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GUELPH PERMEAMETER MEASUREMENTS OF THE TOPSOIL AND UPPER SUBSOIL HYDRAULIC CONDUCTIVITY FOR CHARACTERISING THE STRUCTURAL STATE OF ARABLE LANDS

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Abstract. An attempt at characterising the soil structure dynamics by repeated borehole infiltration measurements was undertaken on 15 measurement sites at two locations. The boreholes were 40 cm deep. Quasi-steady discharges were determined at four different water levels. The resulting field-saturated hydraulic conductivities (K_{fs}) show distinct dependence upon soil texture. K_{fs} does not depend much upon depth when measured after a prolonged period of natural settling of the topsoil. At other instants, the upper topsoil appears to be more permeable due to either tillage operations or the surface micro-cracks caused by drying. Man-induced subsoil compaction is detectable on sandy loam and loamy sand sites. The favourable effect of subsoiling stabilized by liming has been proved. There is a weak negative correlation between log K_{fs} and the initial soil moisture content. It is envisaged that the results can be used as inputs to the simulation models of crop growth and soil water and nutrient regime, e.g., when these models are applied to investigate various functions and roles of soil structure.

Keywords: structure, borehole infiltration, simulation models

INTRODUCTION

The ways in which soil structure affects other components of the abiotic and biotic environment, and is itself influenced by them, are very complex. Among many various soil properties and parameters which can be used as indicators of the soil structure, it is the hydraulic properties of the soil (such as the retention curve and the hydraulic conductivity function) which are of special importance because of their capability of being input into complex simulation models of crop growth, soil water regime, nutrient regime and other relevant processes. In this way, predictions of possible interactions between the soil structure and other elements of the environment (including the socio-economic factors) can be made and the measured or observed data can be interpolated or even extrapolated in the most appropriate manner. A similar approach was adopted, e.g., by Creswell *et al.* [4] and Leummens *et al.* [13].

In this paper, we focus on the field-saturated hydraulic conductivity of the topsoil and upper subsoil, measured with the so-called Guelph permeameter, i.e., a constant-head borehole infiltrometer. The field-saturated hydraulic conductivity only represents a single point of the functional relationship between the hydraulic conductivity and the soil water pressure head (or the soil moisture content). However, it can serve as a characteristic of the instantaneous structural state of the soil, in the sense that it indicates the presence, amount and connectivity of large pores in the soil, those of a textural nature as well as those secondarily created due to mechanical and biological processes.

Some of the results discussed in this paper are related to the so-called whole-profile method of reclamation of soils with dense and acid subsoil horizons. Such horizons may present impenetrable barriers for plant roots even in the soils previously fertilized and limed abundantly, as long as the nutrients and the lime remain in the topsoil only. The method of reclamation, designed and tested in the Research Institute for Soil and Water Conservation by Damaška and his collaborators and described in several reports and manuals (e.g., [14-16]), relies on the combined effect of deep loosening of the soil (subsoiling), intensive application of lime, phosphorus and potassium, ploughing and subsequent growing of deep-rooting crops. The fertilizers and lime, applied immediately before the subsoiling and mixed with the topsoil by the subsequent ploughing, are allowed to leach by natural rainfall into the cracks in the subsoil. This improves the nutrient status and pH of the subsoil so that the plant roots can penetrate into it. If a suitable crop rotation is then applied comprising deep-rooting crops (such as alfalfa or clover) and the use of heavy machinery is minimised, the loosened structure of the subsoil is stabilised and can persist for several years. A possible drawback of this method is the risk of leaching of nutrients into groundwater.

The purpose of our investigations was fivefold:

1) to demonstrate that the Guelph permeameter could be sensibly used for characterising soil structure and its spatial and temporal variation, as well as for obtaining meaningful input data for complex simulation models, and to elaborate in detail the techniques needed for these purposes;

2) to obtain particular values of the field-saturated hydraulic conductivity, K_{fs}, typical for the soils studied and other soils similar to them, such that they could subsequently become inputs to simulation models;

3) to characterise the soil structure and its temporal and spatial variability on the particular lands studied and other lands similar to them;

4) to assess the role which the soil structure and its dynamics may play in a catchment similar to the one studied, in view of possible attempts at revitalisation of the catchment (not discussed in this paper);

5) to assess the effects of the whole-profile reclamation upon the structural state and hydraulic properties of the topsoil and upper subsoil.

