The Impact of Vegetation on Hydraulic Conductivity of Sandy Soil

Ľubomír LICHNER[1], Tomáš ORFÁNUS[1], Katarína NOVÁKOVÁ[2], Miloslav ŠÍR[3] and Miroslav TESAŘ[3]

[1]Institute of Hydrology, Slovak Academy of Sciences, Bratislava, Slovak Republic;
[2]Soil Science and Conservation Research Institute, Bratislava, Slovak Republic;
[3]Institute of Hydrodynamics of the ASCR, Prague, Czech Republic

Abstract: The objective of this study was to assess the impact of vegetation on the hydraulic conductivity of sandy soil at the locality Mláky II at Sekule (southwest Slovakia). The measurements were taken on the surface of a meadow (Meadow site), a 30-year old Scots pine (*Pinus sylvestris*) forest (Forest site) and a glade (Glade site). In the glade, the measurements were also taken in the depth of 50 cm (Pure sand) to reduce the influence of vegetation on the soil properties. It was found that the unsaturated hydraulic conductivity $k_r(-2 \text{ cm})$ as reduced due to the soil water repellency increased in the same order: Forest soil < Glade soil ≈ Meadow soil < Pure sand, similarly as decreased the water drop penetration time t_p: Forest soil > Glade soil ≈ Meadow soil > Pure sand, which could refer to an inverse proportionality between the capillary suction and hydrophobic coating of the soil particles. The saturated hydraulic conductivity K_s increased in the following order: Meadow soil < Glade soil ≈ Forest soil < Pure sand; more than two-times higher K_s at both the Forest and Glade sites than that at the Meadow site could be the result of both the patchy growth of vegetation with some areas of bare soil at the Glade site and the macropores (dead roots) in more homogeneous humic top-layer at the Forest site. The share B_r of flux through the pores with radii r longer than approximately 0.5 mm decreased in the order: Forest soil ≫ Meadow soil > Glade soil ≫ Pure sand, revealing the prevalence of preferential flow through macropores (dead roots) in the Forest site and a negligible share of macropores in the Pure sand.

Keywords: sandy soil; hydraulic conductivity; vegetation; water repellency

The frequency and intensity of heavy rains following long dry and hot spells (and resulting in a pronounced surface runoff and soil erosion) increase as a result of the climate change (Hardy 2003). The infiltration, i.e. the entry of water (or other liquid) into the soil through its surface, separates rain into two parts. One part stored within the soil supplies water to the soil organisms and roots of vegetation, and recharges groundwater. The other part forms the surface runoff (Kutilek & Nielsen 1994).

Sands devoid of vegetation are able to absorb all rainwater up to the rainfall intensity of 300 mm/h (Yair 2003). Plants and biological crusts (cyanobacteria, algae, lichens, nonlichenized fungi, and

Supported by the Science and Technology Assistance Agency, Project No. APVV-51-017804, the Scientific Grant Agency VEGA, Project No. 2/6003/26, the Academy of Sciences of the Czech Republic, Institutional Research Plan No. AV0Z20600510, and the Czech Science Foundation, Project No. GA 205/05/2312.

bryophytes) can increase infiltration and soil water content in fine-grained soils, reduce infiltration, and generate runoff in sandy soils. The biological crust forms a humus fine-grained "umbrella" over the coarser material, resulting in the anisotropy of unsaturated hydraulic conductivity (Yeh *et al.* 1985) and leading an excess of water horizontally to the trees or shrubs, locally increasing the water input to plants. Vegetation and soil animals can also produce the amphiphilic organic compounds (occurring in e.g. root, fungal hyphae, and animal exudates, waxes from plant leaves or needles, as well as decomposing organic matter), which coat soil particles with films that considerably alter the surface properties (Czarnes *et al.* 2000). These compounds are hydrophilic when wet, but below the critical moisture threshold, their hydrophilic ends bond strongly with one another and the soil particles, while hydrophobic ends are oriented towards the free space (air) inducing water repellency (Doerr *et al.* 2000).

