Spatial Variability of Water Repellency in Pine Forest Soil

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Abstract: The variability of water repellency of pine-forest arenic regosols and its influence on infiltration processes were measured in southwest Slovakia. The water drop penetration time (WDPT) tests of soil water repellency and infiltration tests with a miniature tension infiltrometer (3 mm diameter) were performed. Large differences in infiltration were observed over centimetre spatial resolution, with WDPT tests suggesting water repellency varying from extreme to moderate levels. For soils with severe to extreme water repellency determined with WDPT, steady state infiltration was not reached in tests with the miniature tension infiltrometer, making it impossible to estimate sorptivity. Where sorptivity could be measured, the correlation with WDPT was poor. All results suggest that hydraulic properties of soil change below the centimetre scale resolution of the current study, probably due to a presence of unevenly distributed hydrophobic material.

Keywords: spatial variability; water repellency; WDPT test; infiltration; sorptivity

It is now widely accepted that the wettability of surface soil alters considerably depending on its moisture content and coatings by water repellent compounds. These compounds have a biological origin, formed from decaying organic matter (aliphatic hydrocarbons, amphiphilic substances), living or dead organisms (e.g. fungal hyphae) and microbial exudates (Nunan *et al.* 2002). When soil particles are coated sufficiently by these compounds, drying can result in hydrophobic behaviour that resists or retards surface water infiltration. In extreme instances, water infiltration is impeded completely and the soils are classified as water repellent (e.g., Wahl *et al.* 2003, 2005). Most soils appear to wet readily, but the recent development of more sensitive testing approaches, has shown that small levels of water repellency might exist in many soils, with significant environmental impacts (Hallett *et al.* 2004).

The potential impacts of soil water repellency are reduced infiltration capacity, unstable wetting front with fingers (Bauters *et al.* 2000), preferential flow, faster transport of solutes, variations in soil water content (Dekker & Ritsema 1994) affecting plant growth, and possibly increased overland flow and soil erosion. Forecasting and controlling the associated environmental risks of this phenomenon requires measures of water repellency in soil hydrology investigations, but this is complicated by the spatial variability of this property at various scales (Hallett *et al.* 2004).

Several approaches exist for quantifying the soil water repellency. These include: water drop

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penetration time (WDPT) test, molarity of ethanol droplet assessment (Roy & McGill 2002), contact angle by capillary rise (Czachor 2006; Czachor *et al.* 2008), water entry pressure (Bauters *et al.* 2000), index of water repellency (Hallett *et al.* 2004) among others. Graber *et al.* (2006) examined spatial variability of water repellency along several transects of 1.2 m length in a citrus orchard with extremely repellent soils in the central part of the Israel. They used the water drop penetration time test (WDPT), where the time taken for a drop of water to infiltrate soil is a measure of the persistence of water repellency (Dekker & Ritsema 1994). In individual 5 cm × 5 cm soil cores taken at 3 cm spacings along the transect, they found less that 10% variability within cores but extreme variability between cores. This suggests extremely variable infiltration will result along the transect, with major impacts to the first few minutes of infiltration when erosion and preferential flow paths develop.

An environment where more extreme water repellency is commonplace is under coniferous forest. The often low pH of the soil combined with waxes from pine needles and a microbial community dominated by fungi has been shown in numerous studies to contribute to the development of water repellency (Wahl *et al.* 2003). However, no study to date has examined the spatial variability of water repellency at small scale in coniferous forest soil. The objective of this study was to examine the variability of soil water repellency and its relation to water sorptivity for a pine forest in southwest Slovakia. The sorptivity was measured with a 3 mm diameter infiltrometer at 100 cm^3 sample scale. Temporal variability was assessed by taking measurements during hot and dry spells with well-pronounced water repellency.

MATERIALS AND METHODS

Experimental site and sampling

The experimental site is located at Mláky II near Sekule on the Borská nížina lowland (southwest Slovakia) where the sand dunes with surface eolian sand cover about 570 km^2 (Kalivodová *et al.* 2002). Elevation of the studied locality is 150 m a.s.l., the average annual air temperature is 9°C, and annual precipitation is 500–600 mm. The soil was a Regosol formed from wind blown sand (WRB 1994) and had a sandy texture (Soil Survey Division Staff 1993). The thickness of the A horizon varied from 1.5 to 7 cm. The basic physical and chemical properties of the surface horizon are presented in Table 1. Beneath the organo-mineral A horizon was an unconsolidated mineral C horizon of eolian sand that extended to groundwater table at a depth of about 2 m.