This paper presents an overview of results obtained with the Guelph permeameter on the field sites described below. Some other procedures (e.g., the disc infiltrometer of the design by Ankeny *et al.* [2]), not reported in this paper, were used on the same sites in order to make the evaluation of soil structure more complex. The results of these other measurements and their comparison with the Guelph permeameter results, as well as a more detailed analysis of the Guelph permeameter measurements themselves, have been reported in [7] and [12] and are being prepared for publication as separate papers.

MATERIAL AND METHODS

Measurement sites

The following sites were investigated:

- Liblice, district Melník, central Bohemia, in 1993-1994, and
- Horní Třešňovec, district Ústí nad Orlicí, East Bohemia, in 1994.

The research location Liblice lies northwest of the village of the same name. It comprises several large fields managed by an agricultural cooperative in Liblice. The choice was motivated by the fact that the Research Institute for Soil and Water Conservation was preparing a revitalisation study for a part of the catchment of the Košátecký potok stream to which our research fields also belonged. The area is located just at the boundary of a protected region of natural water recharge called "The North Bohemian Cretaceous". The relief is composed of low hills and plateaux, interrupted by valleys and depressions in the places where the upper cretaceous rocks were more susceptible to erosion. The mean annual precipitation is 519 mm, the mean annual temperature is 8.6 °C. Elevations of the measurement sites vary between 185 and 220 m, the latitude is about 50.35° N.

Nine measurement sites were chosen on six different fields within this location. The sites were not situated on a single slope but, in fact, represented a catenal series of soil types developed on different erosional forms of virtually the same parent rock. The parent rock is created by weathered outcrops of the cretaceous, middle-Turonian Jizera formation containing siltstones and fine-grained sandstones with occasional layers of marlites or clayey limestones. This basic parent rock is occasionally overlain by deluvial, deluvio-fluvial or aeolian quaternary sediments of sandy or loessial nature. Geomorphologic and pedologic characteristics of individual measurement sites are given in Table 1 (where the soil types are classified according to FAO, cf. [8] and [24]), while the crops grown on the sites during the investigation are listed in Table 2.

The research location Horní Třešňovec lies west of the village of the same name, north of the town of Lanškroun, in district Ústí nad Orlicí. All measurements were carried out on a single field. The site was chosen because a pilot field experiment was located there which had been designed to test the whole-profile method of soil reclamation described above. The pilot experiment had been conducted since 1989 by the Research Institute for Soil and Water Conservation. The field is situated on a mild eastern slope within a submountainous peneplain of Orlické hory (Adlergebirge) mountains. It has been drained with an underground pipe drainage system. The elevation of the site is about 410 m, the latitude is 49.94° N. The climate may be approximately characterised by the data from a nearby weather station Žichlínek at elevation 360 m (cf. [5] or [21]): average annual precipitation 650 mm, average annual temperature 6.8 °C.

The soil of the field is an Albo-Gleyic Luvisol (in the sense of the FAO classification), loamy, on a thick loess loam layer covering a (crystalline or metamorphic) bedrock. The albic subsoil horizon, occurring at about 27 cm below the soil surface, is very dense and acid and cannot easily be penetrated by the roots of common crops. The pilot experiment, aiming to test the whole-profile reclamation method, was established in autumn 1989. It consists of four plots of the size about 100 x 50 m each, denoted A, B, C and D and located within a larger field. The rest of the field, surrounding

Table 1. Overview of measurement sites in Liblice, central Bohemia

Site	Geomorphology	Soil
1	Upper part of a side valley without a water recipient	Eutric Regosol, loamy sand on quaternary deposits without stones
2,3	Middle part of a long mild slope	Rendzina, sandy loam with stones, on products of siltstone and marlite weathering, sometimes covered with a thin loess layer
4,5	Lower part of a long mild slope	Phaeozem, loam with occasional stones, on colluvial quaternary depositis
6,8,9	Hill top	Rendzina, loamy sand, on products of weathering of siltstone and marlite
7	Hill top	Eutric Regosol, sand, on quaternary aeolian deposits without stones

Table 2. The crops grown on the investigated fields in Liblice, central Bohemia

Site	Crop grown in:	
	1993	1994
1	alfalfa	alfalfa
2,4	onion	winter wheat
3,5	sugar beet	spring barley
6,9	maize	winter wheat
7	spring barley	not measured
8	various vegetables	rape

the research plots, was considered as a zero treatment. The treatments were as described in Table 3(a). The doses applied were 170 kg P/ha, 300 kg K/ha and 3500 kg Ca/ha. The subsoiling reached to the depth of about 40 cm. Clover, sown into spring barley, was a reclamation crop. The reclamation was repeated in autumn 1993 on the lower halves of the test plots. The treatments were as described in Table 3(b). No extra fertilizers were applied (in addition to those required for standard farming). The dose of lime was 3000 kg Ca/ha. No special reclamation crop was used. The crop rotation was as described in Table 4. The sites selected for the infiltration measurements are listed in Table 5.

