Variability of Saturated Hydraulic Conductivities in the Agriculturally Cultivated Soils

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Abstract: The knowledge of the moisture conditions in a variably saturated zone of soil and their management is one of the main possibilities that allow the agronomists to raise significantly the fertility of soils. A progressive scientific method for describing the moisture conditions in a variably saturated zone uses a numerical simulation on a mathematical model. The accuracy of the outputs from the model (i.e. moisture profiles) depends mainly, besides the physical and mathematical structures of the model, on the accuracy of the input data. The upper boundary condition comprises the climate and phenological parameters. The initial condition is represented by the moisture profile at the beginning of the simulation and by the main hydrophysical properties of the soil. One of the main hydrophysical properties of soil is the value of the saturated hydraulic conductivity (K). This study is aimed at the determination of its temporal variability, keeping in mind also its areal one (with respect to the sampling data from various verticals). Several methods exist for the determination of the K values. In this study, a laboratory method with the falling head method (K_{labor}) was used. The areal-temporal variability of the K_{labor} values was evaluated for the vegetation period of the year 2003 on the locality Most pri Bratislave.

Keywords: saturated hydraulic conductivity; method with falling head method; frequency function; distribution function

Due to their high biological activities throughout the year, agricultural soils play a key role in the transport of the precipitation and irrigation water as well as of chemical substances. In general, these soils are non-homogeneous and their properties complicate the water motion and its study to a high extent. Their upper layers are influenced by cultivation, fertilisation, their surface is exposed to mechanical compacting by the rain and irrigation water at higher intensities. This results in changes of hydrological properties of the soil matrix in the upper soil layers or directly on the soil surface (Farkas *et al.* 2009). On the other hand, the factors such as the growth of plants and development of their root systems, activities of the soil fauna, development of cracks during drying of the soil layers, cause or contribute to the "preferable paths" formation for water penetration to originate. Under specific conditions, these paths favour faster water penetration into relatively high water depths. In general, the water motion in such soils is highly irregular, both in time and in space.

Numerous experiments confirm that the soil macropores (cavities after the plant roots, animals, and cracks) enable fast and irregular water flows into considerable depths of the soil profile (Beven & German 1982). This can cause an accelerated intrusion of the solutions applied on the soil surface. This is because of a gradual filling of

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the soil matrix storage capacity, which becomes then water bypassed through the preferred paths. Rao *et al.* (1974) observed in aggregated soil a significant herbicide concentration in the depth of 1.4 m, after a 240 mm dose of its application. In field conditions, pesticides were detected at the drainage and lysimeter outlets after several days to weeks after the application (Steenhuis & Parlange 1991; Bergström & Jarvis 1993).

Water volume in soil between its surface and its groundwater level (GWL) is denoted as storage (W) in the unsaturated soil zone (USZ). It is influenced by the water flows through its upper and lower boundaries. USZ upper boundary is the soil surface with (or without) the vegetation cover. It is directly influenced by the climatic conditions, through evapotranspiration, and it is the place through which the precipitation water enters the lower soil horizons. The lower USZ boundary is usually formed by the GWL. The water that flows between these two boundaries depends upon the soil hydrophysical characteristics (HPCH). The basic HPCHs of the USZ are the saturated hydraulic conductivity (K) and the moisture retention curve. These characteristics are variable in space, some of them also in time, in a relatively short time intervals. For instance, the K value is increasing throughout the year if the soil is covered by vegetation, because of its permanent root system development during the vegetation season. From the HPCH areal variability in connection with the climatic, topographical, and agricultural- production conditions, can be inferred the storage (W) variability in the USZ. To analyse the temporal W variability in the USZ, it is necessary to determine the continuous changes of the soil water balance components during a representative period of time. To arrive at the time series of W in the USZ, a systematic monitoring of the soil moisture (θ) is necessary (Štekauerová & Nagy 2002). However, such monitoring is rather demanding with respect to time, manpower, instrumentation and financing. Another possibility offers the numerical simulation with the help of a mathematical model (Šútor *et al.* 2002). Such simulation would yield the W time series in the USZ, in spite of a definite degree of the problem idealisation, still usually more complex and effective (Štekauerová & Šútor 2000). The adequacy of the numerical simulation results depends upon the processing level of the input data. The results produced are represented with an advantage by a continuous data series for the arbitrarily selected time intervals on the locality in question. Unrealistic input data may result in high differences between the measured and the computed results.