Pedon description:

F –1.5–0 cm: partly decomposed litter layer,

Ao 0–7 cm: surface organo-mineral ochric horizon with colour 10YR 6/2 (according to Munsell designations),

C 7–80 cm: horizon with colour 10YR 7/3–8/3,

C(Go) > 80 cm: colour 10YR 8/3, local spots: 6/8.

The soil was covered mostly by the moss species *Polytrichum piliferum*, then by lichens (*Cladonia* sp.), and in isolated cases by the grass species *Corynephorus canescens*. More detailed description of plant and microbial species on the locality could be found in Lichner *et al.* (2005, 2007).

The top 5 cm soil surface layer was sampled in the pine forest on 18th July 2007. The age of the pine trees (*Pinus sylvestris*) in the forest was about 30 years. Stainless steel cylinders of 100 cm^3 volume and 5 cm height were used for obtaining undisturbed samples by pressing the cylinders into the soil. Samples were taken in three clusters, each containing 3 samples, 5–10 cm apart. Two clusters were located under the pine trees and one cluster between the trees. Thus, the total number of samples was nine. Cylinders were lifted carefully out of the soil and fitted at each end with metal caps to prevent changes in soil water content.

Water repellency estimation

In the laboratory, the caps were removed from the soil samples and the water repellency of the soil surfaces was determined by the water drop penetra-

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

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (%)	C (%)	pH(H_2O)	pH(KCl)
0–1	95.14	2.26	2.60	< 0.05	0.83	5.65	4.39

tion time (WDPT) test. The volume of water in a droplet was 58 ± 5 μl. A total of 10 to 14 drops of distilled water were placed on the surface of each soil sample, and the time that elapsed before the drops were absorbed was determined.

Eight repellency classes were distinguished following Dekker and Ritsema (1994): Class I (wettable, not water repellent): infiltration within 5 s; Class II (slightly water repellent): 5 s < WDPT ≤ 60 s; Class III (strongly water repellent): 60 s < WDPT ≤ 600 s; Class IV (severely water repellent): 600 s < WDPT ≤ 3600 s; Class V (extremely water repellent): 1 h < WDPT ≤ 2 h; Class VI: 2 h < WDPT ≤ 3 h; Class VII: 3 h < WDPT ≤ 4 h; Class VIII: WDPT > 4 h.

Measurement of water transport using miniaturized tension infiltrometer

After finishing the WDPT tests, the soil samples were air-dried until water loss ceased (approximately 10 days at 22°C) and infiltration measurements performed. We used a miniature tension infiltrometer, similar to that described by Hallett and Young (1999). The infiltrometer consisted of a 3.0-mm radius tip that housed a sponge to enable good soil contact and the establishment of a negative pressure head. Water was supplied to the tip via a flexible pipe that connected to a reservoir on a recording balance accurate to 0.01g (Figure 1). Twenty-five infiltration measurements were taken on twelv samples. All measurements were done at –20 mm pressure head and the steady-state rate of water uptake, Q was recorded from the mass loss on the balance. Sorptivity, S, was calculated using (Hallett *et al.* 2004)

$$S = \sqrt{\frac{Qf}{4br}} \qquad (1)$$

where:

b – parameter dependent on the soil-water diffusivity function (taken as 0.55 following recommendations of White and Sully (1987) for soils with unknown b parameter)

r – radius of the infiltrometer tip (3.0 mm)

f – fillable (air-filled) porosity (0.36), measured from the soil density

In some soils the infiltration of water was negligible, so water sorptivity could not be calculated.

RESULTS AND DISCUSSION

Under the pine forest all classes of soil water repellency were identified using the WDPT approach. The most frequent classes were class III (22.5%), class IV (23.3%), and class VIII (20%). Thus, generally, the soils of the research plot could be characterized as strongly or extremely water repellent. Within an individual soil core, extremely variable water repellency was also found. Each core has surface area of 22 cm^2 and over this small area the coefficient of variation of WDPT as a measure of its relative variability ranged between 23 and 135%. The average number of repellency classes identified on an individual core was 3 (Figure 2a).

