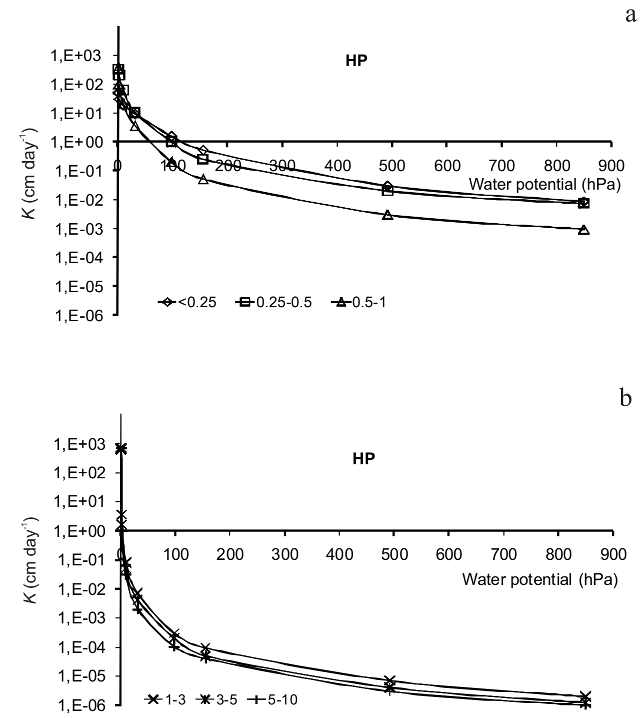

Fig. 1. Hydraulic conductivity coefficients *vs* water potential for Haplic Pheaozem (HP) aggregates: a – < 1 mm, b – >1 mm.

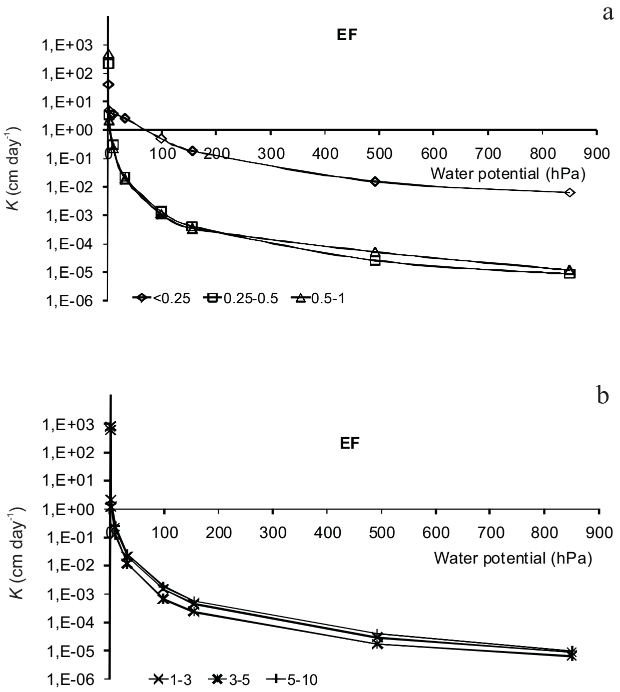

Fig. 2. Hydraulic conductivity coefficients *vs* water potential for Eutric Fluvisol (EF) aggregates: a – < 1 mm, b – >1 mm.

850 hPa. Values of hydraulic conductivity coefficients for that aggregate fraction are significantly different from the coefficients for aggregates >0.25 mm. The low share of large pores, in turn, caused that the relative saturation of the sample varied to a limited extent within that range of pressures. For the remaining aggregate fractions: 0.25-0.5, 0.5-1,1-3, 3-5 and 5-10 mm, the values of the hydraulic conductivity coefficients: 3.4, 2.2, 2.1, 1.1 and 1.7 cm day^{-1} at 2.5 hPa as well as 8.7 10^{-6}, 1.2 10^{-5} and 8.4, 6.3, 9.3 10^{-6} cm day^{-1} at 850 hPa, respectively, are comparable throughout the range soil water potential values studied. The steeper slope of $K(\psi)$ for soil water potential corresponding to ≤150 hPa, compared to the slope of $K(\psi)$ for the finest fraction, results from the relatively higher content of small pores <1 µm that were dewatered at pressure values within that range. Analyzing the distributions of pores by their diameters it was observed that for aggregates of <0.25 mm the distribution has a bimodal character and differs notably from the distributions for the remaining aggregate fractions. For those aggregates it may be assumed that, like in the case of aggregates of HP, the main factor for water movement is the gradient of the capillary component of soil water potential.