It follows directly from the Richard's equation application that the most important hydrophysical characteristic is the saturated hydraulic conductivity K. It is therefore necessary to give the utmost care to the description of this HPCH. This study is aimed at the determination of its temporal variability, but keeping in mind also its areal one (with respect to the sampling data from various verticals). Several methods exist for the determination of the K values. In our study, a laboratory method with the falling head method (K_{labor}) was used. The areal-temporal variability of the K_{labor} values was evaluated for the vegetation period of the year 2003 on the locality Most pri Bratislave.

Locality description

The locality of interest belongs to the land- register of the municipality Most pri Bratislave (Figure 1). It is a lowland region of the Great Danube Plain (Podunajská Nížina) at the western corner of the Rye Island (Žitný Ostrov), to the southeast of Bratislava, the capital of Slovakia. The observation point was on a maize field. The soil type on this locality is chernozem according to the FAO classification system. According to the Kopecky classification scale, the soils are classified as loams to fine sandy loams. According to the USDA texture triangle, the soils are characterised as silty loams (Figure 2). The whole soil profile looked relatively homogenous. At the 160 cm depth, a coarse layer starts of the gravel Danube sediments. GWL is located at the depth of 6 to 8 meters under the surface.

The data from the meteorological station Bratislava- airport were taken to represent the climatic characteristics of the locality of interest. This station is operated by the Slovak Hydrometeorological Institute, Bratislava (SHMI). Its co-ordinates are: 48°10'18" of the northern latitude; 17°12'00" of the eastern longitude. During the years 1980–2004, the annual precipitation varied from 200 mm in the year 1986, to 620 mm in the year 1999.

As to the temperature, the Rye Island belongs to the warmest climatic regions of Slovakia. The highest temperatures are observed in July and August. During the period of 1980–2004, the highest July temperatures at the Bratislava-airport station were 18.5°C to 23.7°C.

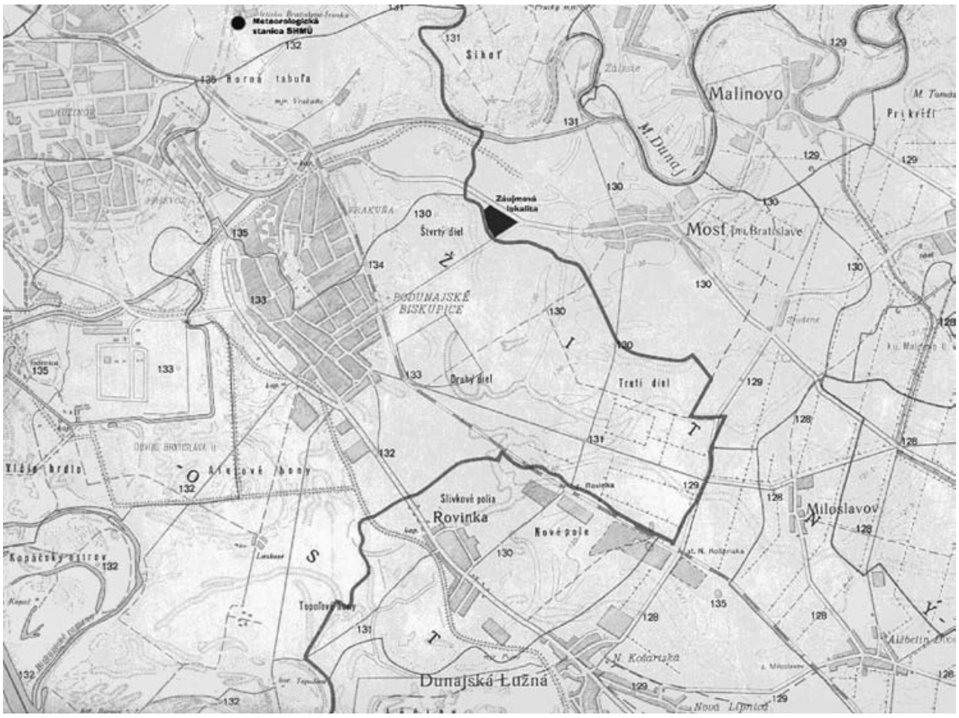

Figure 1. Location of the site of interest in the Most pri Bratislave municipality

