



Estimation of the Flow Conducting Soil Pore Spectra Using Borehole Permeameter and Soil Core Samples

E. Hangen^{1*}, F. Vieten¹, D. Strauß² and M. Wittenbecher³

¹Department of Preventive Soil Protection and Soil Monitoring, Bavarian Environment Agency, Hans-Högn Strasse 12, 95030 Hof, Germany.

²Urban Office of Environment, Fire and Civil Protection, Michelsberg 10, 96049 Bamberg, Germany.

³Department of Soil and Rock Analysis, Bavarian Environment Agency, Leopoldstrasse 30, 95615 Marktredwitz, Germany.

Authors' contributions

This study has been carried out in collaboration between all authors. Author EH designed the experimental set-up, conducted field work and evaluated the obtained data. Authors FV and DS assisted in the planning and realization of the field experiments. Author MW conducted and supervised the extensive soil physical lab analyses. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJPSS/2015/16969

Editor(s):

(1) Radim Vacha, Faculty of Research and Development, Research Institute for Soil and Water Conservation, Czech Republic.

Reviewers:

(1) Philip Hegarty James, Soil Science, University of Maiduguri, Nigeria.
(2) Edgar Iván Sánchez Bernal, Institute of Ecology Universidad del Mar, Puerto Escondido, Oaxaca 71980, Mexico.
Complete Peer review History: <http://www.sciencedomain.org/review-history.php?iid=958&id=24&aid=8677>

Original Research Article

Received 20th February 2015

Accepted 19th March 2015

Published 3rd April 2015

ABSTRACT

Aims: Hydraulic conductivity plays an important role in the evaluation of various soil functions, which in turn may become decisive in urban development plans. Different approaches to measure hydraulic conductivity often inhere in methodological artefacts. To address the subjected soil volume as well as different measurement approaches, in situ measurements using a constant-head permeameter were compared to lab-determined hydraulic conductivities of soil cores at adjacent soil profiles.

Methodology: At a forest, an arable, and a grassland site in a catchment in Northern Bavaria retention characteristics as well as hydraulic conductivities were quantified for 100 cm³- and 250

*Corresponding author: E-mail: edzard.hangen@lfu.bayern.de;

cm³-soil cores and constant-head permeameter measurements conducted. Using the van-Genuchten RETC-program, unsaturated hydraulic conductivities of the soil core samples were calculated.

Results: No volume-related differences between hydraulic conductivities of the 100 cm³- and the 250 cm³-soil cores became evident. Hydraulic conductivities of the soil cores markedly exceeded the values of the borehole permeameter approach. Contrasting the former with the hydraulic conductivities measured with the borehole permeameter, soil pore threshold diameters were derived that might be excluded from the infiltration process. While lab-determined hydraulic conductivities of soil cores were based on almost the whole soil pore spectrum, in-situ measurements mostly reflected matrix flow. This effect was most pronounced at the forest and least pronounced at the arable-land site, pointing to the respective soil pore spectra.

Conclusion: Borehole permeameter measurements should be chosen to illustrate percolation under standard conditions, while the soil-core approach is favourable under wet boundary conditions, when macropores are active, e.g. in the scope of flow and contaminant transport studies.

Keywords: Threshold flow-conducting pore diameter; flow domain; borehole permeameter; soil core sample.

1. INTRODUCTION

The hydraulic conductivity of soils is a very important parameter used for environmental issues, such as determination of soil functions [1], contaminant transport towards groundwater [2], water balance studies [3], and flood forecast calculations [4]. The standard determination of hydraulic conductivity is based on soil core samples, which after saturation are percolated using the constant- or the falling-head method [5]. To address the spatial heterogeneity of soil physical parameters the German Geological Surveys require at least ten parallel samples to obtain representative values for one single soil horizon [6]. Thus, the determination of the hydraulic conductivity is highly time- and labour-intensive. To circumvent this effort hydraulic conductivities are usually derived from pedotransfer tables based on soil texture and dry bulk density data [7]. However, in these pedotransfer tables hydraulic conductivity values of certain texture-density combinations are based on singular measurements (Hans-Peter Schrey, Geological Survey of Northrhine-Westphalia, personal communication), i.e. the foundation of tabulated values is restricted. An alternative to measure hydraulic conductivity of soils straightforwardly are in situ infiltration experiments [8]. Infiltrometers comprise the disk [9], the hood-infiltrometer [10], and the borehole permeameter [8,11]. Field measurements using a Guelph-permeameter were found to provide higher values of hydraulic conductivity than adjacent soil core samples subjected to falling-head procedures [8]. They are also used to determine the contribution of macropores to

hydraulic conductivity [12]. The disk- and the hood-infiltrometer apply preferably for the uppermost topsoil or require laborious soil pit preparation [9]. In contrast, the borehole permeameter is measuring the hydraulic conductivity of the surrounding soil from a small borehole [11], which can be easily extended downward and thus allows measurements also in deeper soil regions. However, if this straightforward approach can be rendered valid with respect to the conductivity data of soil cores accumulated so far remains unclear.