Soil water repellency (hydrophobicity) influences the water transport and retention in soil, plant growth, surface runoff, and soil erosion (Doerr *et al.* 2000). It can be alleviated by cultural practices such as core aeration followed by sand topdressing and the application of a wetting agent (Mitra *et al.* 2006), claying with kaolinite clays (McKissock *et al.* 2002; Lichner *et al.* 2006), liming (to enhance pH), and inoculation with wax-degrading bacteria *Rhodococcus* sp. and *Roseomonas* sp. (Roper 2006). Water repellency (WR) tends to be both spatially and temporally highly variable. It often disappears after prolonged wet periods, but will usually re-emerge during drier periods when the soil moisture falls below the critical threshold (Dekker *et al.* 2001).

The objective of this study was to assess the impact of vegetation on the hydraulic conductivity of sandy soil at the locality Mláky II at Sekule (southwest Slovakia) during hot and dry spells with well-pronounced water repellency.

MATERIAL AND METHODS

Field experiments were conducted at Mláky II near Sekule in the Borská nížina lowland (southwest Slovakia) where sand dunes with surface eolian sand occur on about 570 km^2 (Kalivodová *et al.* 2002). The elevation of the locality studied is 150 m a.s.l., the average annual air temperature is 9°C, and the annual precipitation total 500–600 mm. The measurements were taken on the surfaces of a meadow (Meadow site), a 30-year old Scots pine (*Pinus sylvestris*) forest ("Forest" site), and a glade (Glade site). In the glade, the measurements were also taken in the depth of 50 cm to reduce the influence of vegetation on the soil properties (Pure sand). The soil was a Regosol formed from windblown sand (WRB 1994) and had a sandy texture (Soil Survey Division Staff 1993). The thickness of the A horizon depended on the vegetation cover and was about 15 cm at the Meadow site and about 1 cm at the Forest site. The poorly developed A horizon at the Glade site had a patchy pattern, with the thickness of less than 1 cm below vegetation. Some areas at this site revealed exposed bare soil without A horizon. At all the sites, a wettable C horizon extended to the depth of about 2 m, where the groundwater table occurred. Physical and chemical properties of the soil samples are presented in Table 1.

The grass species predominated at the Meadow site, and the most frequent ones were the species from the family *Poaceae* (*Agrostis capilaris* and *Cynodon dactylon*), than *Achillea millefolium*, *Acetosella vulgaris*, *Anthemis ruthenica*, *Convolvulus arvensis*, *Lepidium ruderale*, *Plantago lanceolata* and *Potentilla* sp. From the moss species, *Brachythecium albicans* was present at this site. From the soil microfungi species, *Alternaria alternata*, *Aureobasidium pullulans*, *Cladosporium cladosporioides*, *Humicola fuscoatra*, *Mortierella* sp., *Mycelia sterilia*, *Paecilomyces* sp., *Penicillium* sp., *Penicillium aspergiloides*, *Penicillium decum-*

Table 1. Physical and chemical properties of the soil samples taken at Mláky II near Sekule (southwest Slovakia)

Site	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (%)	C (%)	pH (H_2O)	pH (KCl)
Meadow	0–5	91.26	2.81	5.93	< 0.05	0.99	5.14	3.91
Pine forest	0–1	95.14	2.26	2.60	< 0.05	0.83	5.65	4.39
Glade	0–5	94.14	0.84	5.02	< 0.05	0.11	5.52	3.96
Glade (= Pure sand)	50–55	94.86	1.74	3.40	< 0.05	0.03	5.54	4.20

bens, *Trichoderma koningii*, and *Trichoderma* sp. were present at the Meadow site.

The soil surface at both the Forest and Glade sites was covered mostly with the moss species *Polytrichum piliferum*, then with lichens (*Cladonia* sp.), and in isolated cases with the grass species *Corynephorus canescens*. From the soil microfungi species, *Alternaria alternata*, *Aspergillus fisheri*, *Aspergillus glaucus*, *Aureobasidium pullulans*, *Chaetomium globosum*, *Humicola fuscoatra*, *Mortierella* sp., *Mycelia sterilia*, *Paecilomyces* sp., *Penicillium* sp., *Penicillium aspergiloides*, *koningii*, and *Trichoderma koningii* were present at both the Forest and Glade sites (Lichner *et al.* 2005, 2007). The nomenclature was used according to Nyholm (1965, 1969), Dostál (1991, 1992), and Marhold and Hindák (1998) for the plant determination, and Tomilin (1979), Domsch *et al.* (1980) and Samson *et al.* (1981) for the fungi determination.