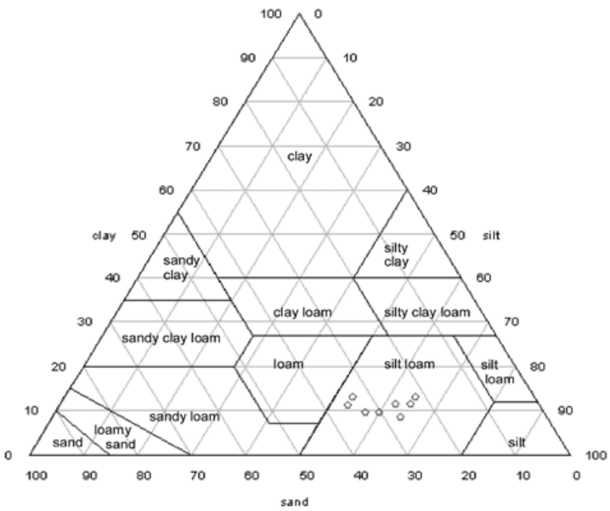

Figure 2. Determination of the soil type on the Most pri Bratislave locality by the USDA texture triangle

The measurement method

In the year 2003, during its vegetation period, the collection of samples was performed on the locality in question, starting from 17 March, 2003. During this day, 40 undisturbed samples were taken with the Kopecky cylinder, (100 cm^3 volume). The samples were taken in five verticals with eight samples in each vertical, up to the assumed active depth of the soil profile (the assumed active plant root system of the maize – 0 to 120 cm). In the ground plan plot, the four verticals formed the four vertices of a square with the sides of two meters each, the fifth vertical was in the middle, in order to characterise best the evaluated soil sample parameters. Because of the impacts of various natural and artificial factors on the real soil, the K value is not constant with respect to time. Therefore, to account for this temporal variability of K, the sampling continued also on the following days of the vegetation period: 14 May, 30 May, 16 June, 25 June, 14 July, 4 August, 16 September, and 15 October, 2003. During these days 205 undisturbed samples were taken. In each of the sampling days (except the first day), the sampling was performed only in the three verticals in each of the sampling site (at the vertices of a rectangular triangle 2 by 2 by 2.83 m).

The values of the saturated hydraulic conductivities denoted as K_{labor} were measured by the laboratory method with the falling head method.

Because the sampling could not be performed exactly at the same location, even on such a small place as defined by a radius of appr. 10 meters, it was necessary to take into account also the spatial variability in the determination of the K_{labor} values. Therefore, in each of the sampling days, samples were taken in the three verticals given above (in five verticals during the first sampling day). Because the sampled population of the K_{labor} of 244 undisturbed samples was further processed statistically, it was necessary to verify first the assumption of its log – normal statistical distribution (Šútor 1986).

The logarithms of the measured K_{labor} values were submitted to the Shapiro-Wilks test of normality (program Statistika, StatSoft, Inc.).

RESULTS AND DISCUSSION

The frequency function (probability density distribution function) of the log- normal distribution is as follows:

$$g(x) = \frac{1}{x} \cdot \frac{1}{\sigma_{\ell n(x)}\sqrt{2\pi}} \cdot e^{-\frac{(\ell n(x) - \mu_{\ell n(x)})^2}{2\sigma^2_{\ell n(x)}}} \quad (1)$$

The distribution function of the log- normal probability distribution is expressed by the equation :

$$G(x) = \frac{1}{x} \cdot \frac{1}{\sigma_{\ell n(x)}\sqrt{2\pi}} \int_0^x \frac{1}{x} \cdot e^{-\frac{(\ell n(x) - \mu_{\ell n(x)})^2}{2\sigma^2_{\ell n(x)}}} dx \quad (2)$$

where:

$g(x)$ – relative frequency of the x values in the class intervals of the statistical sample (%)

$G(x)$ – relative cumulative frequency of the x values in the class intervals of the statistical sample (%)

x – statistical sample values

$\sigma_{\ell n(x)}$ – standard deviation from the statistical sample mean value in the log-normal probability distribution

$\mu_{\ell n(x)}$ – mean value of the statistical sample in the log-normal probability distribution

W-statistic for N = 244 logarithms of the K_{labor} was W= 0.9952, with the error probability in rejecting the normality hypothesis p_p= 0.64. Taking in to account that this hypothesis is rejected at p_p= 0.05, the assumption that K_{labor} logarithms are normally distributed is highly probable (Mikulec 2005).