2. MATERIALS AND METHODS

2.1 Investigation Sites

Sampling sites were located in the catchment of the Kösseine, a small river in the southern Fichtel Mountains, Northern Bavaria. Here, knowledge of soil hydraulic parameters is of special concern, for the area was impaired by wastes of former non-ferrous metal industries [13]. In the Kösseine catchment investigation sites under different land use were selected as characterized in Table 1.

2.2 Borehole Permeameter Measurements

At each investigation site measurements of the hydraulic conductivity were carried out using a portable borehole permeameter [11]. The methodology is based on the determination of water flow out of a borehole with a diameter of about six centimetres. To minimize smearing of the soil pores during hole preparation, walls and

the bottom of the bored auger hole were cautiously brushed up. From a water supply that constitutes of a water reservoir and a flow measuring reservoir connected to a row of linked bubble-towers a constant water table was established in the borehole.

The discharged water volume over time as noted at the water supply system is translated into the hydraulic conductivity, K_{field} , of the respective soil depth interval. After termination of measurements at one soil depth, the borehole was extended to the next lower soil depth, and the measurements were started again. Due to a water level of about 18 cm in the borehole, we used the middle of the water column as reference depth (Table 2). When the water column in the borehole affected several soil horizons, this was considered in the further evaluations. At each investigation site two adjacent boreholes were subjected to permeameter measurements to verify the observed hydraulic conductivity, K_{field} .

$$K_{field} = \frac{\sinh^{-1} \cdot (H/r) - \sqrt{(r/H)^2 + 1} + r/H}{2 \cdot \pi \cdot H^2} \cdot Q \cdot 1440 \quad (1)$$

where:

- K_{field} = Hydraulic conductivity obtained using permeameter [cm/day]
- H = Water level in borehole [cm]
- r = Radius of borehole [cm]

- Q = Discharge from water supply system [cm³/minute]
- 1440 = Conversion factor from [cm/minute] to [cm/day]

Alternative equations, such as proposed by [15] as well as [16], were tested and provided values of K_{field} comparable to Eq. 1.

2.3 Soil Core Sampling

Soil pits were dug about two meters apart from permeameter measurements. This is to ensure a close spatial relation on the one hand, but also to avoid adverse effects upon measurements on the other. Soils were characterized (Table 1) and samples taken horizonwise using 250 cm³-steel rings. To account for the high spatial variability ten steel rings each were extracted per soil horizon according to the prescription of the Working Committee of the Federal Geological Survey [6]. Where horizons were sufficiently thick, ten additional 100 cm³-steel rings were taken to obtain information about volume-related effects on hydraulic conductivity, K_{lab} . Sampled soil horizons are compiled in Table 3.

2.4 Soil Core Analysis

After saturation from below, water flow was determined based on different water levels on both sides of the soil core sample using a lab-permeameter (Soil water Permeameter

Table 1. Properties of investigation sites

	Forest	Arable land	Grassland
Specific land use	Common spruce	Rape	Meadow
Altitude a.s.l.(m)	709	515	498
Soil type	Podzolic cambisol	Regosol	Gleysol
Texture	Loamy sand	Sandy loam to silty sand	Loam to loamy sand
Latitude / Longitude	49°59'17" / 11°59'39"	50°0'57" / 12°7'25"	50°1'6" / 12°8'59"

Table 2. Reference depths of permeameter measurements; n = number of replicates

Forest		Arable land		Grassland	
Borehole A (cm)	Borehole B (cm)	Borehole A (cm)	Borehole B (cm)	Borehole A (cm)	Borehole B (cm)
19 (n=12)	16 (n=8)	12 (n=9)	17 (n=8)	16 (n=4)	17 (n=8)
44 (n=10)	37 (n=6)	29 (n=6)	31 (n=5)	35 (n=9)	32 (n=8)
51 (n=7)	54 (n=5)	48 (n=9)		48 (n=10)	49 (n=8)
		68 (n=10)			60 (n=8)
		89 (n=5)			

Note, that at all three investigated sites no impermeable layer, which lay within twice the distance of the established water level, was encountered below the bottom of the auger hole. For these conditions, the Glover solution (Eq. 1) [14] can be applied for the calculation of the hydraulic conductivity, K_{field}

Table 3. Soil horizon designations of sampled sites and depths of soil core samples referred to centre of steel ring; n = number of replicates

Horizon	Forest		Horizon	Arable land		Horizon	Grassland	
	250 cm ³	100 cm ³		250 cm ³	100 cm ³		250 cm ³	100 cm ³
Ahe-Aeh-	4 cm	-	Ap	17 cm	17 cm	Ah	13 cm	13 cm
Bhs	(n=10)	-		(n=10)	(n=10)		(n=10)	(n=10)
Bv1	19 cm	-		38 cm	-	Go	33 cm	33 cm
	(n=10)	-		(n=10)	-		(n=10)	(n=10)
Bv2	33 cm	-	ilCv	58 cm	58 cm	Gor	43 cm	-
	(n=10)	-		(n=10)	(n=10)		(n=8)	-
IIBvCv	51 cm	-		73 cm	-	Gr	58 cm	58 cm
	(n=10)	-		(n=10)	-		(n=10)	(n=8)