The hot and dry spells were determined on the basis of the daily temperature maximums and daily precipitation amounts as measured at the meteorological station of the Slovak Hydrometeorological Institute in Moravský Svätý Ján at a distance of about 5 km from the locality studied (Table 2). These spells with well-propagated soil water repellency occurred from 13–29 June 2005, 12 July–13 August 2005, 1 July–2 August 2006, and 1 September–30 September 2006. The measurements were taken on 29 June, 2005, 15, 27, and 28 July, 2005, 3 August, 2005, 24, and 25 July, 2006, and 25 September, 2006, with n = 3–5 replicates.

The soil water content θ was estimated by the gravimetric method, with the mass of the soil sample taken before and after drying at 50°C (Kutilek & Nielsen 1994).

The persistence of WR was measured by means of the water drop penetration time (WDPT) test. Three drops of distilled water from a medicinal dropper were placed onto the soil surface and the actual time t_p required for infiltration was recorded. The volume of water in a droplet was 58 ± 5 μl. A standard droplet release height of approximately 10 mm over the soil surface was used to minimise the cratering effect on the soil surface (Doerr 1998). The following classes of the persistence of WR were distinguished: wettable or non-water-repellent soil (the water drop penetration time t_p < 5 s); slightly (t_p = 5–60 s), strongly (t_p = 60–600 s), severely (t_p = 600–3600 s), and extremely (t_p > 3600 s) water repellent soil (Dekker *et al.* 2001).

Infiltration was performed both with a small positive pressure head h_0 = +2 cm with a double-ring infiltrometre and with the negative pressure head h_0 = –2 cm with the mini disc infiltrometer of Decagon Devices, Inc. The double-ring infiltrometer has the inner-ring diameter of 24.5 cm, the buffer ring the diameter of 34.5 cm, and the length of 23.5 cm. Total length of the mini disc infiltrometer is 32.7 cm, the sintered stainless steel disc has a diameter of 4.5 cm and thickness of 3 mm, the suction range is from –0.5 to –6 cm, and the volume of water (ethanol) required to operate is 135 ml. The diagram of the mini disc infiltrometer together with its detailed description can be found in the Minidisk Infiltrometer User´s Manual (Decagon 2005) or at http://www.decagon.com/manuals/infiltman.pdf.

The cumulative infiltration I, numerically equal to the volume of water infiltrating through an individual area of soil in the unit of time, can be calculated from the Philip infiltration equation (Philip 1957):

$$I = C_1\, t^{1/2} + C_2\, t + C_3\, t^{3/2} + C_4\, t^2 + \ldots + C_m\, t^{m/2} + \ldots \quad (1)$$

where:

$C_1, C_2, C_3, C_4, \ldots, C_m$ – coefficients,

t – time.

Zhang (1997) proposed to estimate the sorptivity $S(h_0)$ and unsaturated hydraulic conductivity $k(h_0)$ at suction $h_0 \leq 0$ from:

$$I = C_1(h_0)\, t^{1/2} + C_2(h_0)\, t \quad (2)$$

where:

$C_1(h_0)$ and $C_2(h_0)$ – functions of the soil water content θ and suction h_0.

The sorptivity $S(h_0)$ and unsaturated hydraulic conductivity $k(h_0)$ at suction $h_0 \leq 0$ can be calculated from (Zhang 1997):

$$S(h_0) = C_1(h_0)/A_1 \quad (3)$$

and

$$k(h_0) = C_2(h_0)/A_2 \quad (4)$$

where:

A_1 and A_2 – constants.

