Int. Agrophysics, 1997, 11, 43-88

EVALUATION OF SOIL PHYSICAL CONDITION WITH THE USE OF CERES MODEL, PERMEAMETER AND INFILTROMETER METHODS*

V. Kuráž[1], *F. Doležal*[2]

[1] Czech Technical University, Faculty of Civil Engineering, Thákurova 7, 166 29 Prague 6, Czech Republic
[2]Research Institute for Soil Water Conservation, Žabovřeská 250, 15627 Prague 5, Czech Republic

Accepted February 14, 1997

A b s t r a c t. The following sites were investigated: Tisice (district Melnik, central Bohemia): An irrigation and agronomic experiment station of which some archive data were used as inputs to (and to test the outputs of) the CERES-Barley model. The irrigation and agronomic experiments have been conducted in Tisice since 1955 by the Research Institute of Irrigation Management in Bratislava and its predecessors, the Research Institute of Crop Production in Praha-Ruzyne and the Czech Hydrometeorological Institute. Several additional infiltration measurements were made in 1995.

Liblice (district Melnik, central Bohemia), about 10 km aside from Tisice, on the boundary of a protected region of natural water recharge ('The North Bohemian Cretaceous'). Standard farm fields. Several sites, on various catenal soil forms developed on virtually the same parent rock (see below), were investigated using infiltration tests in 1993-1994.

Horni Tresnovec (district Usti nad Orlici, East Bohemia, in a submountainous peneplain of the Orlicke hory mountains). A pilot experimental field for testing a whole-profile soil reclamation methods. Some treatments of the experiment were investigated using infiltration tests in 1994.

The two latter sites were investigated within a research project on 'Revitalisation of the agricultural and forest catchment' (1993-1995), financed by the Ministry of Agriculture of the Czech Republic. The project was executed by the Research Institute for Soil and Water Conservation in Prague - Zbraslav.

K e y w o r d s: soil physical conditions, CERES model, penetrometer, infiltrometer

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. It is therefore desirable that several different approaches to the study of the soil structure and its functions be tried, even if some of them may seem inappropriate at first sight.

A list of soil properties which characterize the soil structure or are otherwise related to it has already been formulated at the end of the previous multilateral project, 'Assessment of soil structure in agricultural soils' [16]. Among these, the hydraulic properties of the soil (such as the retention curve and the hydraulic conductivity function) have been selected in the present project as the (almost universal) characteristics of the soil structure, having a distinct capability of being input into complex simulation models of crop growth, soil water and 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) are made feasible.

*The project was made with a collaboration with Czech Technical University, Faculty of Civil Engineering, Prague: Ing. Jana Veselá, Josefa Alexandrova and Research Institute for Soil and Water Conservation, Prague - Zbraslav: Ing. Miroslav Poruba, Ing. Pavla Klímová, Ing. Karel Voplakal, Dr. Mojmír Soukup and Dr. Miloslav Pýcha, Assoc. Prof. Josef Šimon, Jan Martinec, Widad Mutwakil Saadalla.

Our contribution to the present project consists of following items:

Using the complex simulation model CERES for demonstrating the influence of soil structure variations upon soil water and nitrogen regime and crop growth.

Exploring (partially) the relations between the CERES input parameters and the independently measurable soil and system properties.

Testing and elaborating the Guelph permeameter and disc infiltrometer methods for measuring saturated and unsaturated hydraulic parameters of a soil, for a twofold purpose: to obtain input parameters for complex simulation models and to characterize the soil structure and its dynamics directly.

Micromorphological analyses of the soil at the Tisice experiment station. This part of the study was made by the Research Institute of Soil Fertility in Bratislava, Slovakia, by Dr. Curlík and his collaborators.

DESCRIPTION OF RESEARCH SITES

Tisice

The irrigation agronomy experiment station in Tisice is situated north of the village of Tišice (district Melnik) in the Labe lowland, beside the Kosatecky potok stream. The exact location of experimental plots has changed several times since the station foundation in 1950. The present experimental area is located on the top of a quaternary fluvial terrace of gravel sand, overlain by permeable sand of aeolian or fluvial origin and by loess. The relief on the terrace is virtually horizontal, slightly undulated. The terrace is surrounded by less elevated alluvial plains and lower terrace plains. The experimental field is divided into 8 plots (blocks) 52 x 68 m.

The site belongs to a warm region with dry moderate winter. The mean annual precipitation is 518.8 mm, the mean annual temperature is 8.6°C. The latitude is 50.27° N, the altitude is 167 m.

The soils of the site are rather heterogeneous and difficult to classify. The soil types vary from Arenic Chernozem (according to the Czechoslovak morphogenetic system [14]) and Luvi-haplic Chernozem (on loess) to Eutric Regosol and Calcaric Fluvisol (the last three taxonomy unit are according to the FAO classification [9,40]). The sandy-loamy topsoil of variable thickness (20-80 cm) with about 2.5% of humus and, on average, 15% of particles under 0.002 mm is underlain by transitional horizons composed of sand or loamy sand with some loamy lenses. Permeable coarse sand occurs everywhere at depths of 120-150 cm. The ground water table is deep, about 4-5 m below the surface.

We refer to previous reports for more detailed descriptions of the Tisice site.

Liblice

The research location Liblice lies northwest from the village of the same name in district Melnik. The location comprises several large field managed by an agricultural cooperative in Liblice. The choice of this location 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 Kosatecky 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 'The North Bohemian Cretaceous'.

The relief is composed of low hills and plateaux, interrupted by valleys and depressions in places where the upper cretaceous rocks were more susceptible to erosion.

The climate is virtually the same as in Tisice. The elevations of 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 are not situated on a single slope but, in fact, represent a catenal series of soil types developed on different erosion forms of 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 characteristiques of individual measurement sites are shown in Table 1. The crops grown on the investigated fields are presented in Table 2.

approximately characterized by data from the nearby weather station in Zichlinek at elevation of 360 m [4,35] average annual precipitation 650 mm, average annual temperature 6.8 ^{o}C.

The field is situated on a mild eastern slope within a submountainous peneplain of Orlicke hory (Adlergebirge) mountains. It has been drained with a system of underground

Table 1. Geomorphologic and pedologic characteristics of individual measurement sites

Site	Geomorphology	Soil
1	Upper part of a small valley without a water resipient	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 weathering of siltstone and marlite, sometimes covered with a thin loess layer
4,5	Lower part of a long mild slope	Phaeozem, loam with occasional stones, on colluvial quaternary deposits
6,8,9	Top of a hill	Rendzina, loamy sand, on products of weathering of siltstone and marlite
7	Top of a hill	Eutric Regosol, sand, on quatenary aelian deposits without stones

Table 2. The crops grown on the investigated fields

Site	Crop grown	
	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

Horni Tresnovec

The research location lies west of the village of Horni Tresnovec, north of the town of Lanskroun, in district Usti nad Orlici. All measurements were carried out on a single field. The site was chosen because of a pilot field experiment, designed to test the so-called whole-profile method of soil reclamation. The experiment had been conducted on this field since 1989 by the Research Institute for Soil and Water Conservation.

The elevation of the site is about 410 m, the latitude is 49.94^{o} N. The climate may be

pipe drainage. The pilot experiment consists of four plots of the size about 100 x 50 m each, denoted A, B, C and D. The rest of the field was considered as a zero treatment.

The soil on 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 soil surface, is very dense and acid and cannot be easily penetrated by the roots of common crops.

A whole profile method of reclamation of soils with dense and acid subsoil horizons was suggested and tested in the Research Institute for Soil and Water Conservation by Damaska and his collaborators. The method was described in several reports and manuals [20-22]. The authors recognized that the dense and acid subsoil could be an impenetrable barrier for plant roots even in the soils which had been fertilized and limed abundantly, but in which the nutrients and the lime remained in the topsoil. Therefore, the method of reclamation relies on a 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 subsoiling should be carried out at an instant when the previous crop has been harvested and the soil is rather dry. The fertilizers and the lime, both applied immediately before the subsoiling and mixed with the topsoil due to subsequent ploughing, are allowed to leach by natural rainfall into the cracks in the subsoil produced by the subsoiling. This will improve the nutrient status and pH of the subsoil so that the plant roots can penetrate into it and survive there. 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 will be stabilised and can persist for several years. After this period, the reclamation procedure is to be repeated, using less fertilizers than in the first case or no extra fertilizers at all. A possible drawback of this reclamation method is the risk of leaching of potassium, lime and maybe nitrates into ground water.

The pilot experiment aiming to test the whole-profile reclamation method described above was established in Horni Tresnovec in autumn 1989. The treatments were as follows:

- 0 - Zero treatment, outside the rectangular test plot,
- A - Subsoiling,
- B - Subsoiling and liming,
- C - Subsoiling and application of P and,
- D - Subsoiling, liming and application of P and K.

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 follows:

- 0 - Zero treatment, outside the rectangular test plot,
- A - Subsoiling,
- B,C,D - Subsoiling and liming.

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:

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

The sites for infiltration measurements were selected as follows:

1) Treatment D - subsoiling, liming and P + K application in 1989, subsoiling and liming in 1993,
2) Zero treatment - west of the experimental plot,
3) Treatment A - mere subsoiling in both 1989 and 1993,
4) Zero treatment - south of the experimental plot,
5) Treatment B - subsoiling and liming in both 1989 and 1993,
6) Treatment C - subsoiling and P + K application in 1989, subsoiling and liming in 1993.

METHODS

A modelling exercise to analyse the role of soil structure in crop production

The CERES-Barley model [24] of crop growth and soil water and nitrogen regime, a component of the DSSAT v. 2.1 [15], was used for an example simulation study of the influence of soil structure variations upon soil water balance, soil nitrogen regime and crop growth.

The actual results of experiments from the Tisice station (cf. above) were taken as input data. These data comprised, in particular:

- true daily weather data measured in Tisice in 1986,
- true average soil properties of the block VII in Tisice,
- true data on nitrogen application (100 kg N/ha), tillage and management related to the non-irrigated treatments of spring barley on the block VII in Tisice in 1986,

- CERES genetic coefficients for the cultivar 'Bonus' of spring barley, estimated primarily by Kren and his collaborators in the Agricultural Research Institute Kromeriz Ltd. and calibrated secondarily in order to make the CERES-Barley model approximate the observed yields, phenology and results of growth analysis of spring barley in Tisice.

This basic set of data (denoted as 'average') was used to derive two other sets (referred to as 'high' and 'low'), differing from the 'average' set only in the values of field capacity (DUL), wilting point (LL), saturation moisture content (SAT = [porosity + DUL]/2) and the initial moisture content (SW = SAT) in the top three layers of the soil (Table 3).

Table 3. Moisture content in the top three layers of the soil

Layer (cm)	Moisture content (% vol.)		
	average	high	low
	at DUL		
0-5	0.199	0.282	0.164
5-15	0.201	0.287	0.172
15-30	0.227	0.283	0.216
	at LL		
0-5	0.111	0.120	0.096
5-15	0.107	0.114	0.094
15-30	0.112	0.128	0.100
	at SAT=WP		
0-5	0.255	0.307	0.233
5-15	0.259	0.300	0.239
15-30	0.276	0.310	0.261

The 'high' and 'low' cases were designed to represent the possible limits of natural variations of soil structure (both texturally determined and caused by soil management) to be encountered within an experimental plot (block) no. VII in Tisice. The 'high' case should typify a well structured and texturally heavier topsoil of higher retention capacity while the 'low' case should illustrate the properties of a structureless, texturally lighter topsoil with low retention. The profiles of the wilting point (LL), field capacity (DUL) and the initial (=saturated) moisture content SAT for the three cases studied are depicted in Fig. 1.

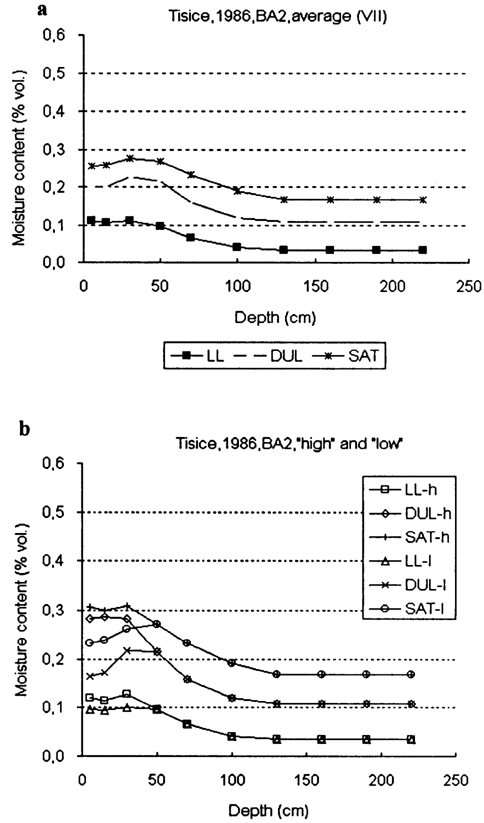


Fig. 1. Vertical profiles of average (a) and maximum and minimum (b) input values of the wilting point (LL), field capacity (DUL) and saturation moisture content (SAT) for the CERES-Barley simulations. The data for depths >=50 cm were taken as the averages of the measured values on block VII in Tisice in 1986. In the three uppermost soil layers, the profiles of LL, DUL and SAT bifurcate, indicating the really possible maxima and minima of the corresponding values. In the simulations, there were used to exemplify the "average" structural state (=average water retention capacity) of the soil, the values (coincinding in depths >= 50 cm) were used to exeplify two extreme structural states of the soil, characterised by "high" and "low" water retention capacity of the topsoil, respectively (b). The graph is biased in the sense that the values of LL, DL AND SAT are plotted against the depths of bottom of the layers which they represent.

All other inputs were the same for all computational runs. We emphasize the fact that even the soil water flow parameters were the same. These parameters were, in particular:

- the upper limit of the first-stage soil evaporation, U (mm);

- the soil water drainage constant, SWCON (d^{-1}), playing in the model a role similar to that of the saturated hydraulic conductivity of the soil;
- the SCS curve number CN2, expressing the infiltration capacity of the soil;
- the coefficients of exponential dependence of the soil moisture diffusivity DBAR upon the volumetric moisture content THETA; this dependence reads ([17 p. 61]; confirmed also by the inspection of the source code of CERES-Barley):

$$\text{DBAR} = 0.88 \exp(35.4\ \text{THETA}) \quad (1)$$

i. e., the coefficients (0.88 and 35.4) are hardwired in the program code.

The results of simulation runs using the above mentioned three sets of input data ('average', 'high' and 'low') were compared with each other and the differences were discussed.