09.02.01.05, Eijkelpark Inc.). After determination of K_{lab} the saturated soil samples (pF = 0) were subsequently dewatered at pressure steps of 60 hPa (pF = 1.8), 300 hPa (pF = 2.5) and 15,000 hPa (pF = 4.2) to quantify the respective fractions of wide-coarse pores (>50 µm pore diameter, Ø), narrow-coarse pores (50 to >10 µm Ø), medium pores (10 to >0.2 µm Ø), and fine pores (≤0.2 µm Ø). The water content at 15,000 hPa was determined at filled-up sub-samples. Additionally, stone content and dry bulk density were determined for each soil core sample.

2.5 Unsaturated Conductivity, K(h), of Soil Core Samples

The program RETC [17], version 6.02, was used to estimate the relation between soil matric potential, h , and the unsaturated hydraulic conductivity, $K(h)$, according to the van Genuchten–Mualem code (Eq. 2 and 3) [18] for the soil core samples:

$$h(\theta) = \frac{I}{\alpha} \cdot \left[\left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{-1/m} - 1 \right]^{1/n} \quad (2)$$

$$K(h) = K_{lab} \cdot \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^l \cdot \left\{ 1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/m} \right]^m \right\}^2 \cdot 864 \quad (3)$$

where:

- $h(\theta)$ = Matric potential as function of water content [cm]
- $K(h)$ = Unsaturated conductivity as function of matric potential [cm/day]
- K_{lab} = Hydraulic conductivity determined for soil core samples [m/s]

- θ = Actual water content [cm³/cm³]
- θ_s = Saturated water content [cm³/cm³]
- θ_r = Residual water content [cm³/cm³]
- m = Empirical parameter [-], $m = 1-1/n$
- n = Empirical parameter [-]
- α = Empirical parameter [1/m]
- l = Connectivity parameter [-]
- 864 = Conversion factor from [m/s] to [cm/day]

Besides texture information, RETC requires values of the hydraulic conductivity determined in the lab, K_{lab} , permanent wilting point and total pore volume. The permanent wilting point (pF = 4.2) represented the residual water content, θ_r , and the total pore volume the saturated water content, θ_s , respectively [19]. For the soils studied here, the criterion $\theta_s \approx 85\%$ of the total pore volume [20] did not apply, for water contents at pF = 1.8 often already exceeded 85% of the total pore volume (pF = 0). The $K(h)$ -values of soil core samples as calculated using RETC were compared to borehole permeameter measurements K_{field} , conducted at comparable soil depths. According to [21,22] it was assumed that $K_{lab} > K_{field}$. Therefore, K_{field} was regarded as unsaturated hydraulic conductivity, $K(h)$, and related to the soil matric potential of the respective soil core sample (RETC 6.02) [17]. Implementing individually measured values of saturated conductivity (K_{lab}), residual water content (θ_r), and the saturated water content (θ_s) as well as texture-specific tabulated values for n , l , and α [23] in the RETC-program, the relation between unsaturated hydraulic conductivity, $K(h)$, and matric potential, (h), was calculated for the soil core samples. This matric potential was regarded as potential capillary rise of water. The equivalent threshold soil pore diameter corresponding to the capillary rise was calculated using the capillary rise-equation (Eq. 4) [24]:

$$h = \left(\frac{2 \cdot \gamma \cdot \cos(\alpha)}{\rho \cdot g \cdot r} \right) \quad (4)$$

where:

- r = Pore radius [μm]
- h = Matric potential, resp. capillary rise [μm]
- γ = Surface tension (= 0,0728 at 20° C) [N/m]
- α = Contact angle (= 0) [degree]
- ρ = Density of water (= 1) [g/cm^3]
- g = Acceleration due to gravity (= 9,81) [m/s^2]

Thus, the threshold maximum diameter of flow-conducting soil pores of K_{field} was estimated.

3 RESULTS AND DISCUSSION

3.1 Soil Core Samples

Comparing the hydraulic conductivities, K_{lab} , of 100 cm^3 - and 250 cm^3 steel ring samples, no directed tendency could be observed. While the 250 cm^3 steel ring samples at the arable land site, i.e. the Ap- and the iCv-horizon, showed higher hydraulic conductivities than the 100 cm^3 steel ring samples, the opposite was true for

most of the grassland site samples, i.e. the Go- and Gr-horizon. Here, the hydraulic conductivities of the 100 cm^3 steel ring samples exceeded those of the 250 cm^3 steel ring samples (Fig. 1). The non-parametric Kruskal-Wallis test provided no significant differences of the K_{lab} -values of each 100 cm^3 - and 250 cm^3 -sample pair.

A volume-relation of the hydraulic conductivity, K_{lab} , was checked against stone content and dry bulk density for those horizons, which were sampled using 100 cm^3 - as well as 250 cm^3 steel rings (Table 3), i.e. 100 soil core samples altogether. However, no volume related grouping of hydraulic conductivities became evident (Fig. 2).