In this study, Eq. (4) was used to estimate the unsaturated hydraulic conductivity k_r(–2 cm) reduced

Table 2. The daily temperature maximums T_m and daily precipitation amounts *DPT* measured in the meteorological station of the Slovak Hydrometeorological Institute in Moravský Svätý Ján (southwest Slovakia); the hot and dry spells are accentuated by shading

Day	June 2005		July 2005		August 2005		July 2006		August 2006		September 2006	
	T_m (°C)	*DPT* (mm)	T_m (°C)	*DPT* (mm)	T_m (°C)	*DPT* (mm)	T_m (°C)	*DPT* (mm)	T_m (°C)	*DPT* (mm)	T_m (°C)	*DPT* (mm)
1.	20.7		25.5	19.1	29.6		22.5		25.5	1.5	24	
2.	24.2		23.0	0.9	32.0	0.1	25.3		26.1		26	0.2
3.	28.8		27.0		27.2	4.0	25.6		21	30.4	24.8	0.7
4.	27.5	23.0	29.0		19.0	2.3	27.3		18.3	2.8	28.5	
5.	22.0	0.1	21.4	23.5	22.6		27.8		20.2	13.7	25.5	
6.	22.2	6.3	22.0		25.5		29.8		23	4.9	25.8	
7.	16.5	0.1	25.0	1.3	22.2	0.1	31.3		18.8	26.4	27.8	4.0
8.	14.8	0.1	17.4	8.7	20.8	0.1	30		22.8	2.7	21.6	
9.	13.7	6.0	18.7	5.0	22.7	0.3	31	5	24.5		21.5	
10.	17.0	0.3	22.5	6.6	27.4		31.5		25.1		23.5	
11.	20.0	2.0	23.0	39.0	27.0		33	0.5	23.8		24.8	
12.	20.7		23.0	0.1	26.5		32		19.8	10.1	25.2	
13.	27.3		28.5	2.6	25.3		32.5		22.2		25.1	
14.	28.3		28.5		26.6	22.4	30.8	0.7	24	6.3	25.8	
15.	27.5		31.1	0.9	19.6	24.0	25.6		23.7	0.5	24.7	
16.	26.8		30.4		21.0	0.4	24.2		26.5		23.2	1.7
17.	28.5		27.6		22.2	1.6	26		30.5		25.1	
18.	26.3		32.5	1.6	27.6		30.3		31.5		23.2	0.7
19.	24.6		27.0	6.2	28.0		33.5		28.5		23	
20.	26.4		25.7		29.2		33.8		27.8	5.1	24.1	
21.	28.0		22.0		25.0	4.2	35.7	2	23.5	0.2	24.3	
22.	27.7	0.2	23.3		21.4	7.9	34.2		21	1.6	24.1	
23.	27.2		23.0	0.7	23.8	0.8	34		24	0.1	24.5	
24.	29.6		26.8		20.1	3.0	32.8		25.7	2	25.3	
25.	33.2		30.7	2.7	27.0	0.2	33.2		19.2	6.6	24.5	
26.	27.0	3.9	27.0	0.1	24.5	0.3	33		23.7	0.2	26.8	0.1
27.	27.7		32.0		25.2	6.2	33.8		23	0.6	24.5	
28.	30.6		35.2		22.3	21.0	34.6		23	2	23.5	
29.	28.5	0.1	35.8		27.5		29.7		19	0.2	24.2	
30.	24.1	6.6	34.5		29.0		31		18.1	9.6	25.2	
31.			27.3		29.5		32.5	1	15.7	4.6		

due to soil water repellency, using A_2 = 2.4 for sandy soil and suction h_0 = –2 cm from Table 2 in the Minidisk Infiltrometer User's Manual (Decagon 2005). More information on the method of estimating the hydraulic conductivity can be found at http://www.decagon.com/manuals/infiltman.pdf.

The first two and three terms of the Philip infiltration equation (1) can be used to estimate the saturated hydraulic conductivity K_s. The first two terms are applicable to relatively short times as follows:

$$I \approx S\,t^{1/2} + mK_s t \qquad (5)$$

with $m = 0.667$ being the most frequently used value (Kutilek & Nielsen 1994).