Table 3. Treatments of the pilot experiment in Horní Třešňovec, East Bohemia, designed to test the whole-profile method of soil reclamation

	1989 (a)
0	Zero treatment, outside the rectangular test plot
A	Subsoiling
B	Subsoiling and liming
C	Subsoiling and application of P and K
D	Subsoiling, liming and application of P and K
	1993 (b)
0	Zero treatment, outside the rectangular test plot
A	Subsoiling
B,C,D	Subsoiling and liming

Table 4. The crops grown on the investigated field in Horní Třešňovec, East Bohemia

1990	spring barley with clover as undercrop
1991	clover
1992	winter wheat
1993	maize for silage
1994	winter wheat

Table 5. Overview of measurement sites in Horní Třešňovec, East Bohemia

1	Treatment D
2	Zero treatment, west of the experimental plot
3	Treatment A
4	Zero treatment, south of the experimental plot
5	Treatment B
6	Treatment C

Apparatus and procedure

The apparatus used was the Guelph permeameter, i.e., a constant-head borehole infiltrometer. The infiltrometer design coincided principally with the one depicted in [19]. The measurement consisted in estimating a quasi-steady discharge Q of water infiltrating into a vertical borehole of the radius a in which the water level was maintained at a height H above the borehole bottom. The walls of the borehole were cleaned before the measurement with a brush or a knife in order to remove from them (sometimes imperfectly) the less permeable film of smeared soil produced by the auger, as recommended, e.g., in [19].

On each measurement site and at each date of measurement, the investigation was carried out in two parallel boreholes, 40 cm deep and 9 cm in diameter, made about 2 m apart. The two boreholes were investigated in an identical way: the water level in each borehole was maintained, gradually, at 30, 20, 10 and 2 cm below the soil surface. The corresponding quasi-steady infiltration discharge, Q (m^3s^{-1}), was measured for each of these water levels.

The Guelph permeameter measurements were accompanied by taking undisturbed 100 cm^3 soil cores and disturbed soil samples at several depths in order to determine the soil moisture content, bulk density and total porosity, as well as two empirical pore-size distribution parameters, still widely used in practice but lacking a strict physical meaning, referred to traditionally as the "maximum soakability" (the volumetric moisture content of a 100 cm^3 core after letting it soak for 24 h while water table has been touching its base) and the "maximum capillary capacity" (the volumetric moisture content of the same core left afterwards to drain on a filter paper for two hours). The grain size distribution of the soils was not determined.

Theory

All standard formulae for evaluating the Guelph permeameter measurements assume that the soil around the borehole is homogenous (in respect of its hydraulic properties and its initial moisture status) and the groundwater table or an impermeable bedrock are infinitely deep. The Glover formulae [9], used in this study, assume, in addition, a steady saturated flow around the borehole and disregard any influence of the surrounding unsaturated zone upon the flow regime; these assumptions are more realistically fulfilled in sandy and gravelly soils or the soils containing abundant macropores. The Glover formulae read as follows:

$$K_{fs} = \frac{CQ}{2\pi H^2} \tag{1}$$

$$C = \arg\sin E - \left[\left(\frac{1}{E}\right)^2 + 1\right]^{1/2} + \frac{1}{E} \tag{2}$$

$$E = \frac{H}{a} \tag{3}$$

where K_{fs} (ms^{-1}) is the field-saturated hydraulic conductivity, Q ($\mathrm{m}^3\mathrm{s}^{-1}$) is the quasi-teady infiltration discharge required to maintain a constant water level in the borehole, π=3.14159 ..., H (m) is the height of water table above the borehole bottom, a(m) is the borehole radius, and C (dimensionless) is a shape coefficient. Another useful formula is:

$$\arg\sin E = \ln\left[E + \sqrt{\left(E^2 + 1\right)}\right] \tag{4}$$

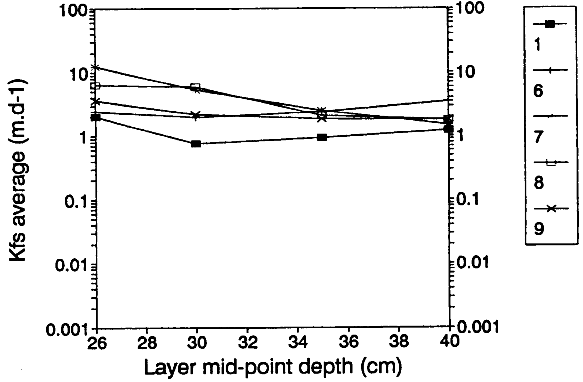
The Glover formulae given above were suggested for routine use by Doležal and Poruba [6] who concluded that the tendency to overestimate the field-saturated hydraulic conductivity K_{fs}, inherent to the Glover formulae because of their neglecting the effect of capillarity, is more or less counterbalanced by the physical effects acting in the opposite direction (like, e.g., smearing of the borehole walls or incomplete soil saturation during the experiment). Moreover, large random measurement errors, e.g., due to soil heterogeneity, may make the use of more complicated formulae and procedures (cf. [18] and [19]) meaningless. The assessment of the unsaturated soil hydraulic properties from the Guelph permeameter measurements alone seems impossible. The so-called matrix flux potential, sometimes suggested as being derivable from these measurements [19], does not in fact carry much new information in addition to that contained in the field-saturated hydraulic conductivity. Similar recommendations were also given in [1]. A practical advantage of the Glover formulae is that, for using them, one need not assume anything about the unsaturated hydraulic properties of the soil.

Each elementary measurement, i.e., the quasi-steady discharge obtained in a certain borehole with a certain water level in it, was processed separately. In each case, the resulting field-saturated hydraulic conductivity, K_{fs}, was regarded as an average characteristic of the soil layer involved, which was assumed to lie between the level of water table in the borehole and the level at 50 cm below the soil surface (i.e., 10 cm below the borehole bottom). The geometry of layers so defined is recapitulated in Table 6. The way in which the field-saturated hydraulic conductivity depends upon the depth is only judged and discussed in this paper in terms of the average conductivities for the layers defined in Table 6. So, for example, the vertical profiles of K_{fs} in Figs 1 and 2 are plotted with regard to the midpoints of these layers. This is an integral representation of the hydraulic conductivity profile. Its differentiation should ideally give a detailed vertical profile of the point

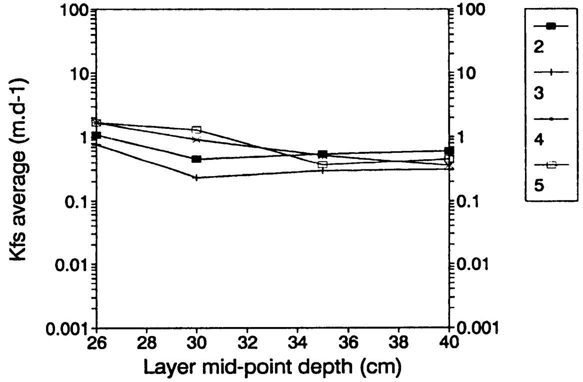
Table 6. The soil layers considered as contributing to individual Guelph permeameter measurements in Liblice and Horní Třešňovec (the figures indicated are depths below soil surface)

Water level in the borehole	Layer considered extends		Layer mid-point
	from	to	
	(cm)		
30	30	50	40
20	20	50	35
10	10	50	30
2	2	50	26

a) Liblice - averages



b) Liblice - averages



c) Liblice - maxima

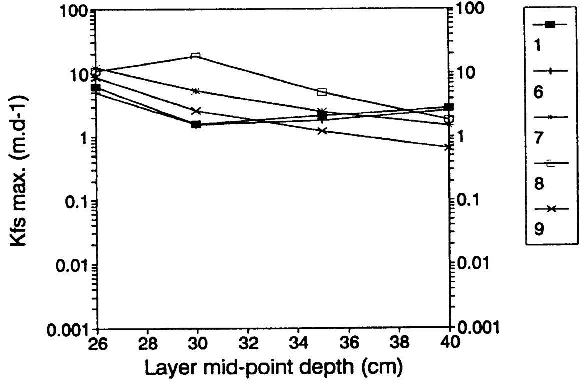
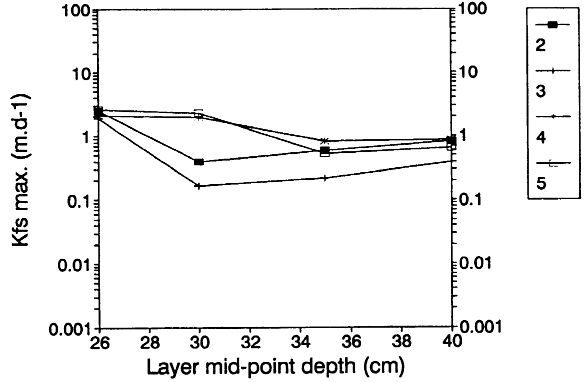
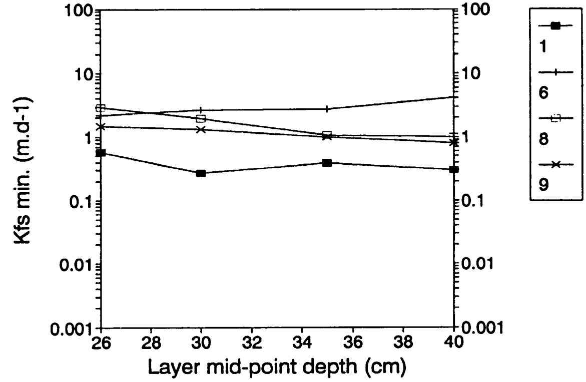