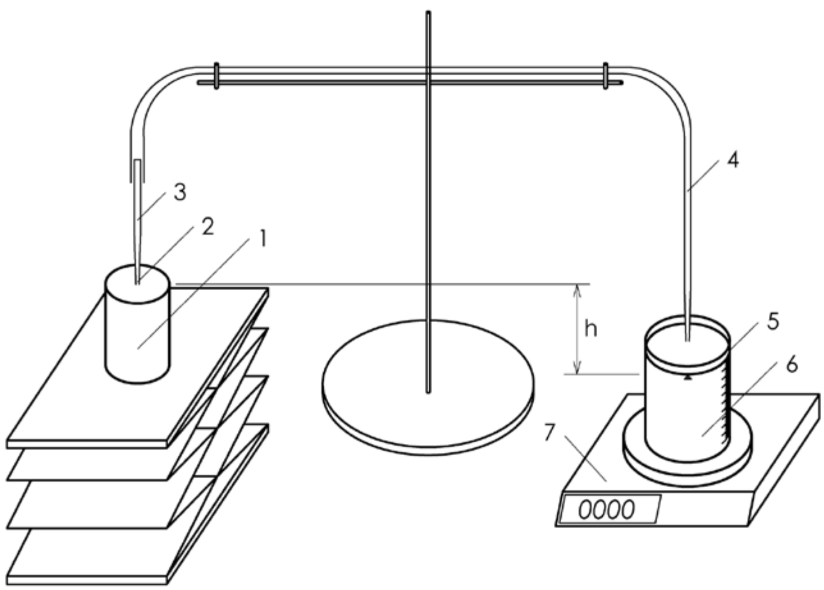

Figure 1. The miniaturized tension infiltrometer apparatus

1 – soil sample, 2 – sponge tip enabling good soil contact, 3 – conductance tube, 4 – flexible pipe, 5 – water table, 6 – reservoir, 7 – balance