The average stone content of ca. 10 mass. % was obviously not high enough to establish an increased flow connectivity due to stone-to-stone contacts. A stone content >55 mass. % was found as a threshold for this effect [25]. Neither, a systematically lower stone content in the 100 cm^3 -soil core samples was observed as likely occurs due to subjective focus upon fine-earth pockets in the horizon plane while sampling with the steel rings of small volume (Fig. 2). However, the upper two horizons (Ah, Go) of the grassland

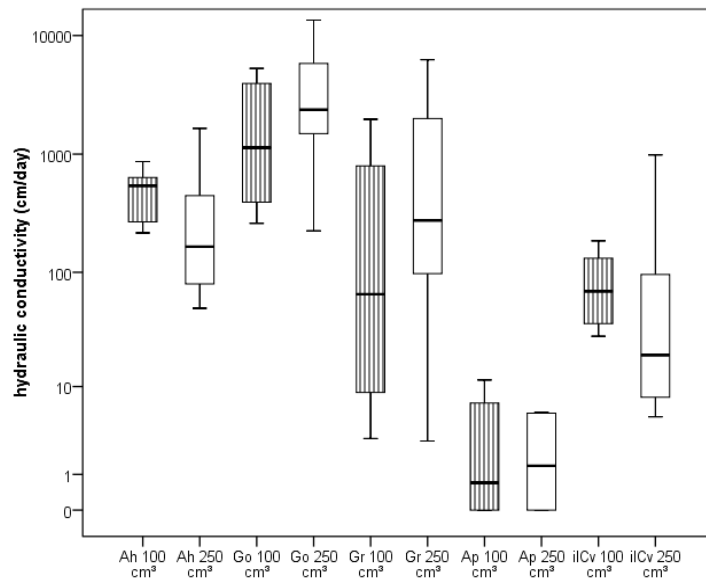


Fig. 1. Box plots of hydraulic conductivities of soil core samples of respective horizons; 100 cm^3 (hatched) vs. 250 cm^3 (white). The abscissa defines the soil horizon and soil core volume (cf. Table 3)

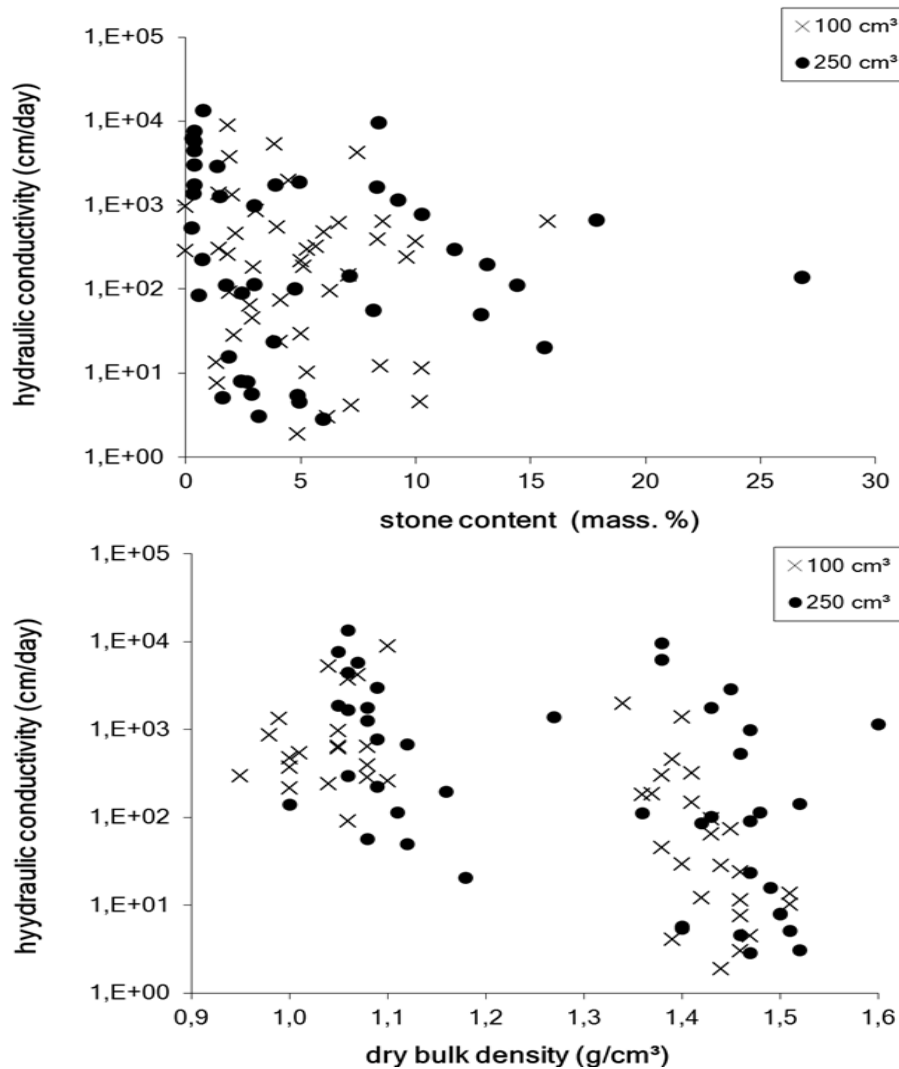


Fig. 2. Hydraulic conductivity of 100 cm³- and 250 cm³-soil core samples a) vs. stone content (top) and b) vs. dry bulk density (bottom)