Relations between some CERES input parameters and measurable soil hydraulic properties

Most of the input parameters of the CERES type of complex simulation models (in particular the parameters listed above, which are also conceivable as quantitative characteristics of soil structure) are not measurable in an independent way. The only direct way how to estimate them is to compare the measured soil water regime with the results of simulation, provided that all other CERES input parameters used in the simulation correspond to the measured case with sufficient accuracy. As this procedure may be prohibitively laborious and lengthy, it is worth trying to study the relations between these parameters and the physical quantities measurable or assessable independently. This was undertaken by W. M. Saadalla, a student of the International Postgraduate Hydrology Courses at the Department of Engineering Hydrology, University College Galway, Ireland, under supervision of F. Doležal [33].

The CERES input parameters investigated by Saadalla [33] were the parameters of the Ritchie's [31] theory of evaporation:

- the upper limit of the first-stage evaporation, U (mm),
- the parameter A (mm $d^{-1/2}$), a characteristique of the second-stage evaporation, according to the equations:

$$\text{ES} = \text{E0S} \quad \text{for } \Sigma\, \text{ES} \le \text{U}$$

$$\Sigma\, \text{E} - \text{U} = \text{A}\, (\text{T}-\text{T}_u)^{1/2} \quad \text{for } \Sigma\, \text{ES} > \text{U} \quad (2)$$

where ES and E0S (mmd^{-1}) are the actual and potential rates of soil evaporation, respectively, Σ ES (mm) is the sum (integral) of the actual soil evaporation ES during a rainless period, starting from the instant when water content of the uppermost soil layer was at field capacity, T(d) is the time and T_u(d) is the time instant when Σ ES = U.

The parameter U is an input variable of the CERES model, while A is given in the standard CERES code a constant value of 3.5 mm d^{-1}. Saadalla [33] changed the program code in order to make A a variable input parameter. The CERES-Maize program (an older version published by Jones and Kiriny [17]) was used in this study because of inaccessibility, at that time, of newer source codes.

A more detailed and physically more correct numerical model of soil water movement S_1D [38] was employed to investigate if the Ritchie's [31] theory of bare soil evaporation is adequate and to estimate the values of A and U from measurable hydraulic properties of the soil. The measurable soil hydraulic properties (the retention curve and the hydraulic conductivity function), needed as inputs to S_1D, were represented by the van Genuchten's [37] set of empirical equations:

$$\theta(h) = \begin{Bmatrix} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1+(-ah)^n\right]^m} & h<0 \\ \theta_s & h \ge 0 \end{Bmatrix} \quad (3)$$

$$K(h) = \begin{Bmatrix} K_s\, K_r(h) & h<0 \\ K_s & h \ge 0 \end{Bmatrix} \quad (4)$$

where:

$$K_r = S_e^L \left[1-\left(1-S_e^{1/m}\right)\right]^2 \quad (5)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (6)$$

and:

$$m=1-1/n; \; L=0.5 \quad (7)$$

and where θ, θ_r and θ_s (dimensionless) are the instantaneous, residual and saturated volumetric moisture contents of the soil, respectively, h is the soil water pressure head (cm, negative if suction), S_e (dimensionless) is the relative moisture content and K_r (dimensionless) is the relative hydraulic conductivity. The variable parameters are θ_r, θ_s, the saturated hydraulic conductivity K_s (cm d^{-1}), the empirical exponent n (dimensionless), and the coefficient a (cm^{-1}, the symbol a being used here instead of the van Genuchten's α to prevent collision with the Gardner's [10] α appearing below in relation to the disc infiltrometer measurements).

Various sets of the S1_D soil parameters (θ_r, θ_s, K_s, a and n) together with various potential soil evaporation rates E0S, were input into S1_D runs simulating a short (20 days) rainless period of evaporation from a bare soil column, initially at field capacity, with the potential soil evaporation rate E0S kept constant during a single run.

The resulting course in time of the actual evaporation rate was compared with that predicted by the Ritchie's theory. The corresponding values of the Ritchie's parameters U and A were estimated by regression. In this way, the dependence of U and A upon θ_r, θ_s, K_s, a and n and E0S could be derived.

A large extent of computation would be needed if the two functions of six variables:

$$U = U(\theta_r, \theta_s, K_s, n, a, EOS) \quad (8)$$

$$A = A(\theta_r, \theta_s, K_s, n, a, EOS) \quad (9)$$

were to be described with sufficient accuracy over sufficiently wide intervals of all their arguments. Therefore, a set of the standard values of arguments was established (corresponding to an average loamy soil and a hot summer weather) and, in turn, each one of the arguments was allowed to vary (acquiring, in addition to its standard value, a minimum and a maximum value) while the other arguments were kept standard.

Table 4. The values of the arguments used in Eqs. (8) and (9)

	θ_r	θ_s	K_s (cm d^{-1})	n	a (cm^{-1})	EOS (cm d^{-1})
min.	0.00	0.32	0.4	1.01	0.004	0.1
stand.	0.01	0.4525	300	1.19	0.0197	0.5
max.	0.2	0.7	500	2.0	0.1	1.0

The methods of field infiltration measurements

It was agreed at the first meeting of the project in Wien (February 1994) that the project participants would measure the soil hydraulic conductivity in the field using preferably the Guelph permeameters and the disc infiltrometers. We adhered to this agreement.

The Guelph permeameter method

The Guelph permeameter method [28], i.e., the method of quasi-steady borehole infiltration, was applied in Tisice, Liblice and Horni Tresnovec. Some experience obtained at other sites is also discussed below. The infiltrometers used were manufactured by the Faculty of Civil Engineering of the Czech Technical University and by the Research Institute for Soil and Water Conservation.

The methodology used in Tisice was as follows [41]: 54 shallow boreholes (8 cm in diameter) were arranged horizontally in a rectangular grid with the mesh size 7.5x7.5 m covering a single block of the Tisice experimental area. Fodder grass (*Dactylis glomerata* L.) had been grown on the block for five consecutive years before the measurement (carried out in spring 1989). 46 of the boreholes were 15 cm deep, the remaining 8 boreholes were 20 cm deep. Water level in the boreholes 15 cm deep was maintained at 10 cm above the borehole bottom. A single Guelph permeameter measurement, consisting in determining the quasi-steady infiltration discharge Q (m^3s^{-1}), was only carried out in each of the 15 cm deep boreholes. The remaining 8 boreholes, 20 cm deep, were used to determine the quasi-steady infiltration discharges at two different positions of the water table, namely at 10 and 15 cm above the borehole bottom.

The results were evaluated using the procedures suggested by Reynolds and Elrick [28]. Their basic formula is:

$$2\pi H^2 K_{fs} + C\pi a^2 K_{fs} + 2\pi H \Phi_{mo} = CQ \qquad (10)$$

where K_{fs} (m s^{-1}) is the field-saturated hydraulic conductivity, Q (m^3 s^{-1}) is the quasi-steady infiltration discharge required to maintain a constant water level in borehole, π = 3.14159 ..., H (m) is the height of water table above the borehole bottom, a (m) is the borehole radius, C (dimensionless) is a shape coefficient dependent upon the ratio $E=H/a$ and upon several other variables, and Φ_{mo} (m^2s^{-1}) is the matrix flux potential at saturation, given by:

$$\Phi_{mo} = \int_{\phi_i}^{0} K[\theta(\phi)]d\phi \qquad (11)$$

where θ (dimensionless) is the volumetric moisture content, ϕ (m) is the matric head (always non-positive, equal to water pressure head in the unsaturated soil and to zero in the saturated soil), ϕ_i (m) is the initial matric head, $\theta(\phi)$ is the retention curve and $K(\theta)$ is the hydraulic conductivity function. The values of C, depending upon $E=H/a$, can be read from a family of graphs obtained by detailed numerical computations and given, e.g., by Reynolds and Elrick [30]. In particular, we worked with a graph labeled 'Guelph loam'. The authors recommend this graph for general use.

The Reynolds and Elrick's basic formula given above imposes only one condition upon two unknowns, K_{fs} and Φ_{mo}. The authors suggest to overcome this problem either by neglecting one of the unknowns or by processing simultaneously two or several measurements made in the same soil but using two or more different values of H and/or a. In the former case, if the third term on the left-hand side of the basic formula is neglected, the formula rearranges as:

$$K_{fs} = \frac{CQ}{2\pi H^2 + C\pi a^2} \qquad (12)$$

and is referred to as 'Laplace analysis' (to express that the flow of water out of the borehole is regarded as saturated and the capillary pull is neglected). If, inversely, the first two terms on the left-hand side of the basic formula are neglected, the formula becomes:

$$\Phi_{mo} = \frac{CQ}{2\pi H} \qquad (13)$$

and is called 'Gardner analysis' (to symbolize that only the unsaturated flow is considered and the influence of gravity is neglected).

The other alternative, consisting in simultaneous evaluation of two (in a deterministic way) or more (by the least squares method) measurements, is called 'Richards analysis'.

In our case, all three 'analyses' were applied to the data measured in Tisice. The Richards-analysis could only be used for the 8 deeper boreholes in which the infiltration measurements were made at two different water heights.

The field-saturated hydraulic conductivity obtained in Tisice by the Guelph permeameter, K_{fs}, were compared with the standard doublering ponding infiltrometer measurements carried out on the same site half a year earlier, and with the laboratory measurements of the saturated hydraulic conductivity, K_{core}, made on undisturbed core samples taken vertically from the same soil at the depth of about 5 cm during the Guelph permeameter measurements. The diameter of the inner ring of the double-ring infiltrometer was 35.7 cm. It was driven to the soil to the depth of 10-20 cm. The water level was maintained in the ring at about 1-3 cm above the soil surface. The field-saturated hydraulic conductivity, K_{inf}, was obtained from the double-ring infiltration measurements with the help of the Brutsaert equation [2,19].

A slightly different procedure was used in Liblice and Horni Tresnovec. On each site of measurement and at each date of measurement, two parallel boreholes, about 2 m apart, 40 cm deep and 9 cm in diameter, were investigated in an identical way: the water level in the borehole was maintained gradually at 30, 20, 10 and 2 cm below the soil surface and the corresponding quasi-steady discharges, Q (m^3 s^{-1}), were estimated. The results were processed assuming that the soil was homogeneous and isotropic, using the Glover formulae:

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

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

$$E = \frac{H}{a} \tag{14}$$

where K_{fs} (ms^{-1}) is the field-saturated hydraulic conductivity, Q (m^{3}s^{-1}) is the quasi-steady infiltration discharge required to maintain a constant water level in 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:

$$argsinh\, E = ln\left[E + \sqrt{\left(E^2 + 1\right)}\right] \tag{15}$$

The Glover formulae given above were suggested for use by Doležal and Poruba [7] who concluded that the tendency to overestimate the field-saturated hydraulic conductivity K_{fs}, inherent to the Glover formulae, 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 [27,28] meaningless.

A controversy between the assumption of soil homogeneity, adopted by the Glover's theory, and the fact that the real soils investigated in Liblice and Horni Tresnovec were systematically heterogeneous in the vertical direction, has not yet been fully solved. As a matter of fact, we regarded the soil as homogeneous for the purpose of evaluating any single measurement (at a certain position of water table in the borehole). Therefore, the resulting hydraulic conductivity K_{fs} can be regarded as an average property of the soil layer lying between the level of the water table and the level of, say, 10 cm below the borehole (50 cm below the soil surface). We denote this value as K_{hom}, to signify that the assumption of soil homogeneity was used in its derivation.

The disc infiltrometer method

Working principles of the disc infiltrometer method and some designs of the infiltrometer itself have been described, e.g., by Perroux and White [26]. In this study, two different infiltrometer types were used. At first, we used a Soil Moisture Equipment Corp. infiltrometer, with a plastic membrane of higher air entry value (about 30-40 cm) and of smaller diameter (about 21 cm), borrowed from the Department of Engineering Hydrology, University College, Galway. Later, another infiltrometer was purchased for the purpose of the present project, manufactured by the Soil Moisture Systems Inc., with a synthetic textile membrane of lower air entry value (only about 15 cm) and of larger diameter (about 24 cm), a version without the pressure transducers. In both cases, a good hydraulic contact between the soil surface and the infiltrometer membrane was established via a thin (1-2 cm) cake of fine sand (grain size 0.1-0.2 mm) laid beforehand onto the soil surface. The lower air entry value of the latter infiltrometer (SMS) required the membrane to be placed onto a pre-wetted sand cake while the SME infiltrometer could be put on a dry sand.

Two parallel measurements, about 2-3 m apart, were made on each site. During each measurement, four different pressure heads were gradually maintained at the membrane of the infiltrometer, namely, -12, -7, -3 and +1.5 cm (negative values mean suctions). The corresponding infiltration discharges were measured. Each measurement on a certain spot was started with the highest suction (-12 cm) and finished with a small overpressure (+1.5 cm). This seems to be more logical than the opposite procedure, used by Ankeny *et al.* [1], who started with a zero pressure head and proceeded with gradually increasing suctions. We think that the procedure by Ankeny *et al.* [1] makes the soil beneath the infiltrometer too wet at the beginning. This, beside bringing about some hysteresis of soil water (due to backward sucking of water from the soil into the infiltrometer in which the suction has suddenly increased) may be a cause for too low (or even zero) infiltration rates at higher suctions. Our methodology of measurement developed gradually. Different values of pressure heads were used during first measurements and the infiltration under overpressure was not always measured. True average diameter of the sand cake, rather than the membrane diameter, was used to characterize the effective infiltration area.

As the measurements were not always long enough to attain a steady-state infiltration, the quasi-steady discharges were estimated by linear extrapolation of the measured data in the coordinates of discharge (Q=dV/dt) vs. reciprocal cumulative infiltrated volume (1/V): the quasi-steady discharge was assumed to correspond to 1/V = 0 (i.e., to the infinite infiltrated volume). This procedure is formally based on the Green-Ampt type infiltration equation [3,12]:

$$\frac{di}{dt} = K\left(1 + \frac{H_f \Delta\theta}{i}\right) \tag{16}$$

where K is the hydraulic conductivity, H_f is the effective suction head at the wetting front, i is the cumulative infiltration depth and $\Delta\theta$ is the soil moisture content increment due to infiltration. However, the Green-Ampt-equation was originally suggested to describe a one-dimensional vertical infiltration. Therefore, its application to our case (with V instead of i, the quasi-steady Q instead of K, and $H_f\,\Delta\theta$ unspecified) can only be understood as a formal extrapolation tool, probably without a deep physical sense.

For evaluation of the disc infiltrometer measurements, we used a method suggested by Doležal and Poruba [7], which is based on the classical Wooding's [39] analysis and presents a slight generalization of the procedures suggested by Reynolds and Elrick [29,30]. The hydraulic conductivity of the soil, K (ms^{-1}), is assumed to depend upon the pressure head h (m) according to the generalized Gardner's [10] formula:

$$K(h) = K_o \exp(\alpha h) \text{ for } h < 0$$
$$K(h) = K_s \quad \text{for } h \geq 0 \tag{17}$$

where α (m^{-1}) is a slope parameter, expressing the speed of hydraulic conductivity decrease with the increase of suction (decrease of h), K_s (ms^{-1}) is the saturated hydraulic conductivity (including the effect of macropores) and K_o (ms^{-1}) is the upper limit of the unsaturated hydraulic conductivity for h approaching zero from the left (excluding the effect of macropores).