Kutílek and Krejča (1987) proposed to use three terms of the Philip infiltration equation:

$$I = C_1\,t^{1/2} + C_2\,t + C_3\,t^{3/2} \qquad (6)$$

where:
C_1 – estimate of sorptivity S

$$K_s \approx (3\,C_1\,C_3)^{1/2} + C_2 \qquad (7)$$

is the estimate of saturated hydraulic conductivity K_s. Eq. (5) and (7) were used to estimate the saturated hydraulic conductivity K_s in this study.

The share of flux through the pores with radii r more than approximately 0.5 mm (macropores) called bypassing ratio B_r, was calculated from:

$$B_r = [K_s - k_r(-2\text{ cm})]/K_s \qquad (8)$$

where K_s calculated from Eq. (5) was used. The pore radius r fit the equation:

$$r = 2\sigma\cos\alpha/\rho g h_0 \qquad (9)$$

where:
σ – surface tension of water,
α – contact angle between the water and the pore wall,
ρ – density of water,
g – acceleration due to gravity,
h_0 = −2 cm – suction in mini disc infiltrometer (Watson & Luxmoore 1986).

The contact angle α was set to about 45° in accordance with the findings by Czachor (2006). It should be mentioned that the bypassing ratio B_r can be considered as a rough estimate only, owing to different areas treated with infiltrometers (the inner-ring diameter of the double-ring infiltrometer was 24.5 cm, and the diameter of the disc of mini disc infiltrometer was 4.5 cm). It is well known that the results of hydraulic conductivity measured with the mini disc infiltrometer depend on the disc diameter (Wang *et al.* 1998), and the results of saturated hydraulic conductivity double-ring infiltrometer depend on the inner-ring diameter (Mallants *et al.* 1997) owing to the heterogeneity of field soils (Kutilek & Nielsen 1994).

It should be mentioned that both grass and moss covers (but not the soil) were removed prior to the measurements. This has the disadvantage that the changes in infiltration can only be ascribed to a combination of the removal of the plant cover and the disturbance of the soil surface (Eldridge 2003).

RESULTS AND DISCUSSION

The results of θ, t_p, $k_r(-2\text{ cm})$, K_s (from both Eq. (5) and Eq. (7)) and B_r, obtained at the locality Mláky II at Sekule (southwest Slovakia) in hot and dry spells with well-propagated soil water repellency (13–29 June 2005, 12 July–13 August 2005, 1 July–2 August 2006, and 1 September to 30 September 2006), are summarised in Table 3. There was a greater variability of the soil hydraulic properties (coefficient of variation > 15%), which is typical given the heterogeneity of soil (Kutilek & Nielsen 1994) and corresponds to other studies in this region (e.g. Šútor 1986). It was found that the unsaturated hydraulic conductivity $k_r(-2\text{ cm})$ as reduced due to soil water repellency increased in the same order: Forest soil < Glade soil ≈ Meadow soil < Pure sand as decreased the water drop penetration time t_p: Forest soil > Glade soil ≈ Meadow soil > Pure sand, which could refer to an inverse proportionality between the capillary suction and hydrophobic coating of the soil particles. Much lower values of $k_r(-2\text{ cm})$ measured at the Forest site (in comparison with the Meadow and Glade sites) could be the result of waxes eroded from pine needles which have been shown to have a large influence on water repellency. These findings are in accordance with those by Buczko *et al.* (2002) in the investigated forest site Kahlenberg containing populations of *Pinus sylvestris* and *Fagus sylvatica* where the WDPT test revealed a significant proportion of severely and extremely hydrophobic samples in the upper 10 cm of sandy luvisols in all plots, whereas the persistence of repellency decreased with the increasing soil depth. The thickness of the humic topsoil in Kahlenberg (3.5–8.5 cm) was higher than that in our Forest site as a result of the higher age of trees (76–114 years in the case of *Pinus sylvestris*).