soil showed a markedly lower dry bulk density irrespective of the sampled volume (Fig. 2). Here, the shallow Go-horizon of the grassland site was lighter and the Ap-horizon of the arable land site was heavier than proposed in other compilations [26]. Expectedly, lowest values of hydraulic conductivity, K_{lab} , were found at soil core samples of comparatively high bulk density (Fig. 2). The pore space of these soil horizons was dominated by fine and medium pores at the cost of wide pores (not shown here). In contrast to other findings [26] soil pore fractions were not related to the organic carbon content of the soil. Due to missing differences in hydraulic conductivity between the 100 cm³- and the 250 cm³-soil core samples only the latter are treated

further on for they were sampled at all three study sites in all soil depths and comprise a soil volume closer to that affected by the borehole permeameter.

3.2 Hydraulic Conductivity of Borehole Permeameter, K_{field} , vs. Soil Core Samples, K_{lab}

In contrast to the device-specific maximum K_{field} of 210 cm/d [11] we measured K_{field} up to 476 cm/d without recognizable fluctuations of the established water level in the borehole. Individual hydraulic conductivities determined in-situ, K_{field} , varied by a maximum factor of 3 (Fig. 3).

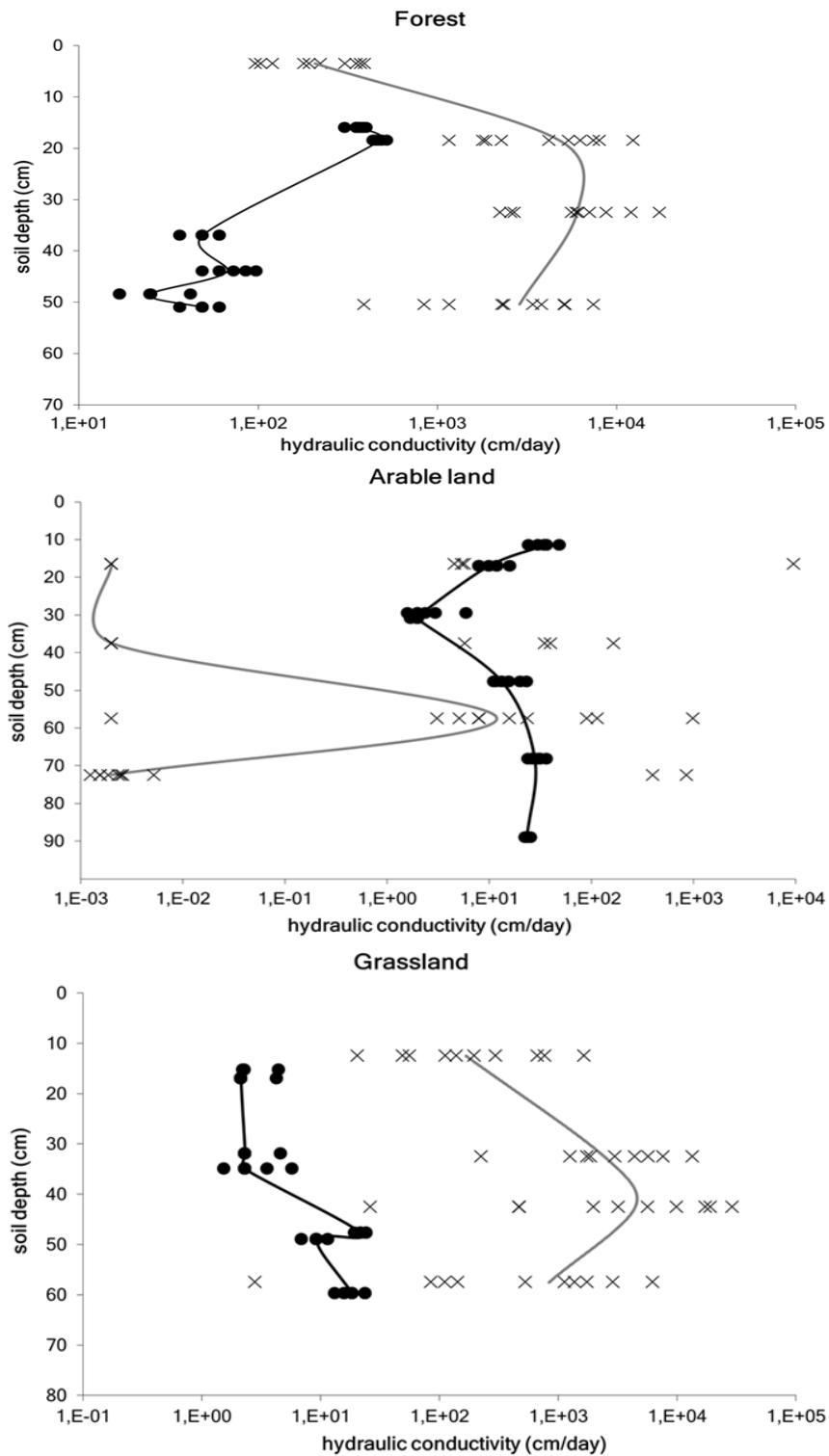


Fig. 3. Hydraulic conductivity of 250 cm³-soil core samples (cross signature) and borehole permeameter (black dots) for the investigation site forest (top), arable land (middle) and grassland (bottom); black line connects the median values of borehole permeameter, gray line connects median values of soil core samples

Compared to the suction-free hood- (179 cm/day) and disk-infiltrator trials (19 cm/day) as reported for another sandy loam soil [10], the shallow hydraulic conductivities, K_{field} , of the sandy loam at our arable land site of about 35 cm/day (Fig. 3) tend more to the disk-infiltrator results. Hood-infiltrator approaches included also macropore flow [10] as did a tension-infiltrator at a silty loam with maximum hydraulic conductivities of 1,900 cm/day [9]. In contrast, the borehole permeameter used here might represent primarily matrix flow. Lower hydraulic conductivities of the borehole permeameter, K_{field} , as compared to those of the soil core samples, K_{lab} , may be assigned to various probable influencing factors: Effects of hysteresis [27] or entrapped air [28] were unlikely, because measurements were conducted at the start of May 2012, i.e. at the end of the groundwater recharge period. Thus, the moisture status in the soil can be assumed to be comparably high and evenly distributed. In our study, K_{field} was based on at least 10 consecutive measurements with a one minute-interval between permeameter readings. Over this 10 minute-period a constant water level was maintained in the borehole according to [11]. This procedure should minimize incomplete saturation under field-conditions as reported by [12]. Slaking of soil during permeameter operation [29], which results