The method consists, first, in plotting the logarithm of the quasi-steady discharge, ln(Q), vs. the pressure head maintained at the infiltrometer membrane, h_o, for all (usually three) measurements during which h_o was negative (i.e., a suction). This plot is then approximated by a straight line (using the least squares regression) of a slope α and an intercept U. Having determined α, we can estimate the upper limit of the unsaturated hydraulic conductivity, K_o, employing the formula:

$$K_o = \exp\left\{U - ln\left(\pi r^2\right) - ln\left[1 + \frac{4}{\pi r \alpha}\right]\right\} \tag{18}$$

where r (m) is the radius of the infiltration area and $\pi = 3.14159$ ... . Then, using the discharge Q_s obtained at a small positive value of the pressure head at the membrane, h_s, we can also estimate the saturated hydraulic conductivity K_s as follows:

$$K_s = \frac{Q_s - \dfrac{4rK_o}{\alpha}}{\pi r^2 + 4rh_s} \qquad (19)$$

K_s should normally be higher than or equal to K_o. If this does not happen (because of the measurement errors), we put $K_s = K_o$.

It should be specifically noted that the procedure just described assumes the soil to be initially dry enough to render the initial unsaturated hydraulic conductivity negligible.

RESULTS AND DISCUSSION

Results of the modelling exercise using CERES-Barley

The results are presented in graphical form in Figs 2 to 4. As expected, the soil moisture content in the uppermost, 5 cm thick soil layer, as well as the total extractable soil water (i.e., the soil water above wilting point) were highest in the 'high' case and lowest in the 'low' case during the whole season (Figs 2a and 3a). The same pertains to the third layer (between 15 and 30 cm of depth, Fig. 2b), except for the last peak (on about the 180th day), when the water content rose more in the 'average' and 'low' cases than in the 'high' case; this is because the available water capacity of the 'high' case was high enough to store most of the rainfall in the overburden layers, releasing less water to the third and deeper layers.

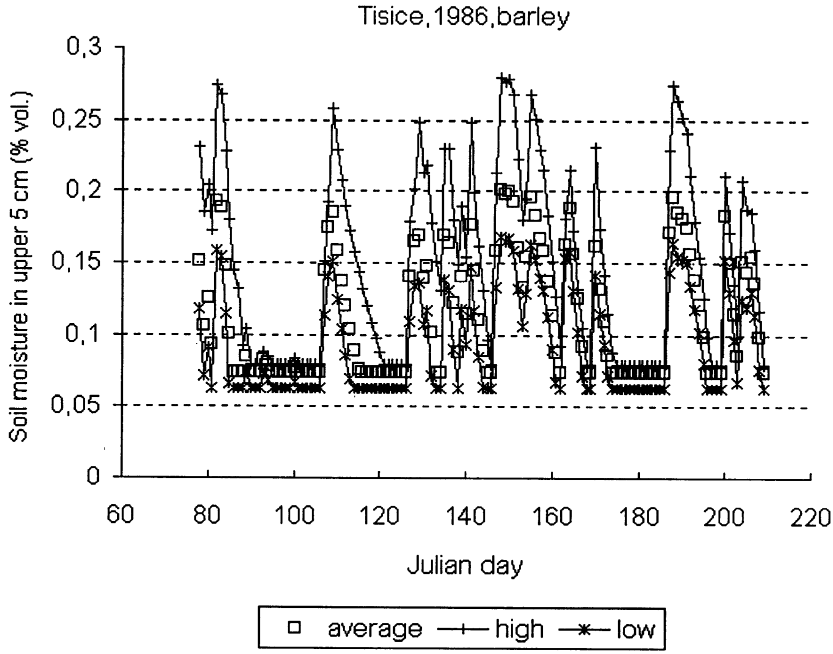
Rather paradoxically, the cumulative actual transpiration was highest in the 'low' case and lowest in the 'high' case (Fig. 3b). This however becomes understandable if we realize (in view of Fig. 2b) that the plant water uptake also takes place from the deeper soil layers; these layers were least supplied with water in the 'high' case, because most water was in this case retained in the upper layers. The following figure (Fig. 3c) confirms this view: the physical soil evaporation, which only takes place from the uppermost layer, was highest in the 'high' case and lowest in the 'low' case.

In our example, the nitrogen fertilizer was applied into the uppermost soil layer. Therefore, the deeper soil layer could only receive nitrogen from the fertilizer if they received water percolating from the surface. Less water percolation into deeper layers means less available nitrogen from the fertilizer in the deeper layers and more nitrogen left in the upper layers. Indeed, the concentration of nitrate in the uppermost layer was highest in the 'high' case (Fig. 4a) but the same concentration in the third layer was highest in the 'low' case, except for a short period between, approximately, the 150th and 160th day (Fig. 4b) when some of the surplus nitrogen retained in the overburden layers (in the 'high' case) was washed out and transported into the third layer.

Correspondingly, the root density in the uppermost layer was highest in the 'high' case and lowest in the 'low' case (Fig. 5a) while quite an opposite trend is observable in the third layer (Fig. 5b) where the highest scarcity of water and nitrogen in the "high" case incited the highest depression of the root density. On the total, this lack of water and nutrients in deeper layers in the 'high' case resulted in lower biomass production (Fig. 6a), lower nitrogen uptake (Fig. 6b) and lower yields.

When interpreting this computational exercise, we must be careful not to overestimate the meaning of the results. One must bear in mind that the flow and transport characteristics of the soil did not have to be described properly by the CERES model. Also of importance might be the prescribed potential root density distribution with depth, which was the same in all three cases, postulating a potential maximum of root density to occur in the second and third soil layer rather than in the uppermost layer. This potential root density distribution was 'approved' by the cereals specialists in the Agricultural Research Institute Kroměříž Ltd. but has not been sufficiently corroborated by experiments.

a



b

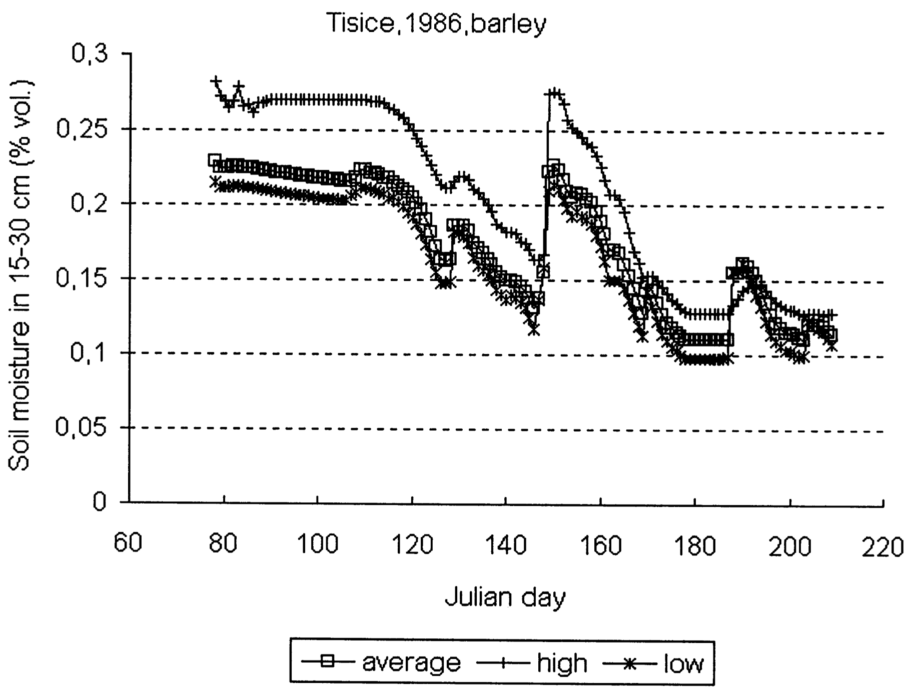
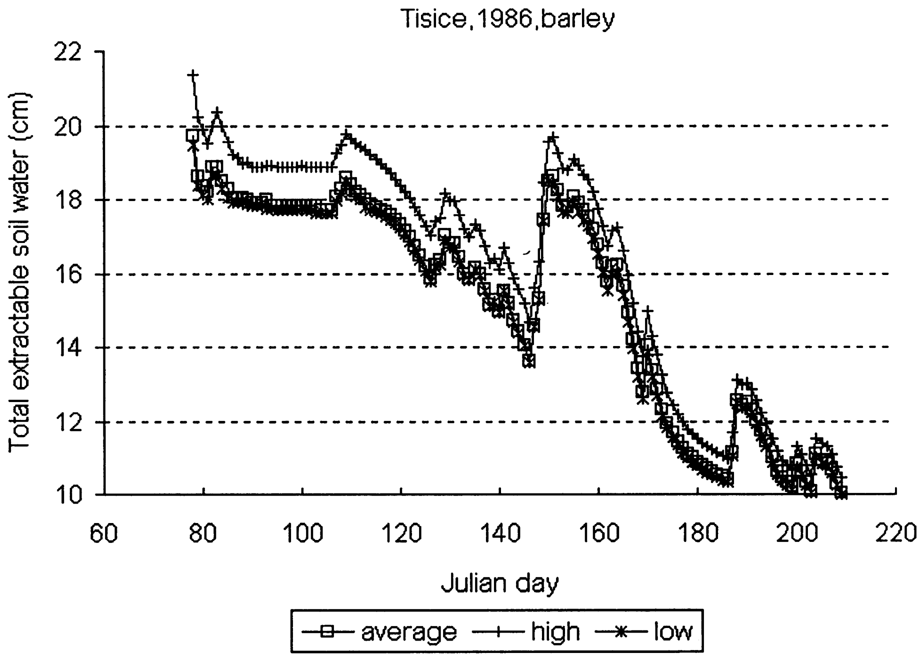


Fig. 2. The course in time, during the growing season of spring barley, of the soil moisture content of the uppermost soil layer (0-5 cm) (a) and third soil layer (15-30 cm) (b), obtained from CERES-Barley simulations with the input data corresponding, respectively, to the "high", "average" and "low" retention capacity of the soil in Tisice.

a



b

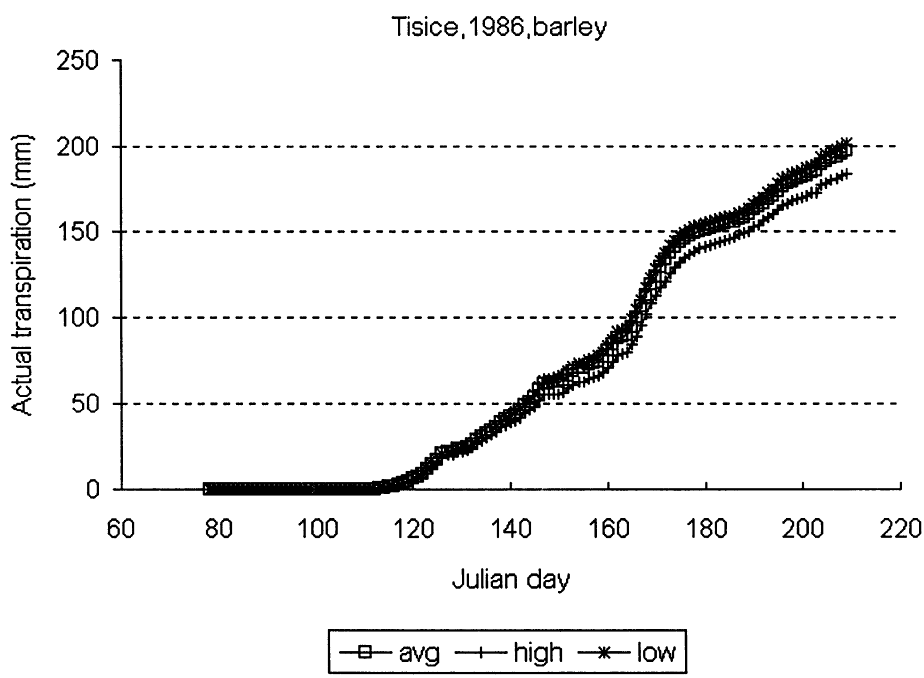


Fig. 3. The course in time, during the growing season of spring barley, of the total plant-extractable water amount in the soil (a), barley of the cumulative actual plant transpiration (b), of the cumulative soil evaporation (c) obtained from CERES-Barley simulations with the input data corresponding, respectively, to the "high", "average" and "low" retention capacity of the soil in Tisice.

c

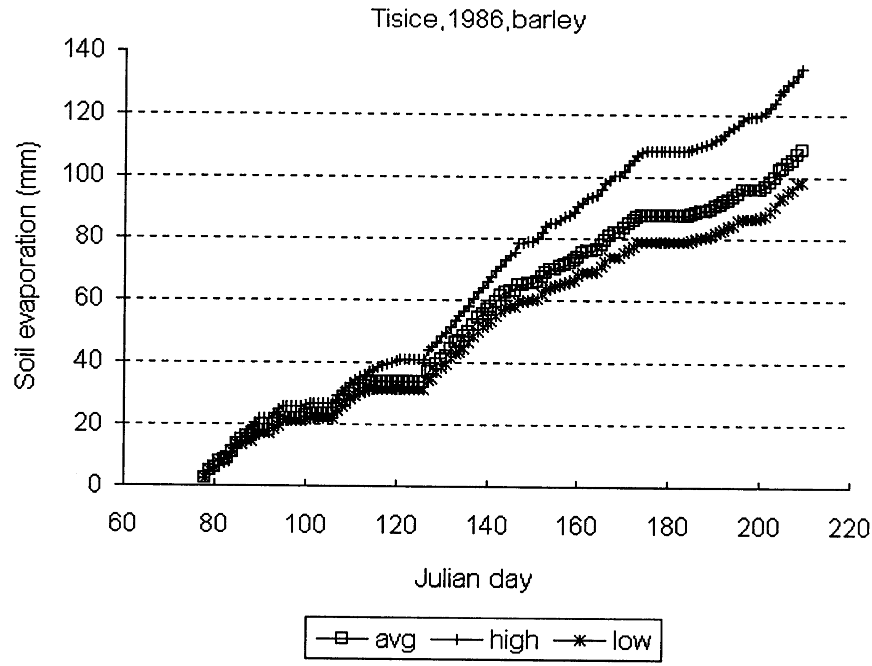


Fig. 3. Continuation.

With the above reservation, we can preliminarily conclude that, in light soils, the seemingly better soil structure (i.e., the one with higher available water capacity and higher field capacity) may result in slightly lower plant production if the precipitation (or irrigation) is insufficient to permeate the bulk of the root zone and to transport the superficially applied nutrients to the plant roots in deeper soil layers.