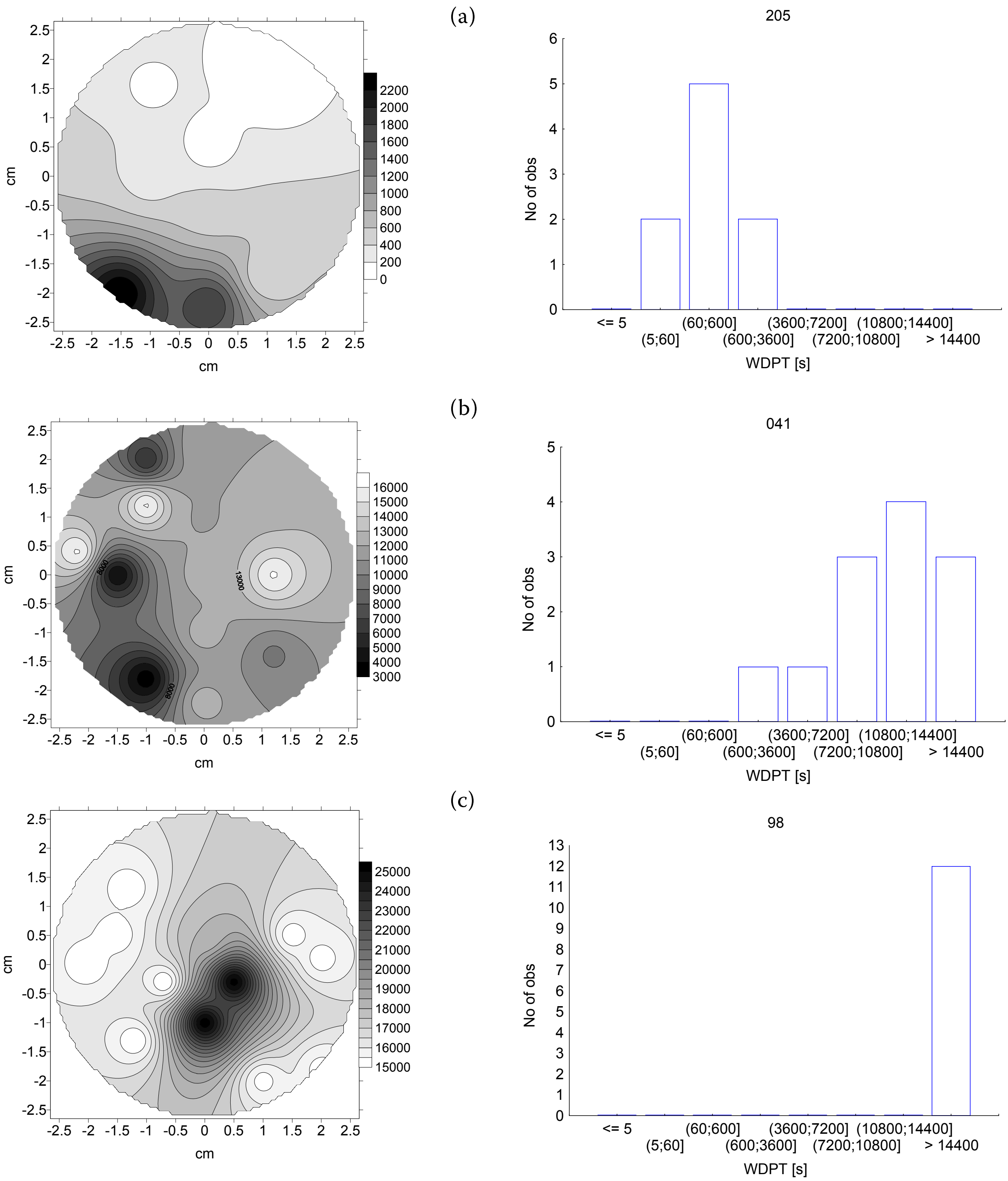

Figure 2. Spatial variability of water drop penetration time (WDPT) values at sample scale (22 cm^2) and occurrence frequencies of particular soil water repellency classes

At most, the soil water repellency extended across 5 classes (Figure 2b; sample 41), with only one sample having only one WDPT class range (Figure 2c; sample 98). The latter was the most water repellent core, however, with WDPTs above 14400 s (class VIII). This might suggest that the highest levels of WDPT values exhibit some type of spatial connectivity. It was interesting that the extreme samples with greatest and least spatial variability in WDPT were only 25 cm apart on the pine forest

Table 2. Descriptive and comparative statistics of various water drop penetration time (WDPT) data sets

WDPT data set	Location	*N*	Mean	SD	*CV* (%)	K-S test
Complete		104	6478	6712	104	
Cluster I	under the tree	34	1234	1383	112	CL. I–CL. II*
Cluster II	between the trees	36	9801	7532	77	CL. I–CL. III*
Cluster III	under the tree	34	9359	6361	68	CL. II–CL. III**

N – number of measurements, SD – standard deviation, *CV* – coefficient of variation, K-S test – Kolmogorov-Smirnov test of significant difference between distributions of particular data sets

*significant difference at $P < 0.001$; **not significant difference at $P > 0.1$

floor. As the scale of measurement increased, the variability of WDPT did not exceed the variability detected at single sample scale (Table 2).

Within a particular sample clusters (each containing 3 samples), it was interesting to find that two of them (Cluster II and Cluster III) had very similar frequency distributions of WDPT values (Figure 3). The difference between them was not confirmed by Kolmogorov-Smirnov test even at the significance level $P = 0.1$ (Table 2). This has nothing to do with the original position of sample clusters (under or between the trees) on the forest floor.

The strong to extreme water repellency detected with the WDPT tests was supported by the tests with the miniature tension infiltrometer. Over 70% of the tests performed had too slow a rate of water uptake for water sorptivity to be determined from early-time steady-state infiltration. On tests where water infiltration did occur, a steady-state occurred between 25 s and 100 s, similar to previous findings by Hallett and Young (1999) (Figure 3). This was observed at a range of repellency classes I–III. The sorptivity was determined for these situations, but there was only a weak relation between the sorptivity and WDPT values (Table 3). In about 30% of the samples tested, no infiltration was observed after a very long time (> 5 hours). On the remaining samples that did show steady-state water infiltration, water began to enter after a prolonged period or progressed chaotically. We assume that such variable behaviour of millimetre-scale infiltration is caused by the heterogeneous distribution of hydrophobic surfaces in different pores. It seems that this property of soil can dramatically change in very short distances in both directions (Wahl *et al.* 2003, 2005).

The impacts on hydrology could therefore be massive, but the impacts of water repellency need to be disentangled from pore structure, which has been shown to influence sorptivity at small-scale significantly (Kutílek & Nielsen 1994). Research by Hallett *et al.* (2004) suggests, however, that the impact of water repellency on sorptivity may exceed pore structure variation.