in decreasing K_{field} in the course of consecutive measurements, was not observed. However, in our study incomplete removal of sealed soil pores [10] due to smearing during borehole preparation could probably have impeded the free flow of water into the soil. In contrast, soil core samples are thoroughly prepared, deaerated and saturated from below, so that a higher proportion of pores are water conductive during the lab measurement of hydraulic conductivity, K_{lab} . A maximum hydraulic conductivity, K_{lab} , of up to 29,000 cm/day was measured in 35 cm depth for soil cores at the arable site. This corresponds to other macropore flow rates, e.g. 43,200 cm/day in a heavy clay soil with cracks [30]. At other sites, even higher values of up to 26,205,120 cm/day [31] and 4,320,000 cm/day for a 6 mm- \varnothing macropore [32] have been observed.

While borehole permeameter measurements were replicated in the same borehole, the soil core measurements represent different sampling spots, and thus are affected by the small-scale heterogeneity of soil [6]. This is reflected by the greater range of hydraulic conductivities of the soil core samples, K_{lab} , as compared to the

borehole permeameter values, K_{field} , particularly at the arable land site (Fig. 3). Singular macropores in the form of wormholes [33], which were recorded in 40 and 70 cm soil depth (not shown here) could account for this finding. Effects of additional macropores resulting from disturbance of the soil core samples [21,22] cannot be totally excluded. In fact, the median volume of the wide soil pores of the analysed steel-ring samples ($n = 118$) amounted to 14 vol.%, which is classified as "high" according to the German soil survey manual [26]. Moreover, the inspection of each steel-ring prior to the determination of the saturated hydraulic conductivity revealed small discontinuities and worm holes in 79% of the soil core samples. The degree of continuity of macropores, e.g. using computer-tomography [34], was not assessed in this field study.

3.3 RETC-calculations

RETC-parameters are rather values of a non-linear parameter optimization than measured values of soil-physical meaning [35]. Nevertheless, providing a rough proportion of water conducting soil pores it could give useful hints, where different soil pore fractions are of special concern. Hence, the median K_{field} of 476 cm/day obtained using the borehole permeameter at the forest site in 19 cm soil depth (Table 2) was compared to the median $K(h)$ -value of the soil core samples taken in 19 cm soil depth, which provided a corresponding matric potential of -22 hPa. Taking this matric potential as capillary rise (Eq. 4) a threshold pore diameter of 135 μm resulted. K_{field} in this soil depth obviously includes fast draining pores of the macropore spectrum of $\varnothing > 75 \mu\text{m}$ [36]. In contrast, K_{field} in the other soil depths of the forest and the grassland sites comprises medium-sized pores of $\varnothing < 75 \mu\text{m}$ (Table 4), i.e. is restricted to the matrix flow domain.