On a more general level, this example illustrates the potentialities of complex simulation models (e.g., of the CERES type) to detect problems and intricacies which could hardly be envisaged by the common sense.

Relations between the Ritchie's bare soil evaporation parameters, the van Genuchten's soil hydraulic parameters and the potential evaporation rate

The results of the Saadalla's [33] example calculations are presented in Figs 7 to 10. It follows from then that:

a) The Ritchie's *U*, i.e., the cumulative water depth representing the first stage of evaporation (occurring at the potential rate):
   - aa) decreases with increasing residual soil moisture content θ_r,
   - ab) is high at very low as well as at very high saturated soil moisture contents θ_s and acquires a minimum at intermediate θ_s,
   - ac) decreases with increasing van Genuchten's parameter *a*,
   - ad) is low at very low as well as at very high values of the van Genuchten's *n* and acquires a maximum at intermediate *n*,
   - ae) increases with increases saturated hydraulic conductivity K_s,
   - af) decreases with increasing potential evaporation rate *EOS*.

b) The Ritchie's *A*, i.e., the parameter expressing rate of soil evaporation in its second stage:
   - ba) decreases with increasing residual soil moisture content θ_r,

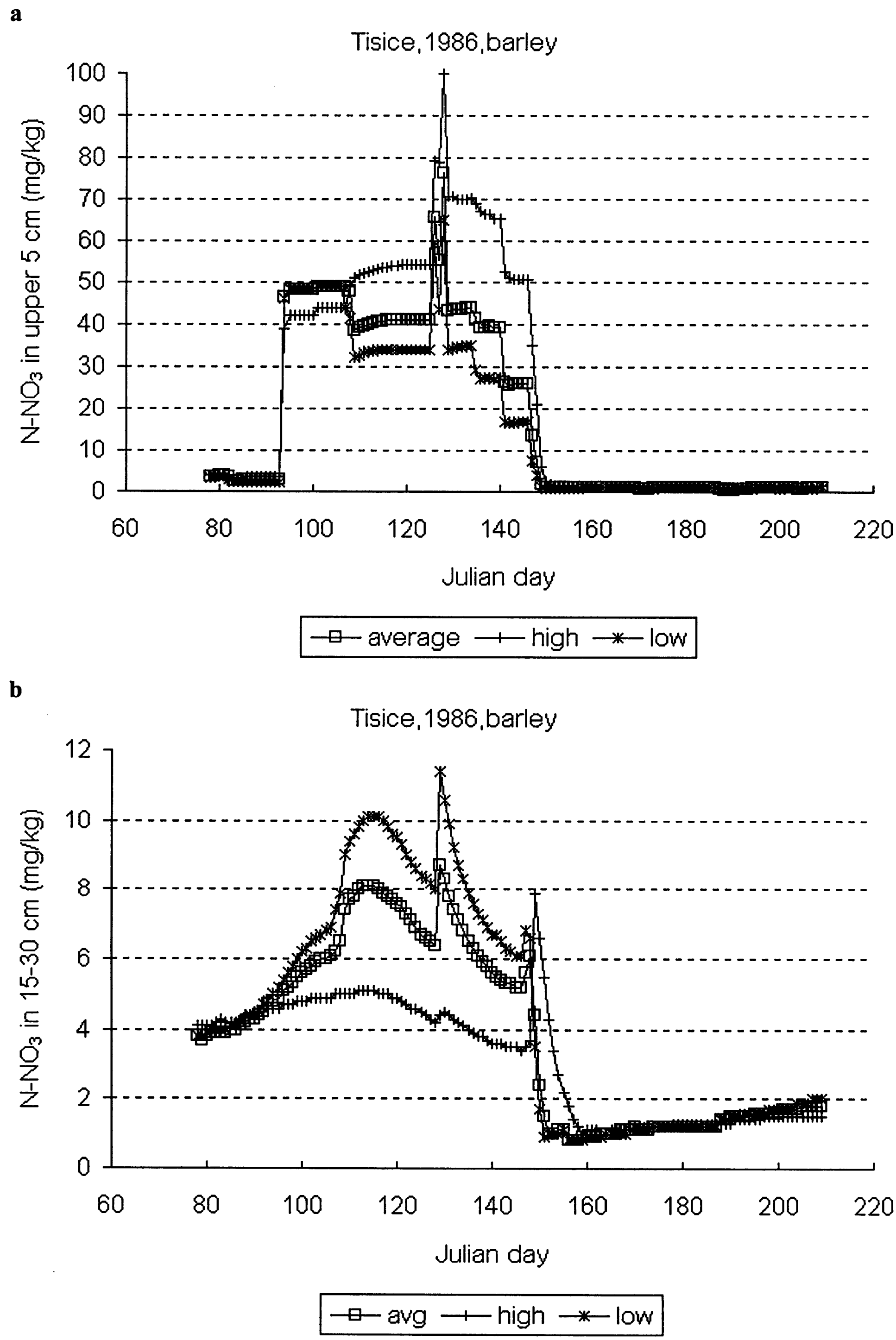


Fig. 4. The course in time, during the growing season of spring barley, of the nitrate nitrogen concentration: in the uppermost soil layer (0-5 cm) (a); in the third soil layer (15-30 cm) (b), obtained from CERES-Barley simulations with the input data corresponding, respectively, to the "high", "average" and "low" retention capacity of the soil in Tisice.

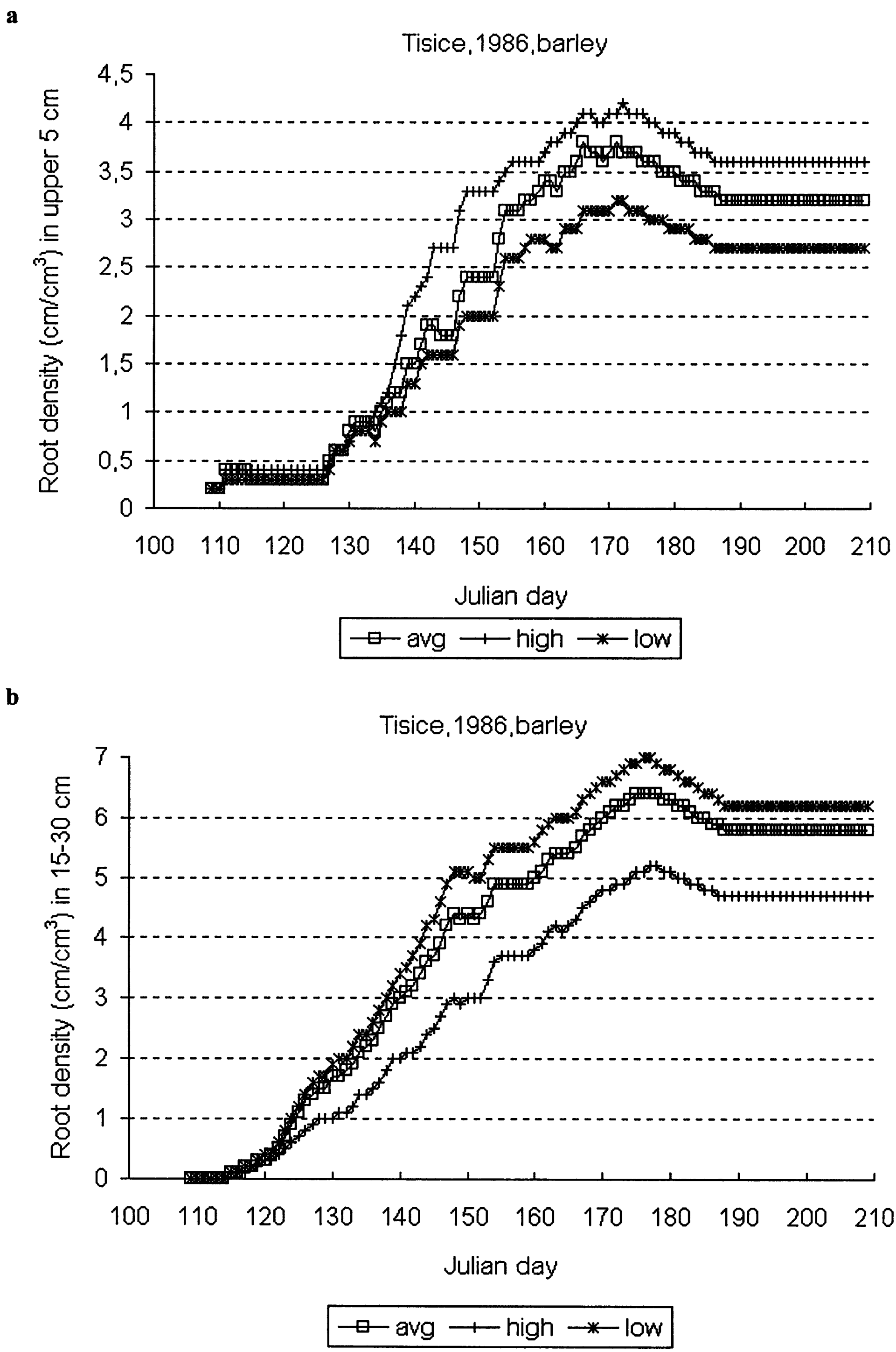
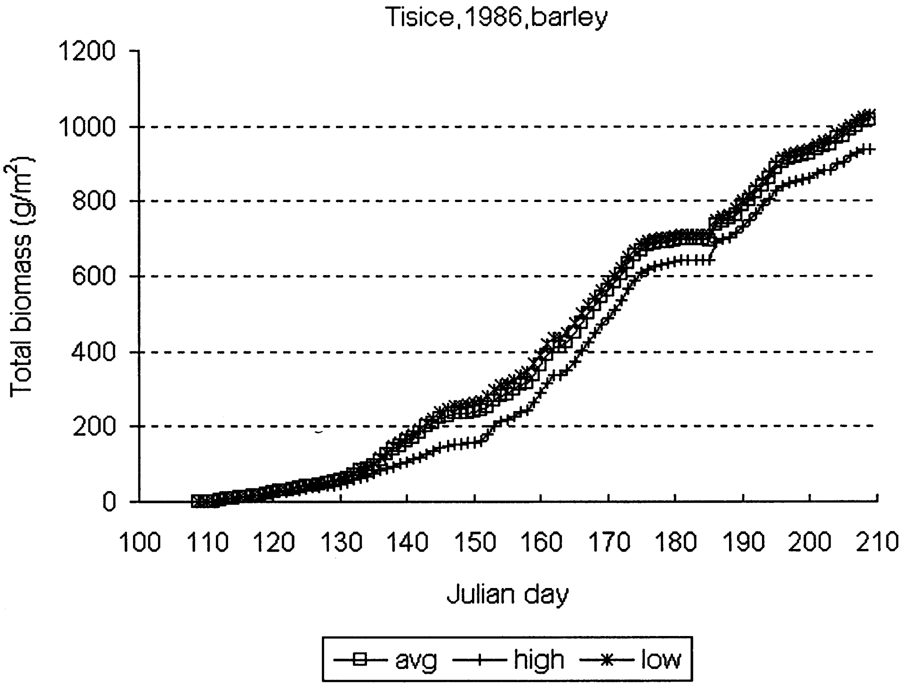


Fig. 5. The course in time, during the growing season of spring barley, of the root length density: in the uppermost soil layer (0-5 cm) (a); in the third soil layer (15-30 cm) (b), obtained CERES-Barley simulations with the input data corresponding, respectively, to "high", "average" and "low" retention capacity of the soil in Tisice.

a



b

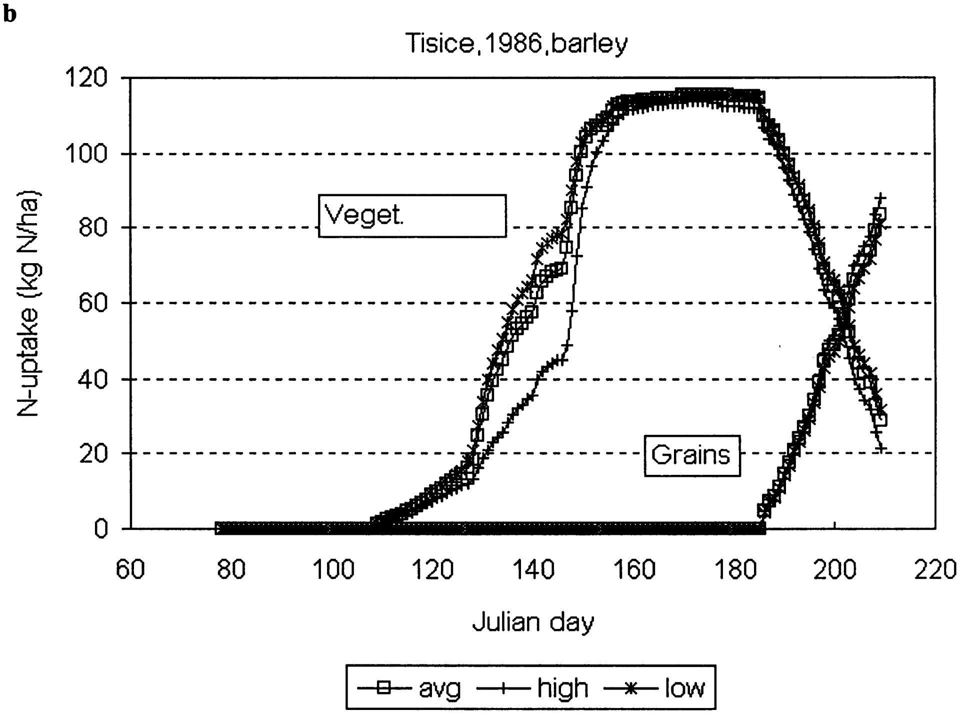


Fig. 6. The course in time, during the growing season of spring barley: of the cumulative total biomass (a) and the total nitrogen content in the vegetative organs and in the grains of barley (b), obtained from CERES-Barley simulations with the input data corresponding, respectively, to the "high", "average" and "low" retention capacity of the soil in Tisice.

bb) increases with increasing saturated soil moisture content θ_s,
bc) decreases with increasing van Genuchten's parameter a,
bd) is low at very low as well as at very high values of the van Genuchten's parameter n and acquires a maximum at intermediate n,
be) increases with increasing saturated hydraulic conductivity K_s,
bf) increases with increasing potential evaporation rate EOS.

The graphs in Figs 7 and 8 also provide tools for semi-quantitative assessment of the values of U and A, if the van Genuchten's soil parameters (θ_r, θ_s, K_s, a and n) and the average expected potential evaporation rate EOS are known. In particular, it appears that the Ritchie's parameter A for the second stage of evaporation is not constant and, even for the same soil, depends on the potential evaporation rate. This dependence should be incorporated into future versions of CERES.