The frequency function for the population of all K_{labor} values is shown in Figure 3 and its corresponding distribution function in Figure 4.

The areal K_{labor} variability values measured during the year 2003 in the studied soil profile (0 to 115 cm) in the Most pri Bratislave locality are shown in Figure 5. It can be seen that a substantial part of the K_{labor} values belongs to the interval (1; 100) cm/d, and that the $\mathbf{K}_{labor}$ values show a slightly rising trend in their time course of the sampling days. A more detailed look at the time – areal variability of the K_{labor} values was possible by their interpretation in the soil profile levels 0–22 cm (Figure 6), 22–57 cm (Figure 7), 57–82 cm (Figure 8), and 82–115 cm (Figure 9). It is evident from these figures that the highest increase of the K_{labor} values can be observed in the upper soil profile layer 0–22 cm (Figure 6). The lower K_{labor} values measured were determined at the beginning of the vegetation season in the upper soil layer. It was mostly because of the soil compaction caused by the agricultural machines transport, and also because of the not yet developed root system of the maize on the locality of interest. The later rise of the K_{labor} values in the upper soil layer during the year has been attributed to the vegetation root system development and to the processes of animal life in the soil on the experimental locality.

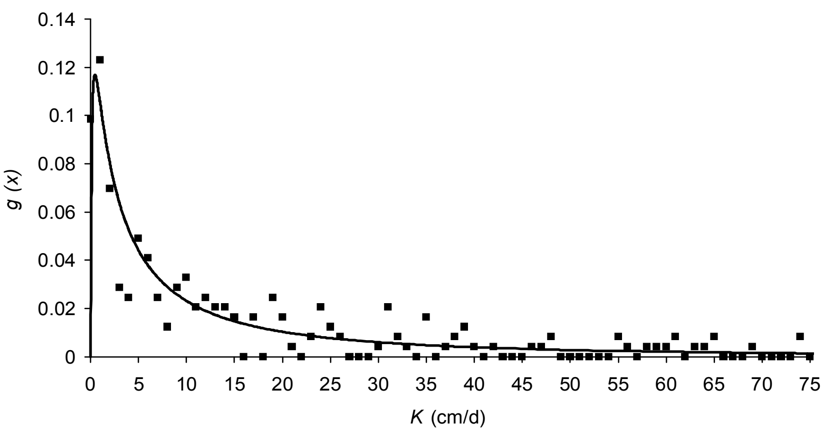

Figure 3. Empirical relative frequency and theoretical density of the log- normal distribution of the K_{labor} values, for all measurements performed on the samples taken during the period 17. 3.–15. 10. 2003 in the soil horizon 0–120 cm, in the locality Most pri Bratislave

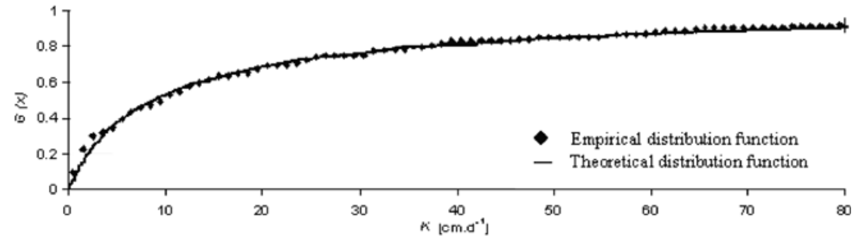

Figure 4. Empirical and theoretical distribution functions of the log- normal probability distribution of the K_{labor} values, for all measurements performed on the samples taken during the period 17. 3.–15. 10. 2003 in the soil horizon 0–120 cm, in the locality Most pri Bratislave