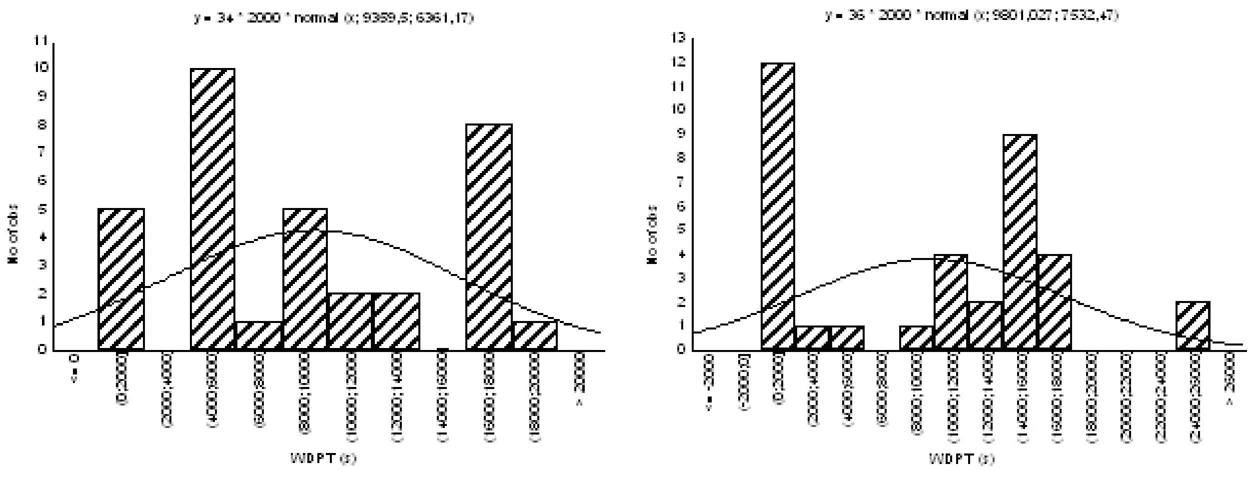

Figure 3. Frequency histograms of water drop penetration time (WDPT) values of clusters II and III

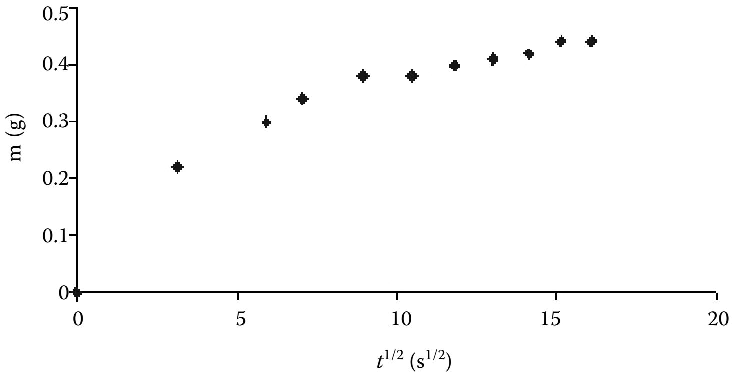

Figure 4. An example of infiltration measurement, when process started immediately after establishing the soil contact. This situation was observed for repellency classes I–III

Biological material (e.g. cells of plant organisms) is unevenly distributed in soil. It contains various organic matters like polysaccharides, lipids, and waxes, all with different affinities to water. Bauters *et al.* (2000) showed that the extent of water repellency in soil pores was extremely sensitive to organic coatings. By changing the concentration of octadecyltrichlorosilane (octadecyltrichlorosilane is an amphiphilic molecule consisting of a long-chain alkyl group ($C_{18}H_{37}$–) and a polar head group ($SiCl_3$–), which forms Self-Assembled Monolayers (SAMs) on various oxidic substrates) from 3.1% to 5.7%, the pore volume affected by water repellent material increased from 37% to 60%.

The results of WDPT and infiltration tests suggested that soil water repellency did not have a contiguous surface distribution at single-sample scales. If a spatial organization of soil water repellency does occur, one should go in search for it at microscopic scale. This is in agreement with the findings of Hallett *et al.* (2004). The infiltration measurements with miniature tension infiltrometer showed early-time steady-state infiltration on sample with WDPT classes I, II, and III only. The values ranged between 0.62 and 1.16 mm $s^{-1/2}$ but there was no direct relationship between sorptivity and WDPT (Table 2).

Table 3. Estimated sorptivities *S* related to repellency classes

S (mm/$s^{1/2}$)	Repellency class
0.95	I
0.88	I
0.86	II
0.73	II
0.62	III
1.16	III
0.67	III

CONCLUSION

The water repellency of pine-forest arenic regosols and its influence on soil water sorptivity were determined. It can be stated that water repellency and hence infiltration are spatially heterogeneous in soil, presumably due to soil biota and terrestrial plants. The WDPT test of soil water repellency exhibited great variability even at the sample scale (22 cm^2), mostly extending across 3 repellency classes, maximally 5 classes. Further increasing of measurement scale did not exceed the WDPT variability. From measurements of soil sorptivity, we conclude that water can infiltrate readily the soil surface, which is hydrophobic up to IIIrd WDPT class. For more than a quarter of the samples tested, minimal water uptake from the infiltrometer occurred even after several hours. These tended to be for cores with severe to extreme repellency (classes VI, VII, and VIII). This study showed that water repellency exacerbated the great variability of soil hydraulic properties.

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