

Water infiltration into the soil – what do measurements indicate?

TOMÁŠ ORFÁNUS – VILIAM NAGY

Slovak Academy of Sciences, Institute of Hydrology, Bratislava, Slovakia,
orfanus@uh.savba.sk

Summary

Physical properties of top-soil organic materials significantly influence initiation processes of infiltration and runoff generation. This paper deals with the specifics of water infiltration through the top surface organic layer of the forest soil. Three field methods (Guelph permeameter, Tension disk permeameter, Single-ring method) and one laboratory method (Falling head) of hydraulic conductivity (K_s) determination are compared and interpreted in the context of their applicability and limitations. The Falling head method provides far different values of K_s if sample cylinders are or are not sealed with grease against the wall effect. The Guelph permeameter is very significant to the position of different horizons' interface, while Tension disc permeameter results are dependent on antecedent soil moisture. The single ring method is applicable with acceptable results only when there is no abrupt interface between horizons in the vicinity of the ring bottom edge.

Keywords: infiltration, saturated hydraulic conductivity, field measurement methods

Introduction

Infiltration of water into the soil or rocks is the most important hydrological process in terms of life persistence on the Earth. It is however extremely difficult to quantify this process in the landscape and hydrologists usually calculate it from the balance equation with known rainfall and runoff terms. Saturated hydraulic conductivity, K_s is a quantitative characteristics for the ability to transfer water through the porous media fully saturated with water. In case of the soil its magnitude depends mainly on soil structure and texture. Measurements of K_s are significantly affected by soil heterogeneity. Spatial variability is manifested in both horizontal and vertical directions. Higher K_s in vertical dimension is typical for structural soils while in layered or compacted soils (e.g. forest roads) we observe prevailing horizontal or lateral conductivity. Except of here mentioned spatial and temporal variability there exists also substantial methodological variability of K_s values caused by the application of different measurement and calculation methods as is reported by Fodor et al. (2011). First mentioned

authors observed methodological variability of K_s which was larger than the spatial variability of K_s values estimated by single method within 10 m² research plot. It means that it could be very tricky matter to select an appropriate method to determine K_s and correctly interpret it in context of local soil-plant conditions as well as in terms of larger-scale catchment hydrological processes. Moreover one must be very careful when comparing or commenting soil hydraulic characteristics between different studies, locations and/or methodologies. Forests are extremely important ecosystems in the landscape and those growing in mountainous areas significantly influence climatological and hydrological conditions of lowlands. Big part of the Pannonian basin is fed by water from rain and water coming from Carpathians. In the last years, in the modern European literature, the issue of forest shape and quality is quite frequent there. It has been discussed either in terms of immision pressure (Fleischer et al., 2005; Schulze et al., 2012), or their languishing as a result of rising climate change and bark beetle infestation (Grodzki et al., 2006; Mezei et al., 2017). All these factors influence hydric properties of forest soils. Carpathians are typical by activity of all these harmful factors.

It has been recognized many times that well developed forest floor horizons alter the hydrological response of soils compared to their response when no forest floor is present (Keith et al., 2010) but still in comparison with the extensive literature on the interception properties of living plants, relatively few works concern the hydrological properties of organic soil horizons created from the dead plant litter.

According to Dziadowiec et al. (2004) the forest floor layers typically contain the following sublevels: (1) litter consisting of almost unchanged plant debris in the first phase of its processing, with tissue structures preserved; (2) the fermentation sublevel consisting of strongly disintegrated and discolored material, the excrements of the small soil fauna and formless humus; (3) the humification sublevel containing mainly formless humus and a small admixture of mineral material; (4) the detritus sublevel consisting of strongly disintegrated and discolored material, usually containing a considerable admixture of mineral material. While the mineral soil horizons are usually a result of a long time soil genesis, the organic matter horizons of the forest soils may change relatively quickly, depending on the vegetation cover (Kodešová et al., 2007).

Above mentioned specific physical properties would logically predetermine forest floor organic horizons to stimulate rain-water infiltration and prevent runoff. Nevertheless, the reality about the forest floor hydraulics is not so trivial. Dead organic matter may cause an increase of wetting contact angle between the water and solid phase of

the soil matrix particularly within the organomineral A-horizon. The soil material then behaves like being water repellent what is caused mostly by leached waxes from the needle litter, presence of fungi hyphae and other types of organic matter (Neris et al., 2013).