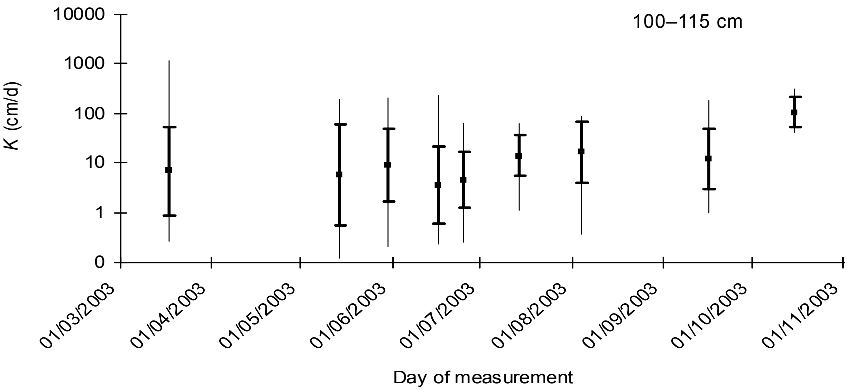

Figure 5. Temporal course and areal variability of the K_{labor} values measured for the whole soil profile depth 0–115 cm on the samples taken during the year 2003 in Most pri Bratislave, expressed by the values of maximum, minimum, arithmetic mean, and the standard deviation from the mean

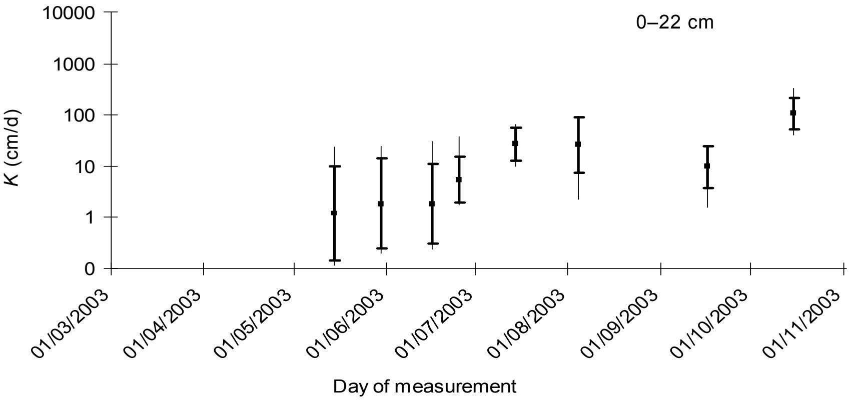

Figure 6. Temporal course and areal variability of the K_{labor} values measured for the soil profile layer 0–22 cm on the samples taken during the year 2003 in Most pri Bratislave, expressed by the values of maximum, minimum, arithmetic mean, and the standard deviation from the mean

In relation to the sampling elevation horizons of the undisturbed samples, the thicknesses of the soil layers were determined in the course of the unsaturated soil zone (USZ). In these layers, the temporal variability of the K_{labor} measured values was then determined (Figure 10).

However, its statistical parameters can be considered only as informative because from some soil layers only few samples were taken with respect to time. More representative results can be obtained in the deeper soil profile layers. Therefore, the K_{labor} temporal variability mean values were determined for those layers, in which also the areal variability was determined. Graphical interpretation of the K_{labor} temporal variability in the soil profiles (0–22 cm, 22–57 cm, 57–82 cm, and 82–115 cm) is shown in Figure 11. It can be also seen, that the highest temporal variability of the K_{labor} mean values can be observed in the upper soil profile layer 0–22 cm.