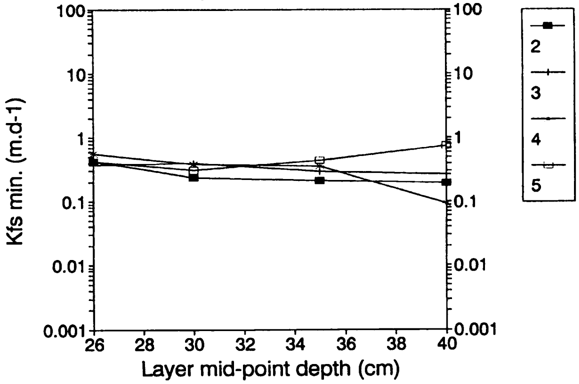
Fig. 1. Vertical profiles of the horizontal field-saturated hydraulic conductivity, K_{fs}, in Liblice. The averages (a), b)) include all boreholes and all dates of measurement, while the "maximum" (c), d)) and "minimum" (e), f)) profiles represent the averages over two parallel boreholes for a particular date on which the K_{fs} values on a given site were maximal or minimal (on average, not necessarily at all depths), respectively. Each value of K_{fs} is plotted against the depth of mid-point of the soil layer to which it pertains.



d) Liblice - maxima



e) Liblice - minima



f) Liblice - minima

Fig. 1. Continuation.

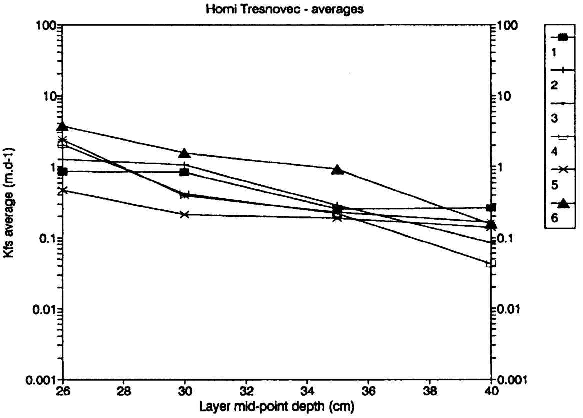


Fig. 2. Vertical profiles of the average horizontal field-saturated hydraulic conductivity, K_{fs}, in Horní Třešňovec. The averages include all boreholes and all dates of measurement. Each value of K_{fs} is plotted against the depth of midpoint of the soil layer to which it pertains.

values of K_{fs}. However, the operation of differentiation appered to be unstable and very sensititve to random fluctuations of the measured integral values. Therefore, we refrained from the attempts at deciphering the measured data in this way.

As the flow of water from the borehole into the soil was mainly horizontal (perpendicular to the borehole walls), we considered the values of K_{fs} as characterising the horizontal hydraulic conductivity of the soil. The averaged hydraulic conductivities plotted in Figs 1a, 1b and 2 were obtained by arithmetic averaging, before the logarithmisation, of the values measured in all boreholes and at all dates.

RESULTS AND DISCUSSION

Altogether, 376 elementary measurements were made in Liblice and Horní Třešňovec in altogether 94 boreholes on 15 different measurement sites. Table 7 gives an overview of the measurements and ascribes short names to individual periods of measurement for quick reference. The measurements provide us with a relatively detailed picture of the spatial and temporal distribution of the horizontal field-saturated hydraulic conductivity, K_{fs}, which is on both sites primarily determined by the grain size distribution of the soil. The measurement sites can be qualitatively ranked into five categories according to their texture or, equivalently, according to their (gradually decreasing) hydraulic conductivity as indicated in Table 8. The fact that the hydraulic conductivity and other hydraulic properties of the soils are texture-conditioned has been anticipated by some simulation models (like, e.g., EPIC [20] or CERES [10,11,23]) which are so designed that some hydraulic properties of the modelled soils can be estimated from their texture, humus content and other basic information.