Material and methods

The research plot, where the forest floor K_S was examined, is situated in location Kokavské lúky in Western Tatras on the hillslope (25° total inclination) covered by spruce (*Picea abies*) forest canopy combined with blueberry (*Vaccinium myrtillus*) understory and generally with well-developed forest floor organic horizon with thickness ranging from 3 to 15 cm. Coordinates of the location are: 49° 6' 30.8'' northern latitude and 19° 51' 53.4'' eastern longitude. The average altitude is 860 m above sea level. The local soils are *Dystric Cambisols* with slight indications of spodic horizon. The organomineral A-horizon is 3(6)–15 cm and (same like the duff layer) it permanently exhibits certain degree of water repellency depending on actual soil water content. The hydrophysical properties of the top 35 cm soil layer are in *Table 1*.

All measurements were performed in an uneven pattern choosing the sites on naturally flat (not inclined) segments of relief and best developed forest floor horizons within the 15×45 meter plot. The particular measurement sites for different methods did not overlap; therefore the methods could be compared only statistically.

Saturated hydraulic conductivity K_S was measured by three field and one laboratory methods, as follows:

1. Measurements of the integral (vertical plus horizontal) K_S of the upper 10 cm layer of the forest floor horizon were performed with Guelph permeameter.
2. The near-saturated hydraulic conductivity of the top surface of the forest floor was measured with Disk permeameter by application of small tension on the soil surface.
3. Single-ring method was used to quantify the K_S in a vertical dimension by shallow ponding surface boundary condition.
4. Laboratory measurements of K_S were performed on the falling head apparatus using 100 cm³ undisturbed soil samples (Kopecky cylinders with diameter and height). Unlike other methods this one enabled us to measure the K_S of particular layers (litter, fermentation layer, humus) of the forest floor horizon separately as the degree of decomposition and mechanical aggregation increases with depth within local forest-floor horizons.

For more details about the above measurement methods and calculation formulas see e.g. (Zvala et al., 2017).

Results and discussion

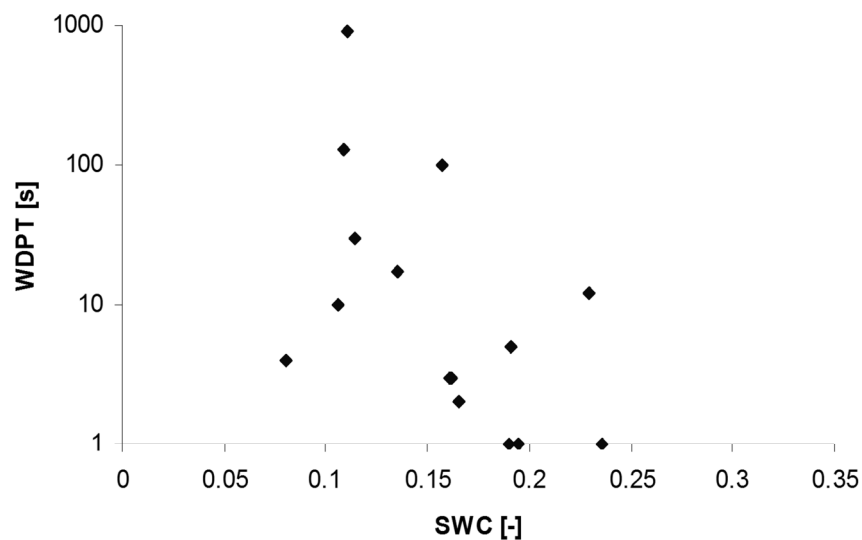
The physical and hydrophysical characteristics of studied organic soil materials (*Table 1*) are strongly influenced by present water repellency, which is detectable in duff and organomineral A-horizon during the whole warm half of the year in studied area (*Figure 1*). The main characteristics of the complex build-up of the organomineral A-horizon and the underlying B_{vs} horizon are in *Table 1*.