It should be mentioned that the values of t_p, $k_r(-2\text{ cm})$, as well as sorptivity and index of water repellency, measured in the studied locality in

Table 3. The impact of vegetation on hydraulic conductivity of sandy soil at the locality Mláky II near Sekule (southwest Slovakia); The results for n measurements are presented in the form: arithmetic mean ± standard deviation

Site	Depth (cm)	n	θ (%)	t_p (s)	k_r (–2 cm) (m/s)	K_s (from Eq. (5)) (m/s)	K_s (from Eq. (7)) (m/s)	B_r (–)
Meadow	0	5	0.39	1398 ± 2714	$(2.45 \pm 2.88) \times 10^{-5}$	$(8.98 \pm 5.66) \times 10^{-5}$	$(3.88 \pm 4.07) \times 10^{-5}$	0.727
Pine forest	0	4	0.22	5241 ± 2104	$(2.50 \pm 2.36) \times 10^{-7}$	$(1.97 \pm 0.43) \times 10^{-4}$	$(1.12 \pm 0.53) \times 10^{-4}$	0.999
Glade	0	4	0.55	1885 ± 3544	$(5.83 \pm 4.26) \times 10^{-5}$	$(1.82 \pm 0.33) \times 10^{-4}$	$(7.37 \pm 3.88) \times 10^{-5}$	0.680
Glade (= Pure sand)	50	3	4.98	1	$(4.60 \pm 1.08) \times 10^{-4}$	$(5.29 \pm 1.68) \times 10^{-4}$	$(3.17 \pm 0.94) \times 10^{-4}$	0.130

dry spells, were significantly different from those measured in wet spells with different initial soil water contents (Lichner *et al.* 2007).

The saturated hydraulic conductivity K_s increased in the order as follows: Meadow soil < Glade soil ≈ Forest soil < Pure sand. More than two-times higher K_s at both the Forest and Glade sites than that at the Meadow site could be the result of both the patchy growth of vegetation with some areas of bare soil at the Glade site, and macropores (dead roots) in more homogeneous humic top-layer at the Forest site. It should be mentioned that K_s calculated from Eq. (7) was only 43.2%, 40.5%, 56.9% and 59.9% of K_s calculated from Eq. (5) for Meadow, Glade and Forest soil, and Pure sand, respectively.

The share B_r of flux through the pores with radii r more than approximately 0.5 mm decreased in the order: Forest soil ≫ Meadow soil > Glade soil ≫ Pure sand, revealing the prevalence of preferential flow through macropores (dead roots) in the Forest site and a negligible share of macropores in Pure sand.

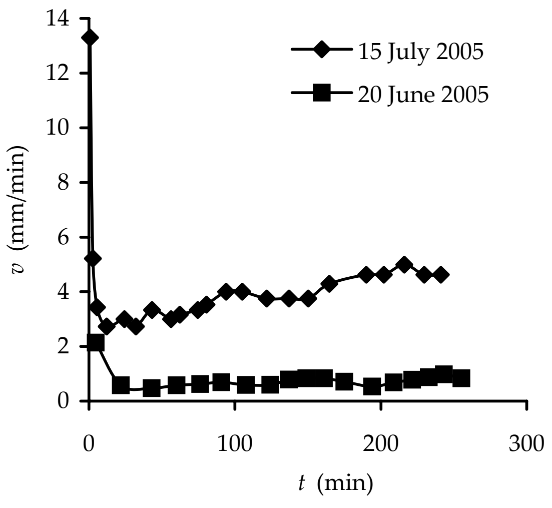

Figure 1. The infiltration rate v vs. time t relationships measured with the double-ring infiltrometer at pressure head h_0 = +2 cm at the Meadow site on 20 June, 2005 (t_p = 1800 s, θ = 0.93%), and 15 July, 2005 (t_p = 24 s, θ = 3.1%)

The infiltration rate v vs. time t relationships measured with the double-ring infiltrometer at the pressure head h_0 = +2 cm at the Meadow site on 20 June, 2005 (t_p = 1800 s, θ = 0.93%), and 15 July, 2005 (t_p = 24 s, θ = 3.1%) are presented in Figure 1. The impact of water repellency on the shape of v vs. t relationship is more pronounced for the latter date with lower persistence of WR (at the beginning of hot and dry spell). An uncommon rise in the saturated infiltration rate after about 30 minutes could be the consequence of the breakdown of hydrophobicity in the studied soil, in conformity with the interpretation of a similar time course of the unsaturated infiltration rate at the pressure head h_0 = –40 mm observed by Clothier *et al.* (2000).