Table 7. Overview of measurements made with the Guelph permeameter in Liblice and Horní Třešňovec

Location	Measurement sites	Short name of the period	Dates of measurement
Liblice	1-9	autumn 93	12.8.-26.8.93
Liblice	1-6, 8-9	spring 94	4.5- 2.6.94
Liblice	1-6, 8-9	summer 94	20.7-25.7.94
Liblice	1-6, 8-9	autumn 94	14.9-4.10.94
Horní Třešňovec	1-6	spring 94	10.5-26.5.94
Horní Třešňovec	1-6	summer 94	13.7-14.7.94
Horní Třešňovec	1-6	autumn 94	22.8-25.8.94

Table 8. Approximate ranking of the sites in Liblice and Horní Třešňovec according to their granulometry and hydraulic conductivity

Rank	Location	Site	Verbal characteristic
1	Liblice	6-9	Sand or loamy sand on the top of the hill
2	Liblice	1	Loamy sand in a side valley without a water recipent
3	Liblice	2-3	Sandy loam in the middle part of a long mild slope
4	Liblice	4-5	Loamy soil at the bottom of a long mild slope
5	Horní Třešňovec	all	Loam or clay loam, with a dense gleyic subsoil

The same idea gave rise to a systematic research of so-called "pedotransfer functions" (cf., e. g., [3] and [22]). Distributions of K_{fs}, including all depths and boreholes on individual measurement sites, are given in Figs 3 and 4. The influence of granulometry is well-defined in Liblice (Fig. 3), but not in Horní Třešňovec (Fig. 4), where all sites were situated on granulometrically the same soil.

Within a single measurement site, the field-saturated hydraulic conductivity, K_{fs}, depends upon the depth below the soil surface (cf. Figs 1 and 2). Its maximum occurs in most cases in the upper topsoil, but the shape of the K_{fs} profile is different on different sites and at different time instants, being in most cases such that K_{fs} either gradually declines downwards (this is the case with virtually all profiles from Horní Třešňovec, cf. Fig. 2) or displays a local minimum indicating man-induced compaction of the upper subsoil. The latter situation frequently occurs in Liblice and is particularly typical for loamy sands and sandy loams with permeable subsoils (e.g., for the measurement sites 1, 2, 3 and 6; cf. Fig. 1).

The two above-mentioned factors (i.e., the grain size and the depth) explain a part, probably a major one, of the field-saturated hydraulic conductivity variation. What remains is:

a) the random variation of K_{fs} in space, as testified by the differences between the values obtained in two parallel boreholes at the same time and depth (not shown);

b) the variation of K_{fs} in time, which is mostly systematic and is caused by the variation of amount, size and connectivity of large pores in the soil due to various factors (tillage operations, activity of living organisms, swelling and shrinking of the soil, spontaneous mechanical settling of the topsoil in the course of the season, frost-induced spontaneous recovery of the topsoil structure during winter, etc.).

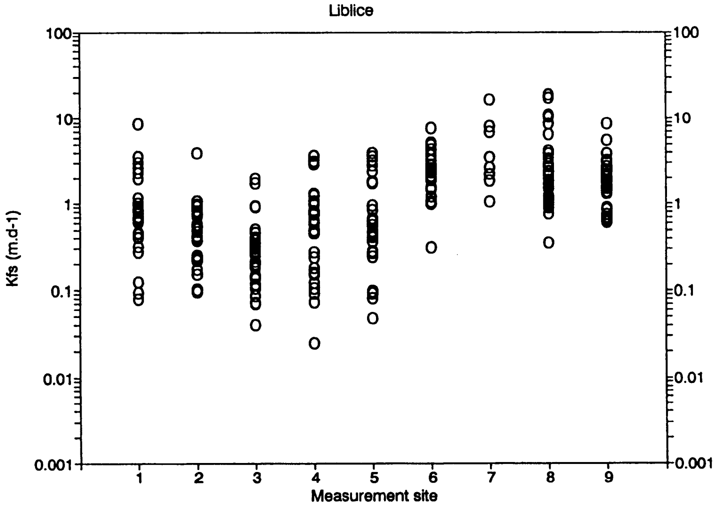


Fig. 3. Distribution of values of the horizontal field-saturated hydraulic conductivity, K_{fs}, on individual measurement sites in Liblice. Included are all boreholes, all dates of measurements and all depths.