Table 1. *Hydrophysical characteristics of the organomineral A-horizon and upper part of the B_{vs} horizon of the soil profile at Kokavské lúky location*

Sampling depth/diagnostic horizon	P	FC	DP (P-FC)	Clay content (%)	$k_{(-2\text{ cm})}$ (cm h ⁻¹)	WDPT (s)	Rock (skeletal) content (%)
10–15 cm/A-hor.	0.66	0.35	0.31	10	0.1	59	9
	+/-	+/-	+/-		0.19	5	
	0.066	0.038	0.066		0.58	165	
30–35 cm/B _{vs} -hor.	0.51	0.26	0.25	22	-	-	35
	+/-	+/-	+/-				
	0.11	0.08	0.09				

Note: (P-porosity, FC-field capacity, DP-drainage porosity, $k_{(-2\text{ cm})}$ – hydraulic conductivity of soil for water determined with tension disk permeameter by applying 2-cm tension, WDPT-water drop penetration time.

Figure 1. *WDPT versus volumetric soil water content detected in duff and A-horizon on the research plot (Kokavské lúky location)*



The methodological variability of saturated hydraulic conductivity provided by different measurement methods exceeds the spatial variability of a single method (*Table 2, Figure 2*). This methodological variability moves in a range of two orders and has impact on the interpretation of measured values in context of particular hydrological processes.

The falling head method provides little realistic values of K_S moving in a range of several tens of meters per hour. These values differ by more than order from all the other methods what is caused by the “wall effect”, i.e. the preferential and rapid flow of water along the inner walls of the sample cylinder. Such wall effect may represent up to 50 or even 70% of the measured K_S value (Fodor et al., 2011).

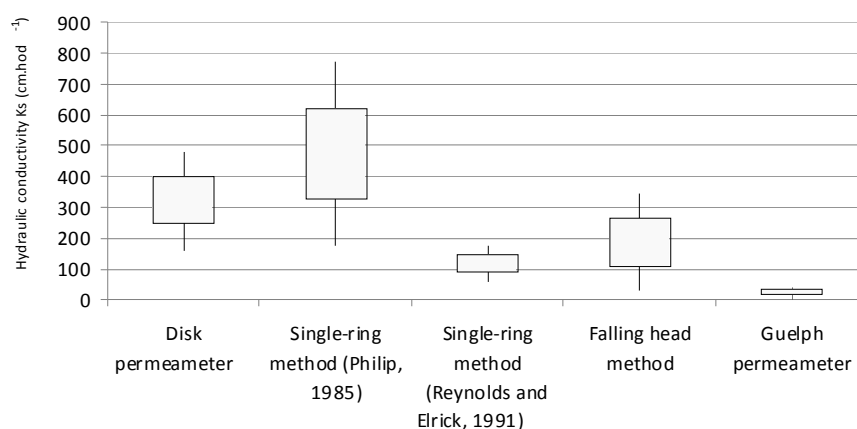
Table 2. Results of measurements of the hydraulic conductivity, K_S by various methods. Numbering of measurements for each method does not relate to the same measurement location

Measurement site	Disk permeameter K_{S-td} (cm.h ⁻¹)	Single ring ^(ER) K_{S-sr} (cm.h ⁻¹)	Single ring ^(Ph) K_{S-sr} (cm.h ⁻¹)	Falling head (cylinders not sealed) K_{S-fh} (cm.h ⁻¹)	Falling head (cylinders sealed) K_{S-fh} (cm.h ⁻¹)	Guelph permeameter K_{S-G} (cm.h ⁻¹)
1.	283.29	102.71	349.92	litter 2921 duff-1 1273 duff-2 1333	litter 295.32 duff-1 256.86 duff-2 48.32	27.06
2.	414.07	165.54	707.40	litter 3201 duff-1 2578 duff-2 866	litter 153.40 duff-1 83.61 duff-2 57.80	6.04
3.	478.80	58.45	175.50	litter 2566 duff-1 1504 duff-2 1589	litter 50.55 duff-1 44.72 duff-2 59.41	5.71
4.	220.87	113.11	390.96	litter 4289 duff-1 2036 duff-2 1778	litter 346.24 duff-1 41.48 duff-2 45.25	30.72
5.	290.42	78.26	255.42	litter 3417 duff-1 1820 duff-2 1060	litter 173.39 duff-1 111.23 duff-2 43.03	42.48
6.	161.13	176.75	770.58		litter 167.60 duff-1 91.74 duff-2 28.58	9.01
Average	308.1	115.8	441.63	2148	116.6	20.2

Considering the local character of the soil-plant system we consider the most realistic results to be those of tension disk permeameter (*Table 2*) as the method avoids influence of underlying organomineral A-horizon

(in depth of 12 cm), which is most of the year strongly water repellent. Moreover, the applied tension prevents rapid water pouring horizontally around the installed infiltrometer. The values gained from the tension disk permeameter method (average value equals 308 cm hod⁻¹) are comparable to values measured with minidisk infiltrometer on the similar location by Hlaváčiková et al. (2014), who report the values 285 and 447 cm hod⁻¹.