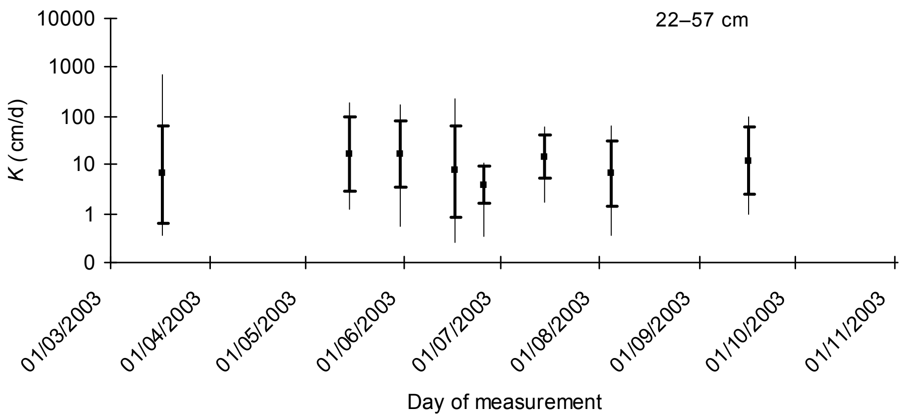

Figure 7. Temporal course and spatial variability of the K_{labor} values measured for the soil profile layer 22–57 cm on the samples taken during the year 2003 in Most pri Bratislave, expressed by the values of maximum, minimum, arithmetic mean, and the standard deviation from the mean (thin lines)

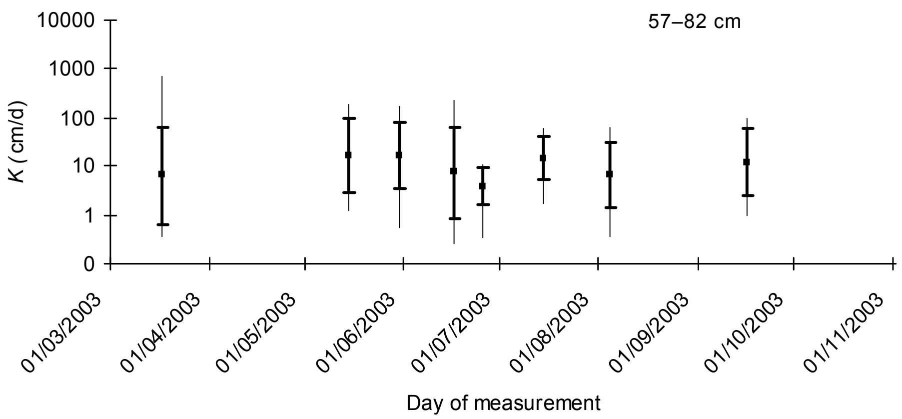

Figure 8. Temporal course and areal variability of the K_{labor} values measured for the soil profile layer 57–82 cm on the samples taken during the year 2003 in Most pri Bratislave , expressed by the values of maximum, minimum, arithmetic mean, and the standard deviation from the mean (thin lines)

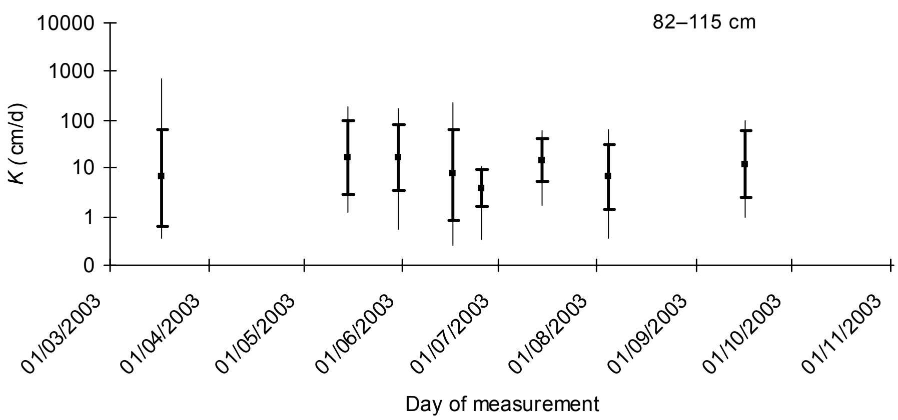

Figure 9. Temporal course and areal variability of the K_{labor} values measured for the soil profile layer 82–115 cm on the samples taken during the year 2003 in Most pri Bratislave, expressed by the values of maximum, minimum, arithmetic mean, and the standard deviation from the mean (thin lines)