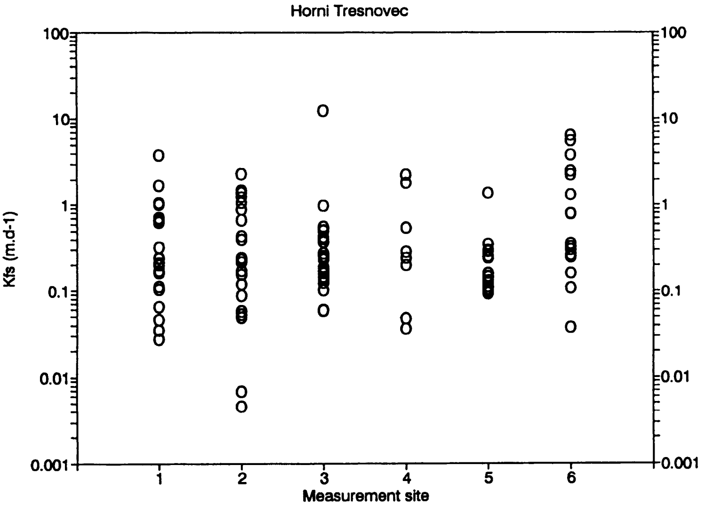


Fig. 4. Distribution of values of the field-saturated horizontal hydraulic conductivity, K_{fs}, on individual measurement sites in Horní Třešňovec. Included are all boreholes, all dates of measurements and all depths.

Some of these processes can be described quantitatively or semi-quantitatively and have already been embodied in some of the complex simulation models (e.g., the EPIC model; cf. [20]).

In Liblice, where the measurements were more frequent and the soil variability was more pronounced, we were able to identify the periods during which the hydraulic conductivity on individual measurement sites was, on average, at its minimum or maximum (excluding erratic extremes). These periods are indicated in Table 9. The vertical profiles of K_{fs} for the "minimum" periods are flat, i.e., such that the hydraulic conductivity does not vary much in the vertical direction and is primarily dependent upon the grain size of the soil (cf. Fig. 1e and f; no minimum was obtained for site 7). This condition of the topsoil can be taken as a reference state and corresponds roughly to what Linkeš *et al.* [17] denote as a "balanced soil bulk density". On the contrary, the "maximum" profiles reveal high variability of K_{fs} in the vertical direction. It is particularly the upper part of the topsoil which becomes much more permeable during these periods (cf. Fig. 1c and d). From what we could observe during our measurements, we infer that there were two main mechanisms which enhanced the topsoil hydraulic conductivity: the man-induced loosening of the soil by tillage operations and the spontaneous micro-cracking of the surface soil due to drying and shrinking. Our measurements were not detailed enough to allow proper distinction between these two mechanisms.

Table 9. The periods when the minimum and maximum values of the topsoil/upper subsoil horizontal field-saturated hydraulic conductivity occured in Liblice

Measurement site	Period of	
	minimum K_{fs}	maximum K_{fs}
1	spring 94	autumn 94
2	spring 94	autumn 94
3	autumn 93	summer 94
4	spring 94	summer 94
5	spring 94	summer 94
6	autumn 93	spring 94
7	not evaluated	autumn 93
8	spring 94	autumn 93
9	summer 94	autumn 94

The measurements in Horní Třešňovec were less frequent so that we only could observe that the field-saturated hydraulic conductivity, K_{fs}, tended to increase in time during spring and summer when the crop was winter wheat (not shown). The state of the soil in spring could be, with some reservation, denoted as a reference state, roughly corresponding to the "minimum" state of the soil in Liblice. It can be seen in Fig. 2 that the hydraulic conductivity (K_{fs}) of the layer between 30 and 50 cm (with the midpoint at 40 cm) is considerably lower, by about one order of magnitude, on the measurement sites 2 and 4 (the zero treatments which had not been subsoiled) than on the other sites.

Figs 5 and 6 show how the field-saturated hydraulic conductivity K_{fs} depends upon the soil moisture content measured at the same time (before the infiltration experiment), in the same soil and, approximately, at the same depth. The full lines in Figs 5 and 6 represent least-squares regression in a semi-logarithmic scale. The correlation is very loose but a tendency of K_{fs} to decrease with the moisture content increasing in observable, idicating that:

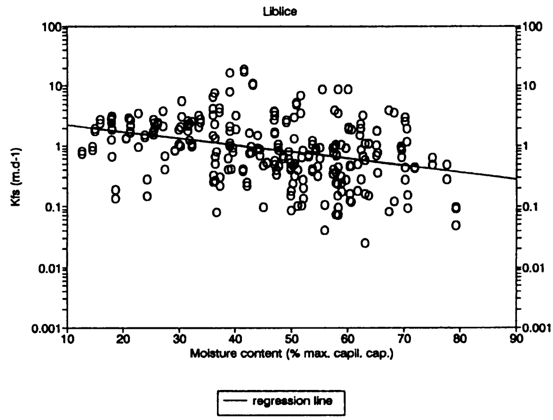


Fig. 5. Dependence of the horizontal field-saturated hydraulic conductivity K_{fs} of the topsoil and shallow subsoil in Liblice upon the soil moisture content in the corresponding depth. Every point corresponds to a single measurement. The soil moisture contents are expressed in per cent of the maximum capillary capacity (approximately equal to the field capacity). The K_{fs} values obtained when the depth of water level in the borehole was 30, 20, 10 and 2 cm below the soil surface correspond to the soil moisture sampling depths 40, 30, 20 and 10 cm, respectively.

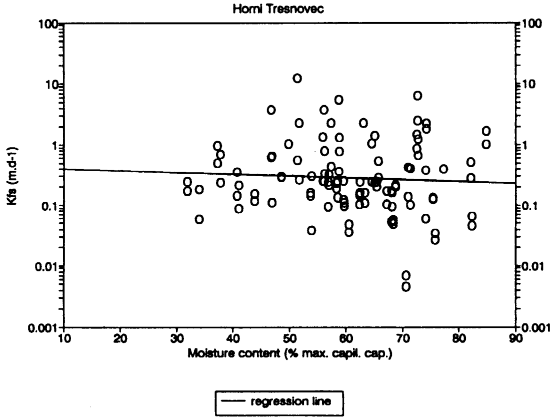


Fig. 6. Dependence of the horizontal field-saturated hydraulic conductivity K_{fs} of the topsoil and shallow subsoil in Horní Třešňovec upon the soil moisture content in the corresponding depth. Every point corresponds to a single measurement. The soil moisture contents are expressed in per cent of the maximum capillary capacity (approximately equal to the field capacity). The K_{fs} values obtained when the depth of water level in the borehole was 30, 20, 10 and 2 cm below the soil surface correspond to the soil moisture sampling depths 40, 30, 20 and 10 cm, respectively.

a) the soils shrink and become micro-cracked (and, therefore, more permeable) when their moisture content decreases;

b) in Liblice, the texturally lighter sites are not only more permeable but also less retentive; they drain and dry more rapidly and low moisture contents occur more frequently in them.

CONCLUSIONS

The Guelph permeameter method confirmed to be a versatile tool for estimating the field-saturated horizontal hydraulic conductivity, K_{fs}, in both topsoil and subsoil. For processing the measurements, one can use the classical Glover formulae [9] which express correctly enough the shape factor, do not require any a priori information about the soil and, being predisposed to overestimate the resulting K_{fs}, are able to counterbalance the tendency of the borehole infiltration method to underestimate it.

We were able, with the Guelph permeameter, to identify the upper subsoil of the loamy sand and sandy loam sites as having been unduly compacted by agricultural machinery and to observe a favourable effect of subsoiling on the loamy Albo-Gleyic Luvisol sites. These effects can, of course, be qualitatively detected by an experienced soil surveyor, but the Guelph permeameter allows to quantify them.

Our measurements suggest that, in the soils of light or medium texture, the field-saturated hydraulic conductivity is primarily texture-dependent. This conclusion is encouraging because it confirms that the areal variation of the soil hydraulic properties can be estimated on the basis of areal variation of their grain size distribution, frequently available due to previous soil surveys.

Beside the soil grain size, the other main factors which determined the field-saturated hydraulic conductivity, K_{fs}, of the soils studied were:

a) the depth below soil surface,
b) the random variation in space (even if the soil texture was locally uniform),
c) the (mostly systematic) variation in time.

In the Liblice sites, we were able to identify the periods during which K_{fs} was at its minimum or maximum. The vertical profiles of K_{fs} for the "minimum" periods were such that K_{fs} did not vary much in the vertical direction and was primarily dependent upon the grain size of the soil. This state of the topsoil can be taken as a reference one.

The two main mechanisms which caused the topsoil hydraulic conductivity to increase above its reference level were the man-induced loosening of the soil by tillage operations and the spontaneous micro-cracking of the surface soil due to drying and shrinking. The micro-cracking mechanism also partly explains the weak negative correlation between K_{fs} and the soil moisture content at a corresponding depth before the measurement.

The whole-profile method of reclamation of soils with dense and acid subsoil horizons has been positively evaluated elsewhere (cf. [14] to [16] and Voplakal's chapter in [21]). We can only say, on the basis of the our one-year measurements, that the reclaimed subsoil probably preserves its higher hydraulic conductivity (K_{fs}) for at least one year after the reclamation.

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