Results obtained with the Guelph permeameter

Tisice

The attempt to apply the so-called Richards-analysis (cf. above) failed because of too high random fluctuation of the measured data. Six boreholes of the total number of eight in which the Richards analysis could be tested gave negative values of the field-saturated hydraulic conductivity K_{fs}; seven of them produced negative values of the matrix flux potential at saturation, Φ_{mo}. This effect was more or less expected: Reynolds and Elrick ([28] and elsewhere) themselves report many cases of negative hydraulic conductivities obtained in this way. Philip [27] showed that the system of equations from which K_{fs} and Φ_{mo} are calculated in the course of the Richards analysis is ill-conditioned and unstable.

Hence, the Laplace-analysis could only be meaningfully used for evaluating the field -

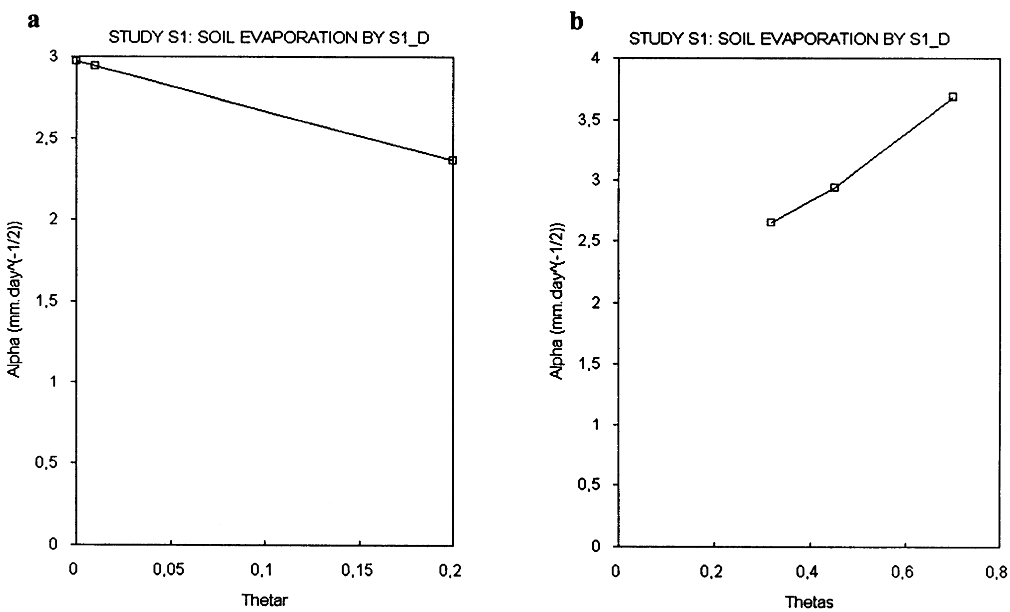


Fig. 7. The dependence of the upper limit of stage-1 evaporation depth, U (mm), upon the van Genuchten soil parameters θ_r (a), θ_s (b), a (van Genuchten α) (c), n (d), K_s (e) and the potential evaporation rate EOS (f). The points were obtained from the S_1D simulations (cf. Fig. S1.1) and are interpolated linearly.

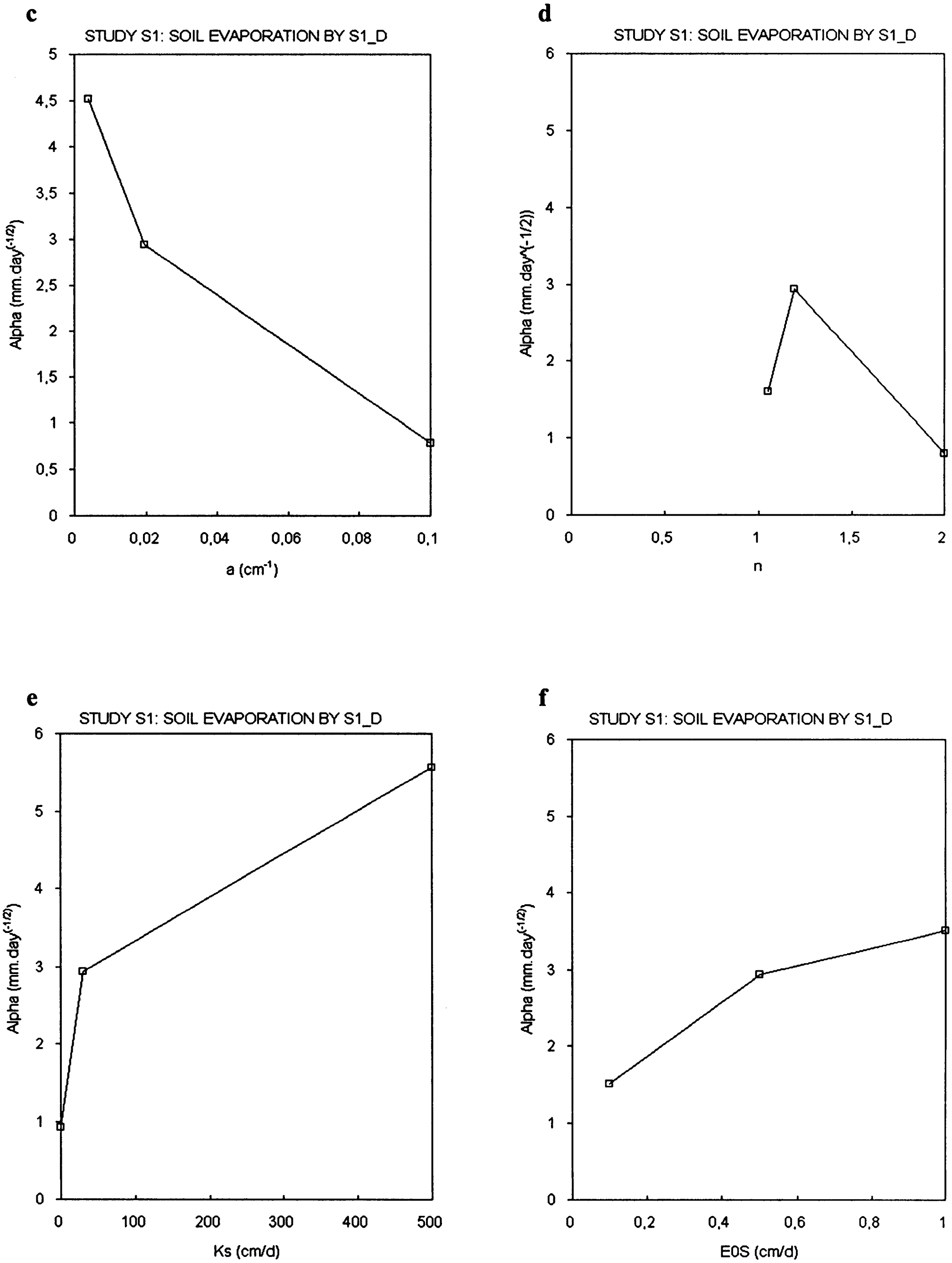


Fig. 7. Continuation.

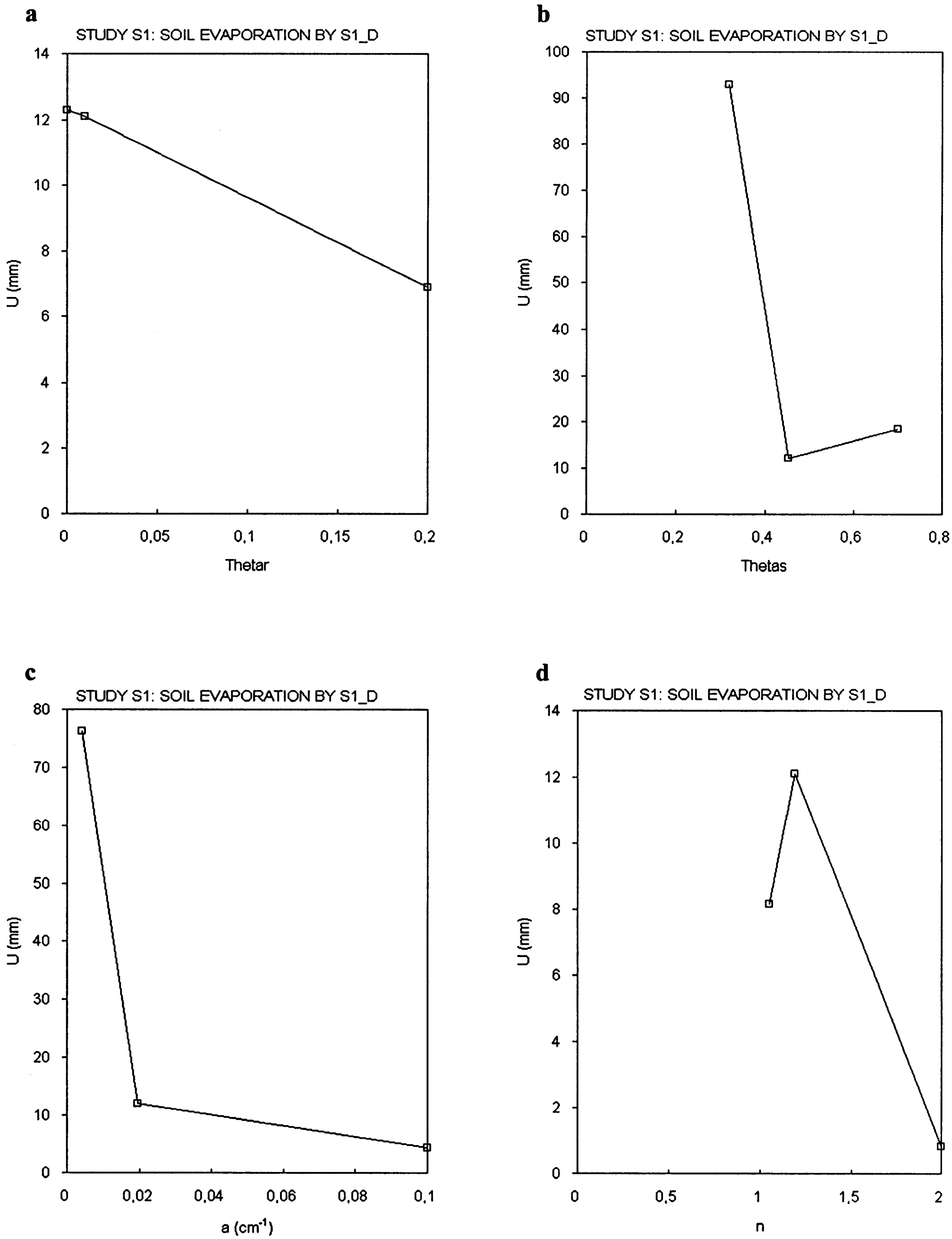
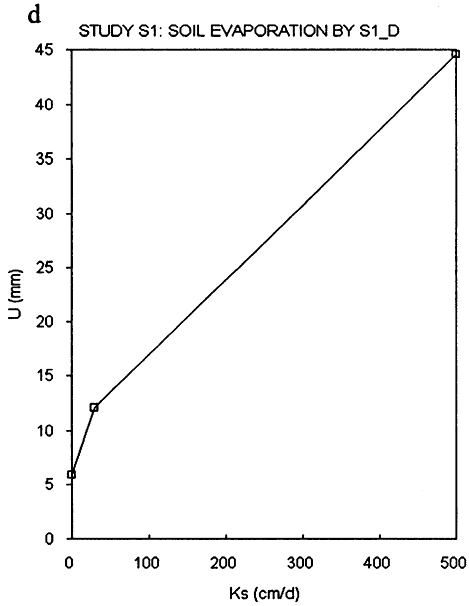


Fig. 8. The dependence of Ritchie's α (mm/day $^{-1/2}$), expressing the speed of decline of the stage-2 evaporation rate, upon the van Genuchten soil parameters θ_r (a), θ_s (b), a (van Genuchten's α) (c), n (d), K_s (e) and the potential evaporation rate EOS (f). The points were obtained by approximation of the S_1D results with the Ritchie's equation (cf. Fig. S1.4) and are interpolated linearly.



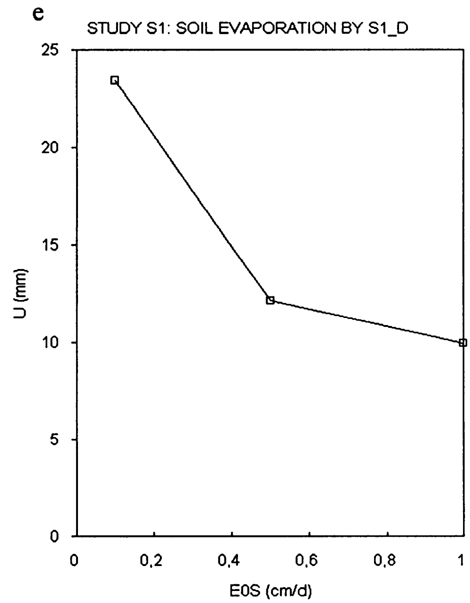


Fig. 8. Continuation.

saturated hydraulic conductivity K_{fs}. The Gardner-analysis was similarly used for estimating the values of the matric flux potential, Φ_{mo}. The basic statistica of the results is given in the Table 5.

The values of K_{fs} and Φ_{mo} were, of course, highly correlated to each other. The reason for this becomes obvious if we compare the formulae used for the Laplace and Gardner-analyses (Table 5); according to these formulae, the ratio of K_{fs} to Φ_{mo} obtained in this way has to be:

$$\frac{K_{fs}}{\Phi_m} = \frac{2H}{2H^2 + Ca^2} \tag{20}$$

which is constant as long as the flow geometry is constant. In view of this fact and of the unreliability of the Richards-analysis, we can conclude that it is of no practical use to evaluate the matrix flux potential or other unsaturated soil parameters derived from it. It seems reasonable to consider the Guelph permeameter solely as an instrument to measure the field-saturated hydraulic conductivity K_{fs}.

The field-saturated hydraulic conductivities K_{fs} obtained from the Guelph permeameter measurements as described above are compared, in the following Table 6, with the analogous values K_{inf} from the double ring infiltrometer and with the laboratory-measured saturated hydraulic conductivities K_{core}.

All three methods yield values of similar order of magnitude which are nevertheless significantly different. The t-tests (assuming, in this case not very correctly, that the distribution of the compared quantities is normal) reject the null hypothesis (stating that the two compared sets of quantities belong to the same population) on the 99 % level of significance.