The values of hydraulic conductivity coefficients for HP and EF in the natural state (with undisturbed structure) against the background of aggregate fractions under study *versus* the soil water potential are shown in Fig. 3. As can be seen from the curves presented, the values of hydraulic conductivity coefficients fall within the ranges of values corresponding to the values of coefficients for aggregates with diameters greater than 1 mm. These are as follows: for HP – 0.1 and 1.1 10^{-9} cm day^{-1}, whereas for EF – 4.1 and 4.8 10^{-8} cm day^{-1} at 2.5 and 850 hPa, respectively.

The relative coefficient of hydraulic conductivity in the soil medium represents more clearly the potential possibility of water movement in the unsaturated zone. Therefore the values of coefficient were calculated for the whole range of variation of soil water potential and subjected to analysis. As can be seen in the presented graphs (Figs 4 and 5), for both soils all the curves are similar in shape, with the coefficient assuming the highest values – throughout the range of soil water potential values – for aggregates of < 0.25 mm. For EF it exceeds the values of the coefficient for the other aggregate fractions by more than one order of magnitude. This is especially noticeable for the lower (in absolute values terms) values of soil water potential. The curves for the remaining aggregate fractions and for the soils in their natural state are grouped close together. The highest values of the relative hydraulic conductivity coefficient for this group, throughout the range of changes in the soil water potential, were recorded for the soils in their natural state. This supports the domination of HP – below the curve for aggregates of <0.25 mm there is the curve for that soil in its natural state,

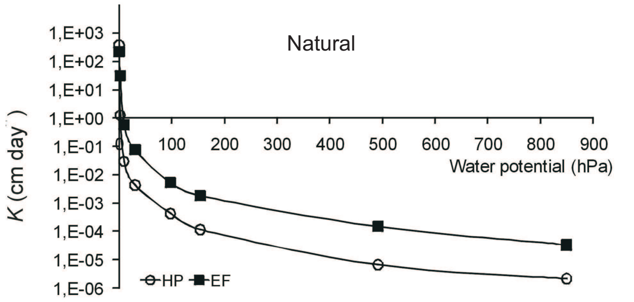

Fig. 3. Hydraulic conductivity coefficients *vs* water potential for Haplic Pheaozem and Eutric Fluvisol in the natural state.

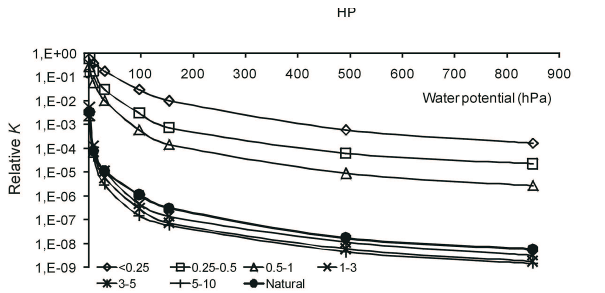

Fig. 4. Relative hydraulic conductivity coefficients *vs* water potential for Haplic Pheaozem aggregates and for the soil in natural state.

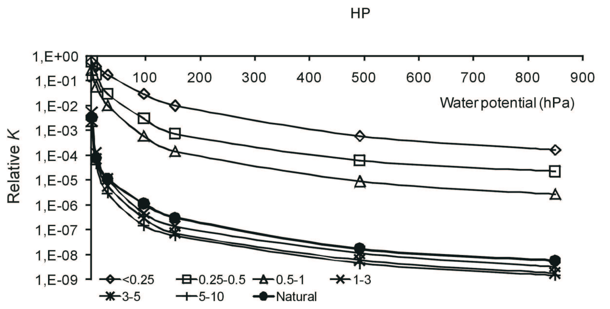

Fig. 5. Relative hydraulic conductivity coefficients *vs* water potential for Eutric Fluvisol aggregates and for the soil in natural state.

characterized by a higher share of aggregates <0.25 mm compared to EF. It is shifted relative to the curve for aggregates <0.25 mm by an order of magnitude, especially for lower values of the soil water potential. It is also supported by the fact that for aggregates of <0.25 mm the dominant motor of movement is capillary transport. Somewhat lower values of the relative conductivity coefficient are observed for aggregates of 0.25-0.5 and 0.5-1 mm, whose curves practically overlap. The lowest values are assumed by the coefficients of conductivity for aggregates of 1-3, 3-5 and 5-10 mm, whose curves are also positioned close to one another. Such distribution of values of the relative hydraulic conductivity coefficient is in an agreement with the distribution of pore sizes obtained for the particular aggregate fractions and for the undisturbed soil in our previous work (Lipiec *et al.,* 2007).