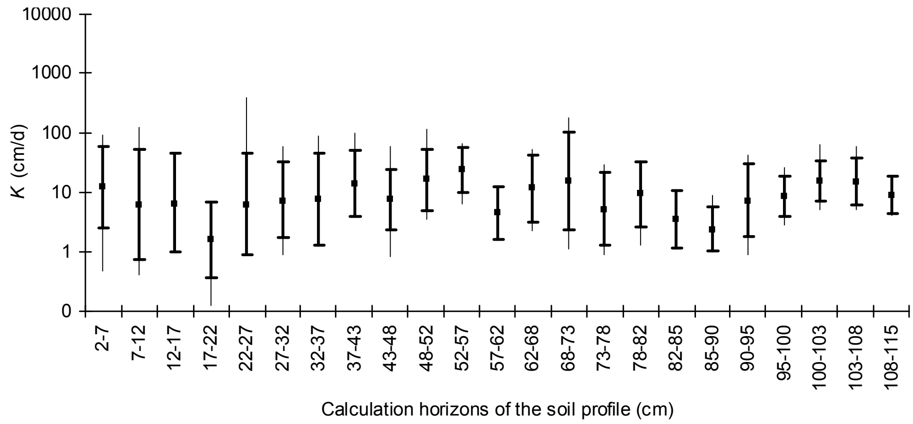

Figure 10. Temporal variability of the K_{labor} values determined in the samples taken on the sampling days of the 2003 vegetation period on the Most pri Bratislave locality, in several calculation horizons of the soil profile, expressed by the values of maximum, minimum, arithmetic mean, and the standard deviation from the mean (thin lines)

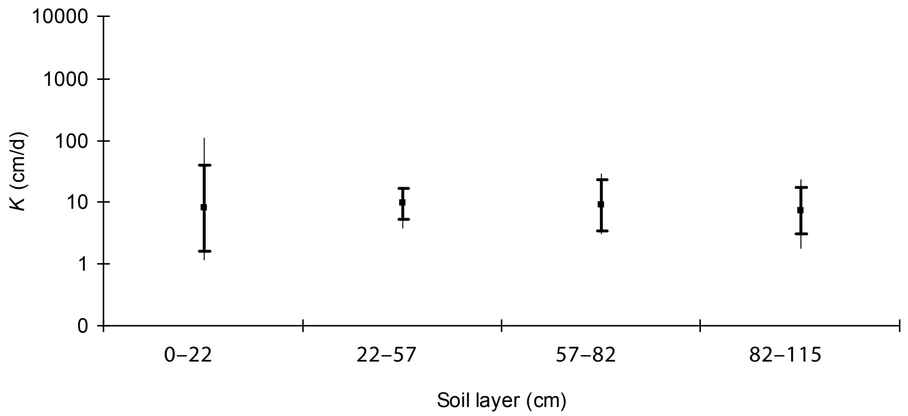

Figure 11. Temporal variability of the K_{labor} mean values in the 2003 vegetation period on the Most pri Bratislave locality; for several layers (0–22; 22–57; 57–82, and 82–115 cm) of the soil profile, expressed by the values of maximum, minimum, arithmetic mean, and the standard deviation from the mean (thin lines)

CONCLUSION

The temporal and areal variabilities of the saturated hydraulic conductivities K_{labor} were evaluated for the vegetation period in the year 2003, on the locality Most pri Bratislave. The study was aimed at the determination of the time course of this soil characteristics during the year 2003, particularly during its vegetation period.

In total, 244 samples of the saturated hydraulic conductivity values were evaluated, by the changing slope laboratory method on the undisturbed samples taken with the Kopecky cylinders.

Shapiro-Wilks normality test was applied to the data observed. It was confirmed that the logarithms of the observed and processed data can be characterised by the normal distribution.

It was further found that the K_{labor} normal values in the course of the vegetation period indicate a slightly rising trend for the whole soil profile 0–115 cm.

A more detailed look at the space-temporal variability of K_{labor} enabled its graphical interpretation in the soil layers of 0–22 cm, 22–57 cm, 57–82 cm, and 82–115 cm.

The increase (not very significant) of the K_{labor} values was observed in the uppermost soil layer (0–22 cm) of the soil profile. The lower K_{labor} values, observed at the beginning of the vegetation period even in the upper soil layer 0–22 cm, were due to the soil compacting by the transport of the agricultural machinery at that time of the year, and also to the not yet fully developed root system of the cultivated vegetation on the experimental plot (maize). The later increase of the K_{labor} values in the course of the vegetation period was caused edirectly by the plant root development, and also by the activities of the animals living in the soil of the locality in question.

The highest temporal variability of the K_{labor} mean values was also observed in the same layer 0–22 cm of the soil profile.

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