The fact that the Guelph permeameter in Tisice gives lower hydraulic conductivities than the double-ring infiltrometer seemingly contradicts to the statement given below that, in Liblice and Horni Tresnovec, the Guelph permeameter hydraulic conductivities are higher (about three times) than the corresponding saturated hydraulic conductivities K_s resulting from the disc infiltrometer experiments. There are, however, several possible explanations of this effect:

Table 5. Values of field-saturated hydraulic conductivity (K_{fs}) and matrix flux potential at sturation (Φ_{mo}) obtained from Gardner-analyses)

Property	No. obs.	Mean	St. dev.	Skewness
K_{fs} (ms^{-1})	54	2.68E-6	3.32E-6	2.57
Φ_{mo}	54	3.04E-7	3.76E-7	2.58

Table 6. Values of the field-saturated hydraulic conductivity obtained by three different methods

Property ($m\ s^{-1}$)	No. obs.	Mean	Std. dev.	Skewness
K_{fs}	54	2.68E-6	3.32E-6	2.57
K_{inf}	70	5.84E-6	4.13E-6	1.39
K_{core}	51	3.43E-6	2.63E-6	1.32

a) The Laplace-analysis formula used in Tisice gives systematically lower hydraulic conductivities than the Glover-formula used in Liblice and Horni Tresnovec.

b) The grassland soil in Tisice was anisotropic in the opposite sense than the arable soils in Liblice and Horni Tresnovec. In other words, the horizontal hydraulic conductivity (prevailingly indicated by the Guelph permeameter) was lower in Tisice and higher at the other two sites, in comparison with the vertical hydraulic conductivity indicated by the infiltrometers (either of the double-ring or of the disc type). This hypothesis is supported by two fact: first, the laboratory-measured hydraulic conductivities, K_{core}, which are vertical conductivities, are higher than the (prevailingly horizontal) values of K_{fs} and, secondly, the unbiasedness of the disc infiltrometer values K_s is partly confirmed by a single rain simulator measurement of infiltration carried out in Liblice (see below).

c) The obstacles to flow occurring on the infiltrating surface may play a non-negligible role in determining the infiltration rate. They can eventually turn the result of an infiltration test into a mere artifact. Such obstacles can be, e.g., the clay smear on the walls of the borehole during the Guelph permeameter test and (probably to a higher degree) the fine sand cake used to put the disc infiltrometer into contact with the soil surface (the saturated hydraulic conductivity of the fine sand we used was about 13.5 m d^{-1}).

Many other researchers report about similar comparisons of various methods of hydraulic conductivity measurements [13,18,25]. A main problem of such comparisons seems to be the lack of a standard method for hydraulic conductivity evaluation. All what we can do is to compare the results of different methods and estimate the statistical parameters of the data sets, not knowing which of the two compared methods is more correct. In other words, we can to some degree describe the random component of the measurement error but cannot say much about the possible systematic error of a method. As an example of the variability inherent in the hydraulic conductivity measurements, one can mention the results of Mohanty *et al.* [23]. They compared five methods (Guelph permeameter, disc infiltrometer, falling head field permeameter, double-tube method and laboratory constant head method). The results differ from each other by two to three orders of magnitude. The lowest average K values and their highest variance was obtained for the Guelph permeameter. The authors explain this observation by the arguments related to the sample size, smearing of walls and air entrapment.

Liblice and Horni Tresnovec

Altogether, 376 elementary measurements (i.e., the measurements of the quasi-steady discharge at a certain level of water table in a certain borehole) were made in Liblice and Horni Tresnovec in altogether 94 boreholes on 15 different measurement sites. The Table 7 gives an overview of the measurements, together with brief names of the periods of measurement which are frequently referred to in the following text and in some of the figures.

This is rather an integral representation of the vertical hydraulic conductivity profile. Its differentiation should ideally give us a detailed vertical profile of the horizontal hydraulic conductivity of the soil. However, the operation of differentiation appeared to be unstable, very sensitive to random fluctuation of the measured integral values of K_{hom}. Therefore, we refrained from the differentiation. It is only the integral values, K_{hom}, which are discussed in this report.

Table 7. Overiew of measurements made in Liblice and Horni Tresnovec

Location	Measurement sites	Brief name of the period	Dates of measurement
Liblice	1-9	autumn 93	12-26.08.93
Liblice	1-6, 8-9	spring 94	4.05-02.06.94
Liblice	1-6, 8-9	summer 94	20-25.07.94
Liblice	1-6, 8-9	autumn 94	14.09-04.10.94
Horni Tresnovec	1-6	spring 94	10-26.05.94
Horni Tresnovec	1-6	summer 94	13-14.07.94
Horni Tresnovec	1-6	autumn 94	22-25.08.94

The Guelph permeameter measurements provided us with a relatively detailed picture of spatial and temporal distribution of the horizontal field-saturated hydraulic conductivity. A symbol K_{hom} is used further on for this hydraulic conductivity, to underline the fact that it is an average value characterizing a certain layer of the soil; this layer (more exactly: the whole flow domain) is considered homogeneous in the theory. However, a soil heterogeneity in the vertical direction is admitted by allowing different K_{hom} in different (even partially overlapping) soil layers.

We assumed that the flow of water out of the borehole 40 cm deep was significantly influenced by the hydraulic conductivity in the soil layer between the level of the water table and the level of 10 cm below the borehole bottom (i.e., 50 cm below the ground surface). In the graphs, we plot the corresponding values of K_{hom} with respect to the vertical coordinates of the geometrical midpoints of the layers which are as follows:

If the water table in the borehole is at the depth of X (cm):	then the midpoint of the layer of influence lies at the depth (cm): (50 + X)/2
30	40
20	35
10	30
2	26

The soil hydraulic conductivity on both sites (Liblice and Horni Tresnovec) is primarily determined by the grain size distribution of the soil. The measurement sites can be qualitatively ranked into five grain size categories with gradually decreasing hydraulic conductivity:

1) Sands or loamy sands on the top of the hill in Liblice (measurement sites No. 6-9).
2) Loamy sands in the small valley without a water recipient in Liblice (measurement site No. 1).
3) Sandy loams in the middle part of a long mild slope in Liblice (measurement sites No. 2 and 3).
4) Loamy soils at the bottom of a long mild slope in Liblice (measurement sites No. 4 and 5).
5) Loams or clay loams, with the dense gleyic subsoil, in Horni Tresnovec (all measurement sites).

The distribution of the K_{hom} values, including all depths and boreholes on individual measurement sites, is given in Fig. 9. Influence of the grain size distribution upon the value of the mean K_{hom} is well-defined in Liblice (Fig. 9a) where different measurement

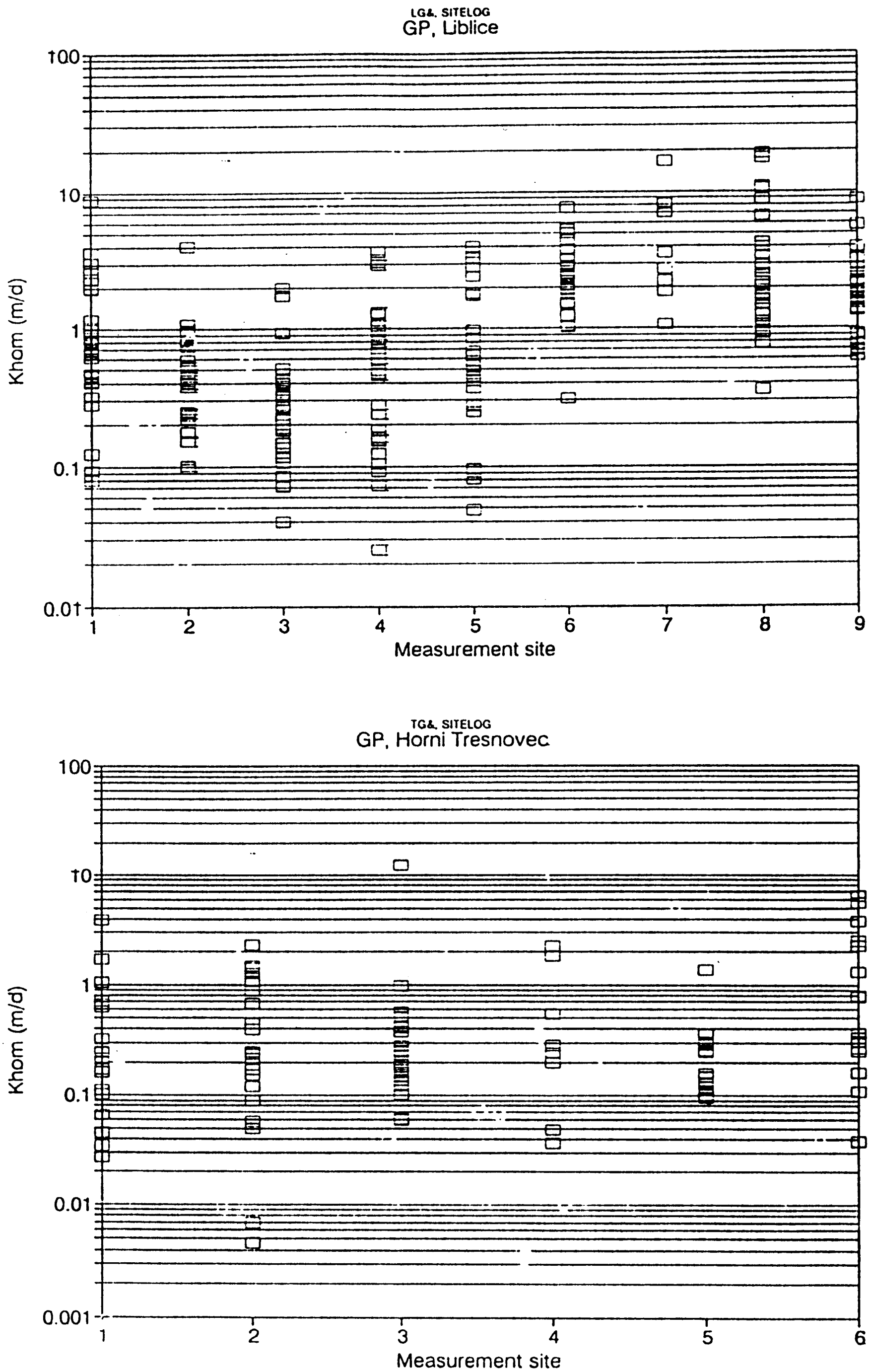


Fig. 9. Distribution of values of the horizontal field-saturated hydraulic conductivity K_{hom}, measured by the Guelph permeameter, for individual measurement sites in Liblice and Horni Tresnovec. Included are all boreholes, all dates of measurements and all depths.

sites were located on soil of different granulometry. On the contrary, there is no systematic difference visible between individual measurement sites in Horni Tresnovec (Fig. 9b), simply because all sites were situated on granulometrically the same soil.

Within a single measurement site, the hydraulic conductivity K_{hom} depends upon the depth below the soil surface. In most cases is K_{hom} at maximum in the upper topsoil. However, the shape of the K_{hom} profile in deeper soil layers is different in different soils. K_{hom} either declines gradually downwards (this is the case of virtually all profiles in Horni Tresnovec, Fig. 13) or displays a local minimum corresponding to the man-induced compaction of upper subsoil. The latter situation occurs frequently in Liblice and seems to be particularly typical for loamy sands and sandy loams with permeable subsoil (e.g., the measurement sites 1, 2, 3 and 6; Figs 10a and b).

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

a) the random variation of K_{hom} in space, as testified by the differences between K_{hom} values obtained in two parallel boreholes at the same time and depth,
b) the variation of K_{hom} in time, which is mostly systematic; it is caused by tillage operations, by activity of living organisms, by spontaneous mechanical settling of the topsoil in the course of the season and by other mechanisms (causing, e.g., a spontaneous recovery of the topsoil structure during winter). 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., in the EPIC model; [34] p. 60-62).

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 was at its minimum or maximum (excluding the erratic extremes) (Table 8).

Table 8. Periods of minimum and maximum of hydraulic conductivity values obtained for Liblice

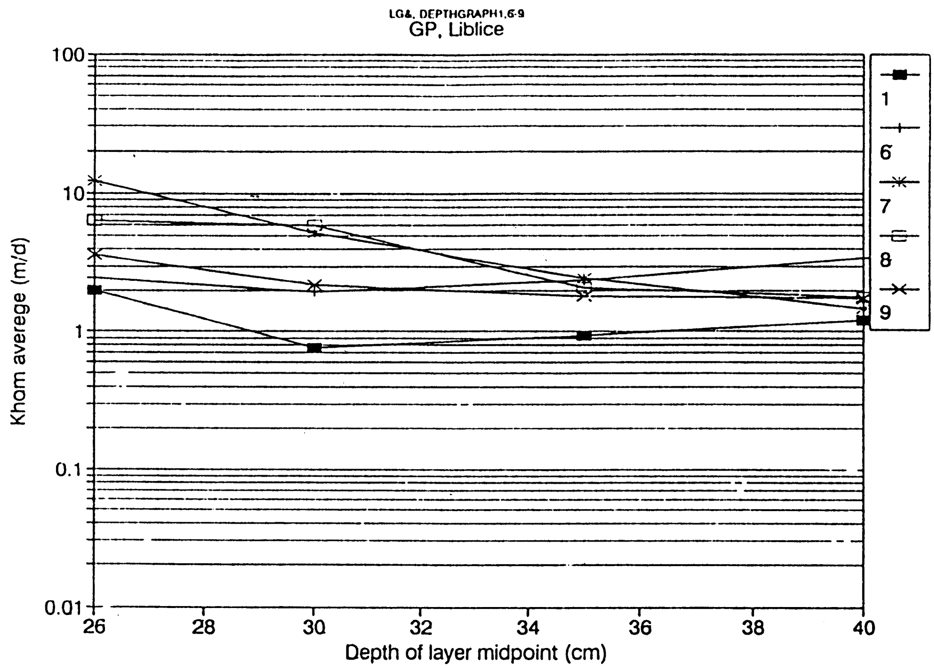
Measurement site	Period of min. K_{hom}	Period max. K_{hom}
1	spring 94	autumn 94
2	spring 94	autumn 94
3	autumn 93	summer 94
4	spring 94	summer 94
5	spring 94	summer 94
6	autumn 93	spring 94
7	not evaluated	not evaluated
8	spring 94	autumn 93
9	summer 94	autumn 94

The vertical profiles of K_{hom} for the 'minimum' periods are flat, i.e., the hydraulic conductivity does not vary much in the vertical direction and is primarily dependent upon the grain size distribution of the soil (cf. Figs 11a and b). This state of the topsoil can be taken as a reference.

On the contrary, the 'maximum' profiles reveal high variability of K_{hom} in the vertical direction. It is in particular the upper part of the topsoil which become much more permeable in these periods (cf. Fig. 12a and b). There are probably two main mechanism which may cause a rapid increase in hydraulic conductivity of the topsoil: the man-induced loosening of the soil by tillage operations and the spontaneous cracking of the surface soil due to drying and shrinking. Our measurements were not detailed enough to allow proper distinction between these two mechanisms.

The measurements in Horni Tresnovec were less frequent and the soil properties varied little among the measurement sites. The hydraulic conductivity, K_{hom}, show a tendency to increase in time during the spring and summer parts of the winter wheat growing season. The state of the soil in spring can be, with some reservation, denoted as a reference state, roughly corresponding to the 'minimum' state of the soil in Liblice.