Figure 2. Measurement results of hydraulic conductivity of forest-floor soil horizons by different methods



On the other hand the measurements by a single-ring method (infiltration cylinder mounted in depth of 10 cm) are evidently influenced by the properties of organomineral A-horizon with its saturated hydraulic conductivity estimated in field with minidisk method being three orders lower (*Table 1*) and mean WDPT equal to 100 seconds (Orfánus and Fodor, 2011). The level of biochemical and mechanical decomposition and physical aggregation increased with depth within the forest floor organic horizon. As was expected the saturated hydraulic conductivity determined by the falling head method was decreasing with depth within the organic horizon. Average values of K_s were 3265 cm hod⁻¹ for the very top litter layer, 1836 cm hod⁻¹ for the moderately decomposed material layer and 1320 cm hod⁻¹ for the intensively decomposed and aggregated organic layer.

Surprisingly, the Guelph permeameter measurements provided the lowest values of K_s . Actually, the measurements were done within the hole drilled down to the interface between the organic forest-floor horizon and the organomineral A-horizon of the soil profile. This strongly water repellent interface makes the vertical component of the

hydraulic conductivity substantially retarded and therefore in studied location we can consider the determined values of K_s by Guelf permeameter as good estimates of the K_s horizontal component. The average value was 20 cm h^{-1} .

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The average K_s value determined by tension disk permeameter was 308 cm hod^{-1} . This measurement method can be likened to natural conditions during the intensive rainfall situations but without ponding. Since these values are much higher than any realistic rainfall intensity in this climatic conditions we can state that in the studied area there is almost no chance for the overland runoff generation although temporarily the local ephemeral rivulet runoff could be formed on areas with strong water repellency.

The results of various measurement/calculation methods used to determine the hydraulic conductivity of forest-floor organic soil horizon point to certain important facts relevant for the hydrological processes in forested catchments:

Conclusions

Important facts relevant for the study of hydrological processes in forested catchments come out from the results provided here by determination of forest floor K_s by applying different measurement and calculation methods.

1. The needle litter represents a permanent source of hydrophobic substances causing strong water repellency of the duff and

- organomineral A horizons in local humid mountainous climate during the prevailing period of year.
2. The high volume of macropores and preferential flow paths within the organic forest floor horizon is make water readily to infiltrate although the K_s decreases with depth as the degree of mechanical and biochemical decomposition and physical aggregation of organic matter increases in direction from raw litter on the top towards underlying fermented duff layer and amorphous humus layer.
 3. Falling head method performed on Kopecky cylinder samples can be significantly influenced by the wall effect, which causes by order overestimated values of K_s as was shown here by comparing the results from sealed ad unsealed samples. We fully recommend using sealed samples for this type of analyses.
 4. Generally very high values of K_s prevent the overland flow generation except of cases when the soil is oversaturated by long-term rains. On the other hand, a serious retardation of infiltration on the boundary between the forest-floor organic horizon and the organomineral A-horizon was observed. At our research plot the K_s determined by single-ring method was lower than K_s determined by tension disk permeameter (where measurements were not influenced by the water repellent interface) what is not a typical case. This conclusion is supported by measurements with Guelph method, which was also influenced by water repellent interface and provided the lowest values of K_s . The values of K_s determined by Guelph method could be attributed to the horizontal component of the K_s tensor only.
 5. The interpretations of different K_s determinations as well as the results of the irrigation experiment indicate that catchments forested with *Picea abies* with well-developed forest floor may be prone to generation of shallow subsurface runoff which may contribute to flood peaks during the extreme rainfall events.
 6. The irrigation experiment has proved that despite the high retention capacity of spruce-forest soils the subsurface runoff can be generated within the forest floor layers above the water repellent organomineral horizon even during the common rainfall events.

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