CONCLUSION

It can be stated that soil biota and terrestrial plants can change the physical properties of soils through both the hydrophobic coating of the soil particles and the surface-vented macropores. The unsaturated hydraulic conductivity seems to be strongly influenced by the hydrophobic coating due to different plant coverage, which corresponds to the results of WDPT tests. On the other hand, the surface-vented macropores lead the majority of water from ponding (i.e. under the conditions similar to a heavy rain event), as indicated by high values of the share of flux through the pores with radii longer than approximately 0.5 mm. A further study is proposed to make evidence of these statements and to find the direct quantitative link between the variability in the parameters assessed and physical changes of soil due to different canopy activities.

Acknowledgements. The authors thank Alexander Daneček, Zuzana Nižnanská and Michal Sebíň (Institute of Hydrology SAS, Bratislava) for their assistance in the field measurements. Dr. Olívia Ďugová (Institute of Landscape Ecology SAS, Bratislava) is greatly acknowledged for the microfungi determination, Zuzana Nižnanská for the plant determination, and Dr. Pavol Faško (Slovak Hydrometeorological Institute, Bratislava) for providing the data from the meteorological station of the Slovak Hydrometeorological Institute in Moravský Svätý Ján. Special thanks are expressed to Dr. Viliam Novák (Institute of Hydrology SAS, Bratislava) and the anonymous reviewer for their valuable comments to the manuscript.

References

Buczko U., Bens O., Fischer H., Hüttl R.F. (2002): Water repellency in sandy luvisols under different forest transformation stages in northeast Germany. Geoderma, **109**: 1–18.

Clothier B.E., Vogeler I., Magesan G.N. (2000): The breakdown of water repellency and solute transport through a hydrophobic soil. Journal of Hydrology, **231–232**: 255–264.

Czachor H. (2006): Modelling the effect of pore structure and wetting angles on capillary rise in soils having different wettabilities. Journal of Hydrology, **328**: 604–613.

Czarnes S., Hallett P.D., Bengough A.G., Young I.M. (2000): Root- and microbial-derived mucilages affect soil structure and water transport. European Journal of Soil Science, **51**: 435–443.

Decagon (2005): Minidisk Infiltrometer User's Manual. Decagon Devices, Inc., Pullman.

Dekker L.W., Doerr S.H., Oostindie K., Ziogas A.K., Ritsema C.J. (2001): Water repellency and critical soil water content in a dune sand. Soil Science Society of America Journal, **65**: 1667–1674.

Doerr S.H. (1998): On standardizing the "Water Drop Penetration Time" and the "Molarity of an Ethanol Droplet" techniques to classify soil hydrophobicity: a case study using medium textured soils. Earth Surface Processes and Landforms, **23**: 663–668.

Doerr S.H., Shakesby R.A., Walsh R.P.D. (2000): Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Reviews, **51**: 33–65.

Domsch K.H., Gams W., Anderson T.H. (1980): Compendium of Soil Fungi. Academic Press, London.

Dostál J. (1991): Key for Determination of Vascular Plants I. Slovenské pedagogické nakladateľstvo, Bratislava. (in Slovak)

Dostál J. (1992): Key for Determination of Vascular Plants II. Slovenské pedagogické nakladateľstvo, Bratislava. (in Slovak)

Eldridge D.J. (2003): Biological soil crusts and water relations in Australian deserts. In: Belnap J., Lange O.L. (eds.): Biological Soil Crusts: Structure, Function, and Management. 2nd Ed. Springer, Berlin, 315–325.

Hardy J.T. (2003): Climate Change. Causes, Effects, and Solutions. Wiley, Chichester.

Kalivodová E., Kubíček F., Bedrna Z., Kalivoda H., Gavlas V., Kollár J., Gajdoš P., Štepanovičová O. (2002): Sand Dunes of Slovakia. Luka-Press, Bratislava. (in Slovak)

Kutílek M., Krejča M. (1987): A three-parameters infiltration equation of the Philip's type solution. Vodohospodářský časopis, **35**: 52–61. (in Czech)

Kutilek M., Nielsen D.R. (1994): Soil Hydrology. Catena, Cremlingen-Destedt.