The shape of curves of the relative coefficient of hydraulic conductivity for the two soils in their natural state and for the particular aggregate fractions showed that the large drop in the values of hydraulic conductivity coefficient from saturation to soil water potential of about 150 hPa indicates the domination of water movement through macropores. Whereas, the flat nature of the curves starting from soil water potential of 150 to 850 hPa indicates the domination of mezopores and micropores in the water movement. The possibilities of water transport in structural soils one should also note that the hydraulic conductivity coefficient depends not only on the volume of soil pores but also on their continuity. In structural soils with large gaps the hydraulic conductivity coefficient in bulk soil increases, while the rate of water flow within the soil aggregates decreases rapidly due to the shrinkage of the soil (Horn and Smucker, 2005; Youngs, 2008). The results obtained showed that the higher values of hydraulic conductivity coefficient within the whole range of water potential changes were observed for the fractions of <0.25, 0.25-0.5 and 0.5-1 mm than those bigger than 1 mm of HP. For EF, the higher values of hydraulic conductivity coefficient throughout the range of variability were recorded for the aggregates <0.25 mm than those bigger than 0.25 mm. It can be assumed, therefore, that the dominant type of flow for those aggregate fractions, compared to larger aggregates, is the inter-aggregate flow (Ben-Hur *et al.*, 2009; Carminati *et al.*, 2008). This is particularly visible for water potential values close to saturation. For the aggregate fraction of 1-3, 3-5 and 5-10 mm of the HP the shapes of the hydraulic conductivity coefficient curves are similar in character. The curves dis- play a large drop in the values of the coefficient throughout the range of changes in soil water potential (from 10^3 to 10^{-6} cm day^{-1}). A particularly large drop is observed within the range of potentials close to saturation. Similar courses occur for the hydraulic conductivity coefficient curves for those aggregate sizes and for aggregates of 0.25-0.5 and 0.5-1 mm of EF. However, this drop begins from the value of about 10^2 cm day^{-1} to the value of *ca.* 10^{-6} cm day^{-1}. It can be assumed, therefore, that for those soils and those aggregate fractions the dominant flow is the slower flow – the intra-aggregate flow.

As it has been emphasised, the water flow is also determined by the shape and continuity of soil pores, and by their distribution by their diameters in particular. It can be concluded, therefore, that those factors also have an effect on such a shape of the curves of hydraulic conductivity. For EF aggregates <0.25 mm, and for HP aggregates <0.25, 0.25-0.5, and 0.5-1 mm, up to the soil water potential value of approx. 100 hPa the curves of the hydraulic conductivity coefficient display a plateau, while from the value of 100 hPa they drop fairly rapidly. This confirms the domination of the inter-aggregate flow within that range of soil water potentials.

For the soils in their natural state the hydraulic conductivity curves have similar shapes, the values of coefficient for EF being higher than those for HP by an order of magnitude throughout the range of changes in the soil water potential. At the same time the curves are very steep, which may indicate that the water flow mechanisms are similar in both soils. However, in soils with undisturbed structure the shapes and continuity of pores, apart from the aggregate distribution, have a decisive impact on water movement. It can be a reason, why EF showed the higher hydraulic coefficients in this case.

CONCLUSIONS

1. The distribution of the values of the hydraulic conductivity coefficient of Haplic Phaeozem relative to the particular aggregate fractions displays a bimodal character similar to that of the pore size distribution, the first maximum for both distributions coinciding with pore radius of about 0.7 μm, while the second maximum for aggregates of 0.25-0.5 and 0.5-1 mm is shifted towards higher radius values compared to aggregates of <0.25 mm.

2. The values of hydraulic conductivity coefficient for the fraction of <0.25 mm of Eutric Fluvisol are significantly higher than those for the remaining fractions.

3. For the aggregate fraction of <0.25 mm of Eutric Fluvisol and for the aggregate fractions of <0.25 and 0.25-0.5 mm of Haplic Phaeozem the dominant mechanism of water flow is the inter-aggregate transport, while for the remaining (larger) aggregate fractions of both the soils the dominating flow mechanism is the intra-aggregate transport of water.

4. Analysis of the shape of curves of hydraulic conductivity coefficient for the soils in their natural state as well as for the particular aggregate fractions revealed that the notable drop in the values of the relative coefficient of hydraulic conductivity at around 150 hPa indicates the domination of water flow through macropores, while the plateau on the curves between soil water potential values of 150 hPa and 850 hPa indicates the domination of mezopores and micropores in water transport.

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