While K_{lab} comprehends the entire pore space, macropores are excluded from K_{field} . In the measurement of K_{field} an estimated soil volume of 1,620 to 6,840 cm^3 is involved [11]. This could be rendered for a higher probability of a participation of macropores in the flow process [8]. In our comparison between K_{lab} and K_{field} , however, the probability of occurrence of continuous macropores is much higher for K_{lab} due to the smaller soil core volume of 250 cm^3 . In the case of K_{field} -determination these effective macropores could have been blocked by smearing of the borehole walls. Alternatively, if the macropores

Table 4. Exemplary threshold diameters of hydraulically active soil pores based on borehole permeameter measurements as related to the RETC-K(h) value of adjacent soil core samples

Investigation site	Median K_{field} in soil depth	Horizon of related soil core sample in soil depth	Matric potential of median K_{field} using the RETC-K(h) relation of corresponding soil core sample	Threshold pore diameter
Forest	476 cm/day in 19 cm	Bv1 in 19 cm	-22 hPa	135 μ m
	49 cm/day in 37 cm	Bv2 in 33 cm	-90 hPa	33 μ m
Grassland	2 cm/day in 16 cm	Ah in 13 cm	-159 hPa	19 μ m
	2 cm/day in 32 cm	Go in 33 cm	-519 hPa	6 μ m
	16 cm/day in 60 cm	Gr in 58 cm	-69 hPa	43 μ m

within the wetting-bulb are not continuous they may act as an “internal drainage” [37], i.e. water accumulated in a macropore enters the surrounding soil matrix. Thus, the overall observed K_{field} -value might represent matric flow conditions.

Instead of calculating the $K(h)$ -values using the RETC-program, the direct measurement of the unsaturated conductivity of the soil core samples using the evaporation method [38] may have resulted in more accurate threshold pore diameters. However, the combination of K_{lab} and K_{field} , related by a specifically parameterized RETC proved to be a supportive tool, when a rough estimate of water conducting soil pore fractions is of special concern, e.g. in when modelling matrix- plus macropore flow [39] in contaminant transport studies.

4. CONCLUSION

Rapid borehole permeameter measurements integrate a comparably great soil volume and can provide a consistent vertical distribution of hydraulic conductivities. While hydraulic conductivity values of soil core samples comprise the total pore spectrum and are highly affected by continuous macropores, borehole permeameter measurements rather represent matrix flow. By combining both measurement approaches further information of water conducting pore fractions can be obtained, which could be utilized as information in dual-porosity models.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Lehmann A, Stahr K. The potential of soil functions and planner-oriented soil

evaluation to achieve sustainable land use. Journal of Soils and Sediments. 2010; 10:1092-1102.

2. Šimůnek J, Sejna M, van Genuchten MTh. The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and solutes in variably-saturated media. Version 2.0., U.S. Salinity Laboratory Agricultural Research Service, U.S. Department of Agriculture, Riverside, California. 1998;178.

3. Schulla J. Model description WaSIM. Technical report.2012;330. Available:http://www.wasim.ch/downloads/doku/wasim/wasim_2012_en.pdf (Access: 24/10/2014).

4. Blöschl G, Reszler C, Komma J. A spatially distributed flash flood forecasting model. Environmental Modelling and Software. 2008;23:464-478.

5. Klute A, Dirksen C. Hydraulic conductivity and diffusivity: Laboratory methods. In: SSA-SSSA. Methods in Soil Analysis, Part 1, Physical and Mineralogical Methods. Agronomy monograph. 1986;9:687-734.

6. Geological Survey of Northrhine-Westphalia. Methodenvergleich Bodenphysik, Teil 2: Entwässerung ungestörter Bodenproben. 2012;53. German.

7. Rawls WJ, Gimenez D, Grossman R. Use of soil texture, bulk density, and slope of the water retentions curve to predict saturated hydraulic conductivity. Transactions of the ASAE. 1998;41:983-988.

8. Reynolds WD, Elrick DE. Measurement of field-saturated hydraulic conductivity, sorptivity and conductivity-pressure head relationship using the “Guelph permeameter”. 1985;9-33. Available:<http://pbadupws.nrc.gov/docs/ml0037/ml003744523.pdf> (Access:21/10/2014)