We can see on Fig. 13 that the hydraulic conductivity K_{hom} at the midpoint depth of 40 cm, in Horni Tresnovec, is considerably lower (by about one order of magnitude) on the measurement sites 2 and 4 than on the other



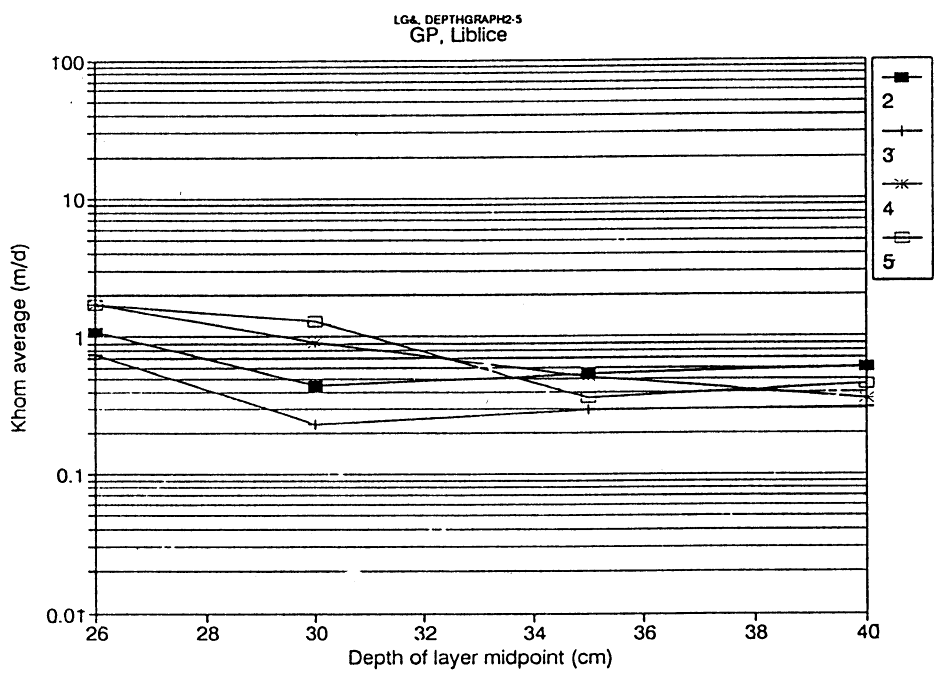
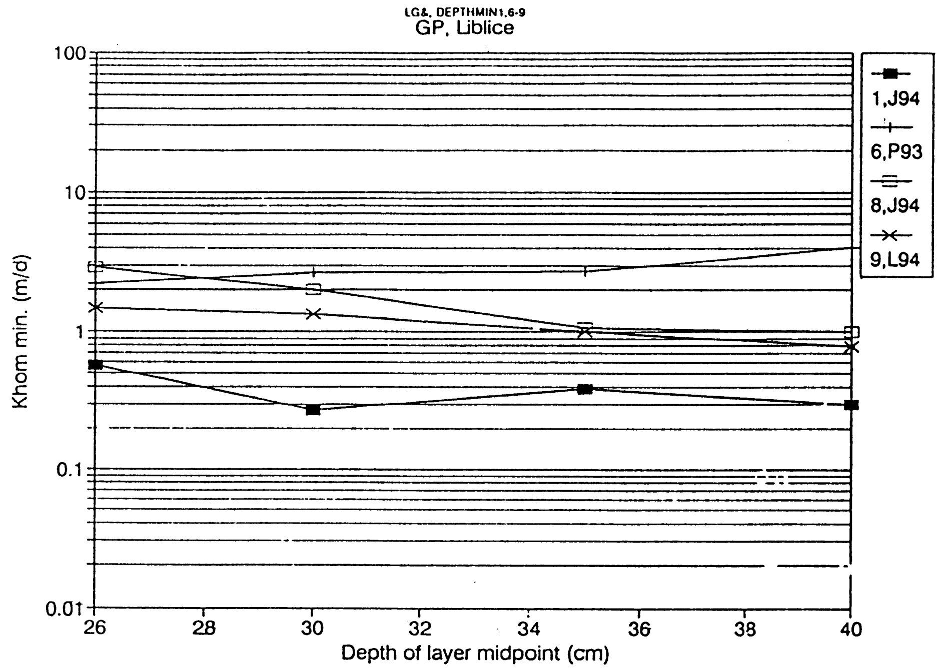


Fig. 10. Vertical profiles of the average horizontal field-saturated hydraulic conductivity K_{hom} measured by the Guelph permeameter, for the more permeable measurement sites (Nos 1 and 6-9) and for the less permeable measurement sites (Nos 2-5) in Liblice. The averages include all boreholes and all the dates of mesurement. Each value of K_{hom} is plotted against the depth of midpoint of the soil layer to which it pertains.



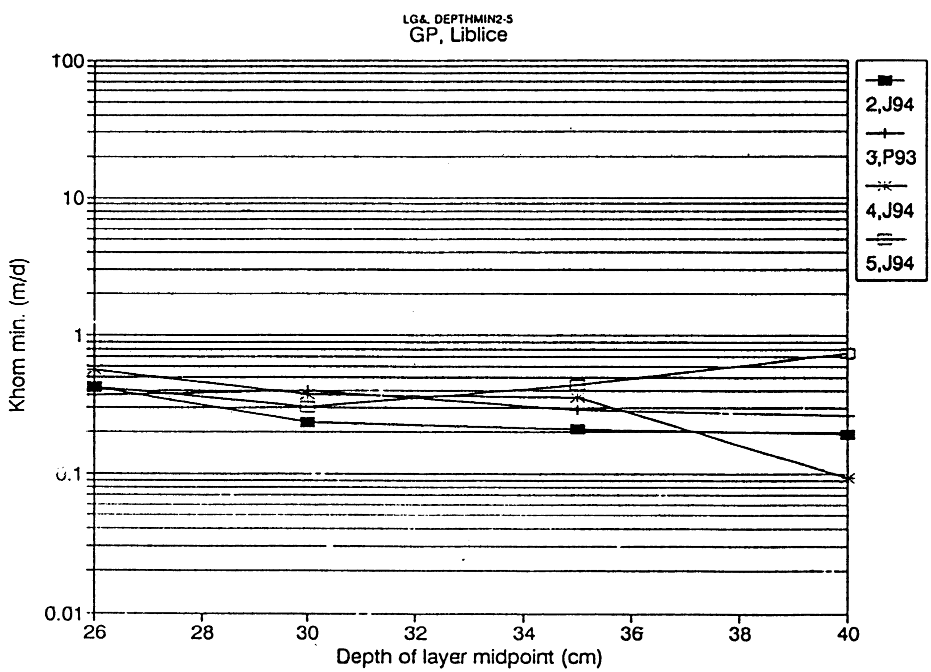
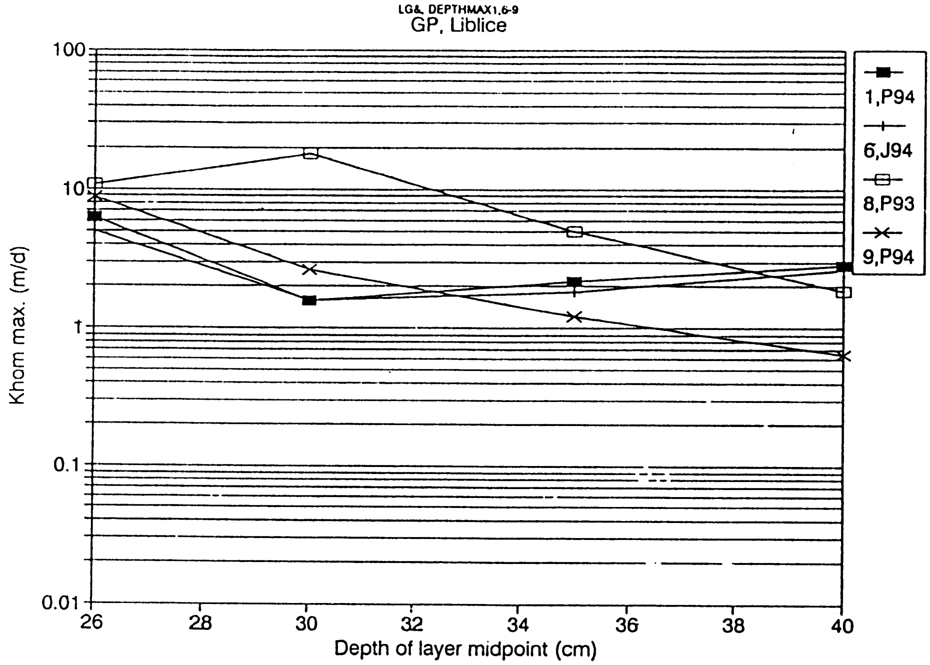


Fig. 11. Vertical profiles of the typical minimum horizontal field-saturated hydraulic conductivity K_{hom}, measured by the Guelph permeameter, for the more permeable measurement sites (Nos 1 and 6-9) and for the less permeable measurement sites (Nos 2-5) in Liblice. Each value of K_{hom} is plotted against the depth of midpoint of the soil layer to which it pertains and is actually an average of two measurements (in two parallel boreholes) on a given date. The meaning of the legend: P93=autumn 1993, J94=spring 1994, L94=summer 1994.



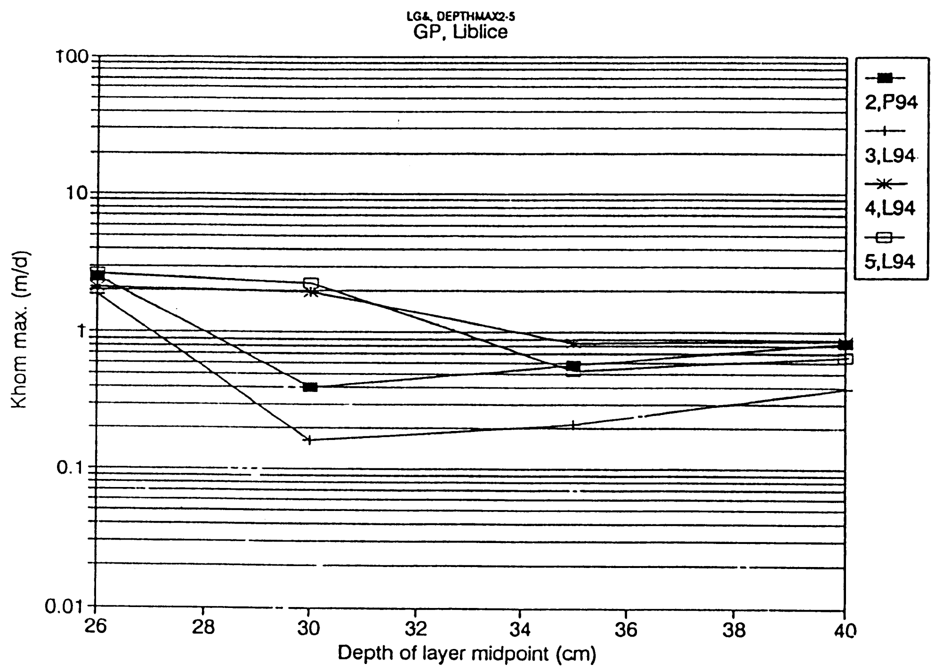


Fig. 12. Vertical profiles of the typical maximum horizontal field-saturated hydraulic conductivity K_{hom}, measured by the Guelph permeameter, for the more permeable measurement sites (Nos 1 and 6-9) and for the less permeable measurement sites (Nos 2-5) in Liblice. Each value of K_{hom} is plotted against the depth of midpoint of the soil layer to which it pertains and is actually an average of two measurements (in two parallel boreholes) on a given date. The meaning of the legend: P93=autumn 1993, J94=spring 1994, L94= summer 1994, P94=autumn 1994.

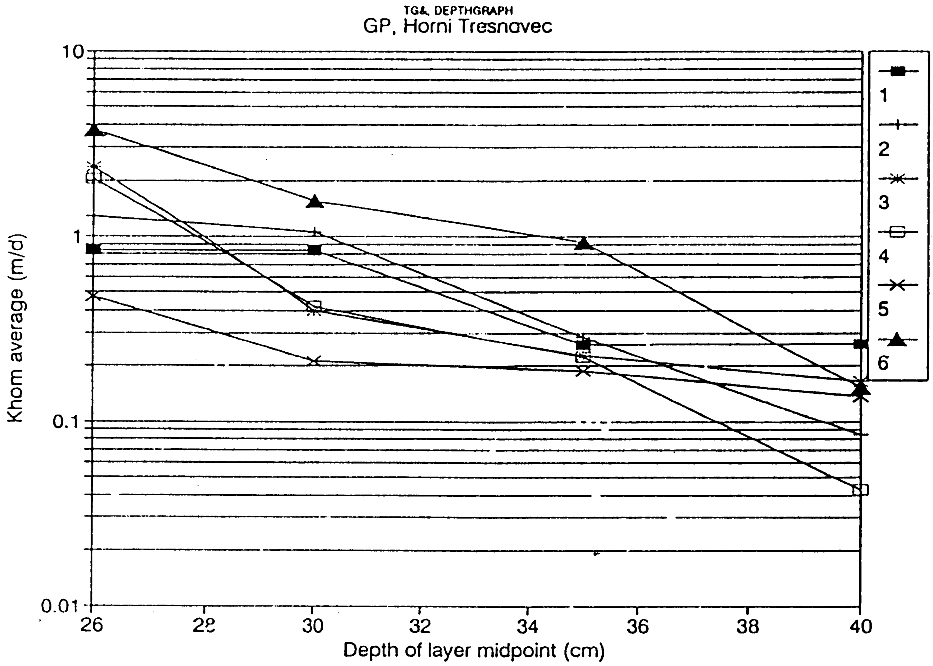


Fig. 13. Vertical profiles of the average horizontal field-saturated hydraulic conductivity K_{hom}, measured by the Guelph permeameter, for all measurement sites (Nos 1-5) in Horni Tresnovec. The averages include all boreholes and all dates of mesurement. Each value of K_{hom} is plotted against the depth of midpoint of the soil layer to which it pertains.