Lichner Ľ., Nižnanská Z., Faško P., Šír M., Tesař M. (2005): The impact of plant cover and weather on soil-hydrological parameters of a water repellent soil at the locality Mláky II at Sekule. Acta Hydrologica Slovaca, **6**: 321–329. (in Slovak)

Lichner Ľ., Dlapa P., Doerr S.H., Mataix-Solera J. (2006): Evaluation of different clay mineralogies as additives for soil water repellency alleviation. Applied Clay Science, **31**: 238–248.

Lichner Ľ., Hallett P.D., Feeney D., Ďugová O., Šír M., Tesař M. (2007): Field measurement of the impact of hydrophobicity on soil water transport under different vegetation over time. Biologia, Bratislava. (submitted)

Mallants D., Mohanty B.P., Vervoort A., Feyen J. (1997): Spatial analysis of saturated hydraulic conductivity in a soil with macropores. Soil Technology, **10**: 115–131.

Marhold K., Hindák F. (1998): Checklist of Non-Vascular and Vascular Plants of Slovakia. Veda, Bratislava. (in Slovak)

McKissock I., Gilkes R.J., Walker E.L. (2002): The reduction of water repellency by added clay as influenced by clay and soil properties. Applied Clay Science, **20**: 225–241.

Mitra S., Vis E., Kumar R., Plumb R., Fam M. (2006): Wetting agent and cultural practices increase infiltration and reduce runoff losses of irrigation water. Biologia, Bratislava, **61** (Suppl. 19): S353–S357.

Nyholm E. (1965): Ilustrated Moss Flora of Fenoscandia. Vol. II. Musci. Fasc. 5. CWK Gleerup, Lund, 407–647.

Nyholm E. (1969): Ilustrated Moss Flora of Fenoscandia. Vol. II. Musci. Fasc. 6. Natural science research council, Stockholm.

Philip J.R. (1957): The theory of infiltration: 1. The infiltration equation and its solution. Soil Science, **83**: 345–357.

Roper M.M. (2006): Potential for remediation of water repellent soils by inoculation with wax-degrading bacteria in south-western Australia. Biologia, Bratislava, **61** (Suppl. 19): S358–S362.

Samson R.A., Hoekstra E.S., van Oorschot C.A.N. (1981): Introduction to Foot-Borne Fungi. Centraal voor Schimmelcultures, Baarn. (in Dutch)

Soil Survey Division Staff (1993): Soil Survey Manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18.

Šútor J. (1986): Spatial variability of soil hydraulic properties. Vodohospodársky Časopis, **34**: 284–313. (in Slovak)

Tomilin B.A. (1979): Guide to Fungi. Nauka, Leningrad. (in Russian)

Wang D., Yates S.R., Lowery B., van Genuchten M.Th. (1998): Estimating soil hydraulic properties using tension infiltrometers with varying disk diameters. Soil Science, **163**: 356–361.

Watson K.W., Luxmoore R.J. (1986): Estimating macroporosity in a forest watershed by use of a tension infiltrometer. Soil Science Society of America Journal, **50**: 578–582.

WRB (1994): World Reference Base for Soil Resources. Wageningen/Rome.

Yair A. (2003): Effects of biological soil crusts on water redistribution in the Negev desert, Israel: a case study in longitudinal dunes. In: Belnap J., Lange O.L. (eds.): Biological Soil Crusts: Structure, Function, and Management. 2nd Ed. Springer, Berlin, 303–314.

Yeh T.-C.J., Gelhar L.W., Gutjahr A.L. (1985): Stochastic analysis of unsaturated flow in heterogeneous soils. 3. Observations and applications. Water Resources Research, **21**: 465–471.

Zhang R. (1997): Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Science Society of America Journal, **61**: 1024–1030.

Corresponding author:

Ing. Ľubomír Lichner, CSc., Ústav hydrológie SAV, Račianska 75, 831 02 Bratislava, Slovak Republic
tel.: + 421 249 268 227, fax: + 421 244 259 404, e-mail: lichner@uh.savba.sk