9. Buczko U, Bens O, Hangen E, Brunotte J, Hüttl RF. Infiltration patterns and macroporosity of silt loam soils under two different tillage systems. *FAL Agricultural Research*. 2003;53:179-188.
10. Schwärzel K, Punzel J. Hood infiltrometer – a new type of tension infiltrometer. *Soil Sci. Soc. Am. J.* 2007;71:1438-1447.
11. Amoozegar A. A compact constant-head permeameter for measuring saturated hydraulic conductivity in the vadose zone. *Soil Sci. Soc. Am. J.* 1989a;53:1356-1361.
12. Jury WA, Horton R. *Soil physics*. 6th edition. John Wiley and Sons, New York; 2004.
13. Maršálek P, Svobodá Z, Randák T, Švehla J. Mercury and methylmercury contamination of fish from the Skalka Reservoir: A case study. *Acta Vet. Brno*. 2005;74:427-434.
14. Amoozegar A. Comparison of the Glover solution with the simultaneous equations approach for measuring hydraulic conductivity. *Soil Sci. Soc. Am. J.* 1989b; 53:1362-1367.
15. Elrick DE, Reynolds WD, Tan KA. Hydraulic conductivity measurements in the unsaturated zone using improved well analysis. *Ground Water Monit. Rev.* 1989; 9:184-193.
16. Logsdon SD, Jaynes DB. Methodology for determining hydraulic conductivity with tension infiltrometers. *Soil Sci. Soc. Am. J.* 1993;57:1426-1431.
17. van Genuchten, MTh., Šimůnek J, Leij F, Sejna M. RETC, 6.02, code for quantifying the hydraulic functions of unsaturated soils; 2009. Available:www.hydrus3d.com (Access: 24/10/2014).
18. van Genuchten MTh. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 1980;44:892-898.
19. Lenartowicz M. Mathematical modelling of water and solute vertical transport on the example of chloride ion: in the plant-soil column in the Požary basin. *Ecohydrology and Hydrobiology*. 2003;3:323-339.
20. Dane JH, Hopmans JW. Water retention and storage. In: J.H. Dane and G.C. Topp (eds.) *Methods of soil analysis*. Part 4: Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI. 2002;675.
21. Fallico C, Migliari E, Troisi S. Characterization of the field saturated hydraulic conductivity on a hillslope: measurement techniques, data sensitivity analysis and spatial correlation modelling. *Hydrol. Earth Sys. Sci. Discuss.* 2005; 2:1247–1298.
22. Bagarello V, Provenzano G. Factors affecting field and laboratory measurement of saturated hydraulic conductivity. *Transactions of the ASAE*. 1996;39:153-159.
23. Schaap MG. Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Version 1.2; 2002;6. Available:<http://www.cals.arizona.edu/research/arch/rosetta/download/rosetta.pdf> (Access: 07/10/2014).
24. Batchelor GK. *An introduction to fluid dynamics*. Cambridge, University Press, Massachusetts. 1967;615.
25. Urbanek E, Shakesby RA. Impact of stone content on water movement in water-repellent sand. *European Journal of Soil Science*. 2009;60:412–419.
26. Ad-hoc-AG Boden. *Bodenkundliche Kartieranleitung*. 5th edition. Schweitzerbart, Stuttgart; 2005;438. German.
27. Ritsema CJ, Dekker LW, Nieber JL, Steenhuis TS. Modeling and field evidence of finger formation and finger recurrence in a water repellent sandy soil. *Water Resour. Res.* 1998;34:555-567.
28. Hangen E, Gerke HH. Field measurements of air and water pressures in a heterogeneous forest-reclaimed lignitic mine soil. *Vadose Zone Journal*. 2007;6: 849-854.
29. Angulo-Jaramillo R, Vandervaere, JP, Roulier S, Thony JL, Gaudet JP, Vauclin M. Field measurement of soil surface hydraulic properties by disc and ring infiltrometers - a review and recent developments. *Soil and Tillage Research*. 2000;55:1-29.
30. Beven K. The Grendon Underwood field drainage experiment. Institute of Hydrology, Wallingford, U.K., Rep. 65. 1980:30.
31. Ehlers W. Observations on earthworm channels and infiltration on tilled and untilled loess soil. *Soil Sci.* 1975;119:242-249.
32. Peterson AE, Dixon RM. Water movement in large soil pores. *Res. Div. Coll. Agr. Life Sci., University of Wisconsin, Madison*. Res. Rep. 1971;75:1-8.
33. Hangen E, Buczko U, Bens O, Brunotte J, Hüttl RF. Infiltration patterns into two soils

- under conventional and conservation tillage: influence of the spatial distribution of plant root structures and soil animal activity. *Soil and Tillage Research*. 2002; 63:181-186.
34. Rogasik H, Onasch I, Brunotte J, Jegou D, Wendroth O. Assessment of soil structure using X-ray computed tomography. Geological Society, London, Special Publications. 2003;215:151-165.
35. Wessolek G, Kaupenjohann M, Renger M. (in German) Bodenphysikalische Kennwerte und Berechnungsverfahren für die Praxis. Technical University of Berlin. *Bodenökologie und Bodengenese*. 2009; 40:82. German.
36. Soil Science Glossary Terms Committee. *Glossary of Soil Science Terms* 2008. Madison, WI; Soil Science Society of America; 2008.
37. Booltink HWG, Bouma J. Sensitivity analysis on processes affecting bypass flow. *Hydrol. Proces*. 1993;7:33-43.
38. Schindler U, Durner W, von Unold G, Müller L. Evaporation method for measuring unsaturated hydraulic properties of soils: Extending the range. *Soil Sci. Soc. Am. J.* 2010;74:1071-1083.
39. Gerke HH, van Genuchten MTh. Evaluation of a first-order water transfer term for variably-saturated dual-porosity models. *Water Resour. Res.* 1993;29: 1225-1238.

© 2015 Hangen et al.; This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:

The peer review history for this paper can be accessed here:
<http://www.sciencedomain.org/review-history.php?iid=958&id=24&aid=8677>