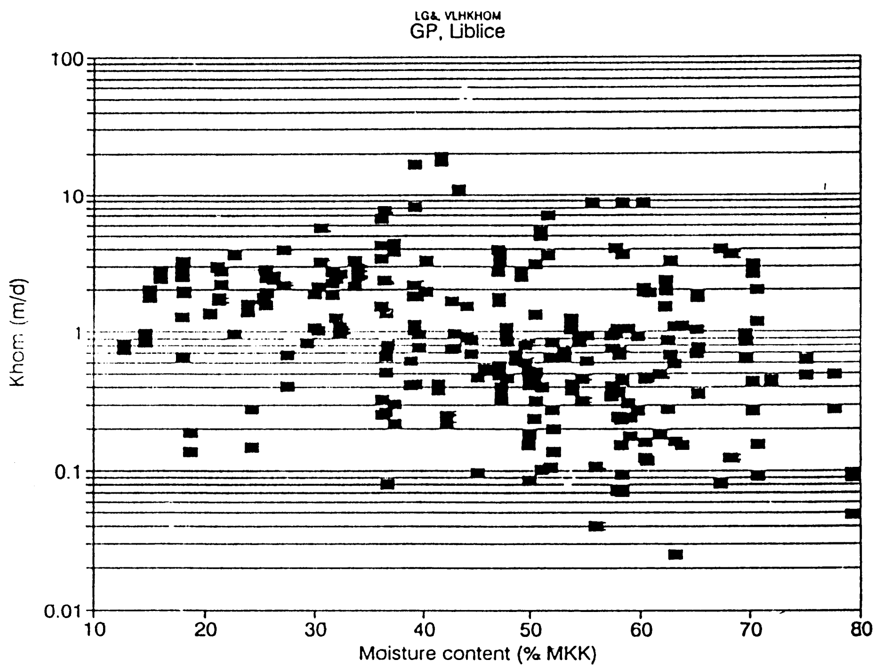
measurement sites. The reason for it was that the sites 2 and 4 were located on the zero treatment plots which had not been subsoiled. This is probably the only explicit effect of the whole-profile soil improvement method which we could observe with our instruments.

Figs 14a and b show the dependence of the hydraulic conductivity K_{hom} upon the soil moisture content (in per cents of the maximum capillary capacity, i.e., roughly, in per cents of the field capacity) at the same time in the same soil and at approximately the same depth. The correlation is very loose but a slight tendency of K_{hom} to decrease with increasing moisture content is observable. This trend can be explained if we realize that the soil probably shrinks and becomes cracked when its moisture content decreases. Therefore, the field-saturated hydraulic conductivity increases with a decrease of the soil moisture content and vice versa.

Other measurements

The Guelph permeameter was used to determine the hydraulic conductivity of two relatively homogenous sandy profiles of artificial infiltration tanks in Karane (at the confluence of the Jizera and the Labe rivers) which recharge the Prague's main groundwater source. The data were processed using the Laplace analysis described above. The results show very good reproducibility in all layers of the profile without exception. They also agree well with a previous measurement made by the vertical infiltration method about 20 years ago.

We can therefore conclude that most of the discrepancies between hydraulic conductivities obtained by various infiltration methods (including the Guelph permeameter method) are caused by the attributes which make the inert sand mass dissimilar to the real agricultural soils. These attributes are, e.g., the presence of humus and clay, presence of



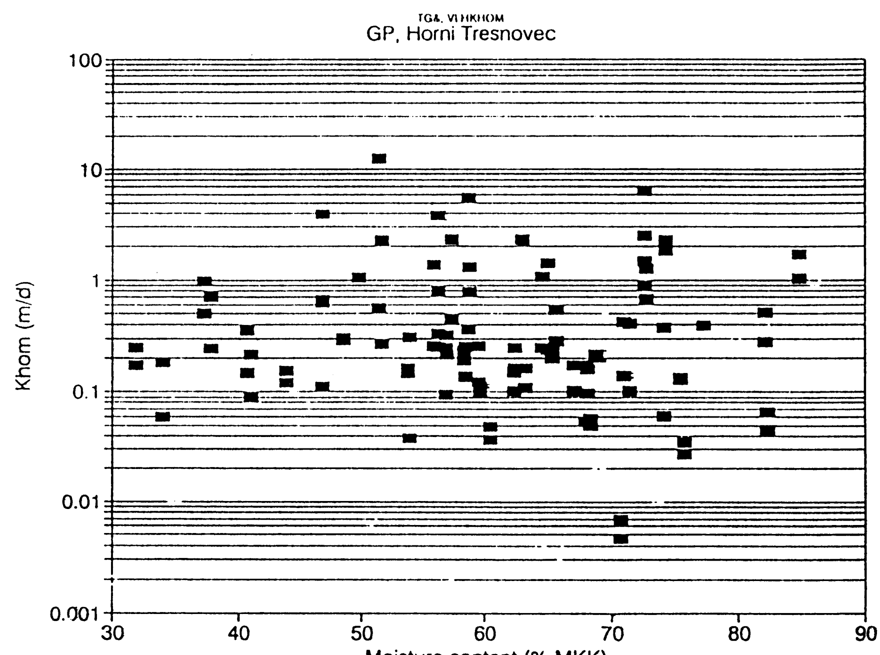


Fig. 14. Dependence of the horizontal field-saturated hydraulic conductivity K_{hom} of topsoil and shallow subsoil in Liblice and Horni Tresnovec measured by the Guelph permeameter, upon the soil moisture content in the corresponding depth. Every point corresponds to a single measurement. The soil moisture contents are expressed in percent of the maximum capillary capacity (MKK), approximately equal to the field capacity. The results obtained at the depth of water level in the borehole equal to 30, 20, 10 and 2 cm below the soil surface correspond to the soil moisture sampling depth 40, 30, 20 and 10 cm, respectively. The boreholes were 40 cm deep.

macropores and other preferential flow paths, anisotropy, heterogeneity, etc. It seems essential that one always measure the hydraulic properties (and, thereby, the soil structure) of agricultural soils by several different methods, rather than by a single method.

Results obtained with the disc infiltrometer

Tisice

Two test measurements with the disc infiltrometer were only made in Tisice in 1995. The purpose was to make a preliminary comparison between two slightly different structural states of a soil which is texturally identical. The two measurement sites were about 4 m apart. They were both located in a part of the experimental area which was texturally lightest and therefore most permeable.

The site 1 was shortly after the sowing of soybeans. The plant had not yet emerged, the soil surface was compacted a little with a roller and covered with a soft but compact crust created by a previous rain.

The site 2 was covered by a low, young canopy of spring wheat. The plants were about 7-8 cm high. The soil surface was loose, not touched with a farm implement since the sowing date. A soft but compact crust created by a previous rain coated the soil surface similarly as on the site 1.

Values of soil hydraulic parameters were obtained by evaluation of the disc infiltrometer measurements (Table 9).

The values of α were virtually identical on both sites (the only purpose of providing six decimal places in them is to show that they are not exactly identical). The values of K_o and K_s behave in a manner which is intuitively

Table 9. Hydraulic parameters obtained for Tisice

Site	α (m^{-1})	K_o ($m\ s^{-1}$)	K_s ($m\ s^{-1}$)
1	20.165439	2.039E-6	8.736E-6
2	20.165599	9.257E-7	1.233E-5

understandable: the looser soil on the site 2 contains probably more large pores (macropores) and less medium pores. Therefore, the saturated hydraulic conductivity K_s, including the effect of macropores, is higher on the looser site 2 and lower in the more compacted soil of the site 1. The opposite is true for the upper limit of the unsaturated hydraulic conductivity, K_o, which does not include the conductive contribution of macropores. However, these trends were not confirmed by measurements on the other sites (see below).

Liblice and Horni Tresnovec

Altogether, the disc infiltrometer measurements were carried out on 35 spots at altogether 11 measurement sites in Liblice and Horni Tresnovec. Three or four elementary measurements (the quasi-steady discharge estimation at a certain value of pressure head at the membrane) were made on each spot.

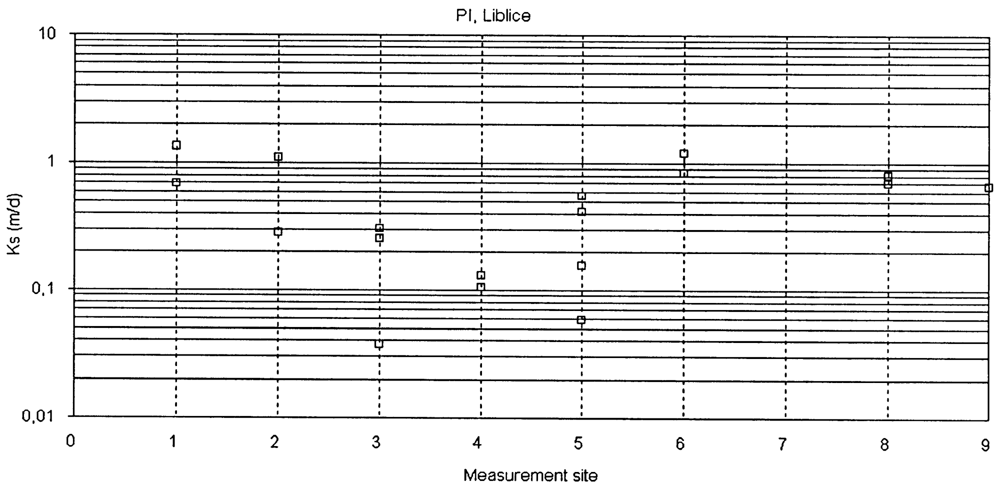
The Table 10 contains an overview of the measurements.

The disc infiltrometer measurements were made less frequently than the Guelph permeameter measurements. Some of the conclusions stated above in relation to the Guelph permeameter also pertain to the disc infiltrometer, in particular:

a) the values of the obtained hydraulic parameters are to some degree controlled by the soil granulometry (except, probably, for the parameter α), as can be seen from Figs 15 and 16 (for Liblice),

Table 10. Overview of measurements made in Liblice and Horni Tresnovec

Location	Measurement sites/apparatus	Brief name of the period	Dates of measurement
Liblice	3.5/SME	spring 94	05.05.94
Liblice	6.9/SMS	summer 94	02.06.94
Liblice	1-6.8-9/SMS	autumn 94	18.07-18.08.94
Horni Tresnovec	1-3/SME	spring 94	18.04-11.05.94
Horni Tresnovec	1-3/SMS	autumn 94	24-26.08.94



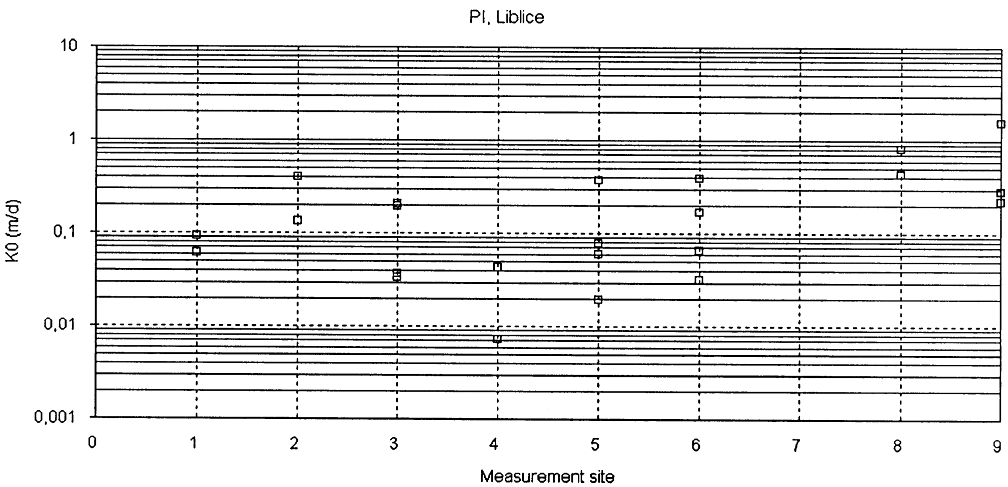


Fig. 15. Distribution of values of the vertical saturated hydraulic conductivity K_s and the upper limit of vertical unsaturated hydraulic conductivity K_o of the soil surface layer measured by the disc infiltrometer, for individual measurement sites in Liblice. Included are all infiltration spots and all dates of mesaurement.

b) all three hydraulic parameters provided by the disc infiltrometer (α, K_o and K_s) tend to decrease when the soil moisture content increases (cf. Figs 17 to 19).

Since the measurements were only made on the soil surface, we cannot say anything about the vertical distribution of the hydraulic parameters α, K_o and K_s in the soil profile. To overcome this shortage, we recommend that in future the disc infiltrometer measurements are also made on undisturbed bottom surfaces of shallow pits of different depths.

All three parameters (α, K_o and K_s) are mutually correlated (cf. Figs 20 to 22). The square of the correlation coefficient varies between 0.2 and 0.8. The degree of correlation is highest between α and K_o. This may indicate that the disc infiltrometer measurements, made

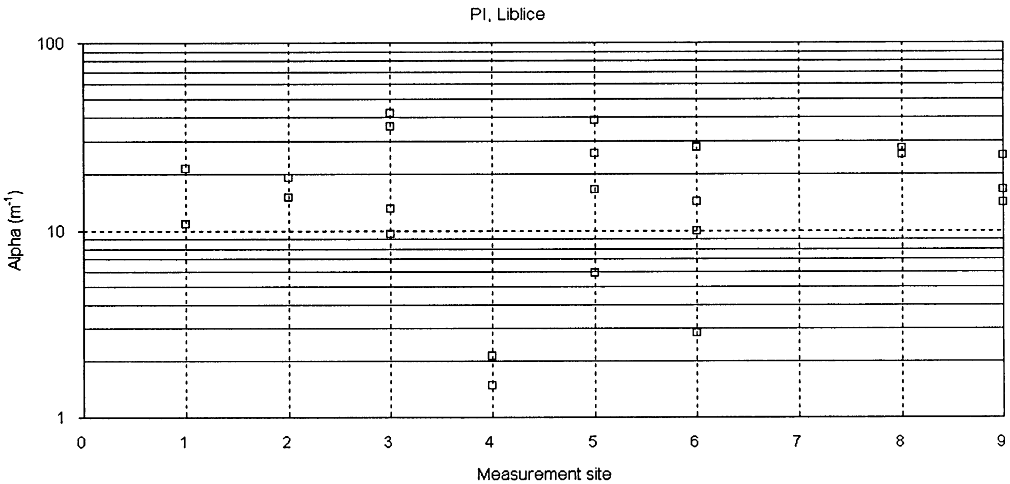


Fig. 16. Distribution of values of the exponential parameter α, expressing the speed of decline of vertical unsaturated hydraulic conductivity of the soil surface layer with the decrease of the soil water pressure head, for individual measurement sites in Liblice. α was measured by the disc infiltrometer. Included are all infiltration spots and all dates of measurement.

in the way as we made them, do not provide enough information for estimating three independent parameters. The measuring procedure should therefore be supplemented by other measurements (e.g., using a portable 'quick-draw' tensiometer) which would provide the missing information.

The positive correlation between K_o and K_s contradicts to the preliminary observation made in Tisice (see above) which indicated a negative correlation between them.

We also tried to compare the horizontal, field-saturated hydraulic conductivity K_{hom}, obtained from the Guelph permeameter measurements for the shallowest layer of topsoil, with the vertical saturated hydraulic conductivity K_s provided by the disc infiltrometer at approximately the same time. A relation between both is given in Figs 23a and b. Even though the number of observation is insufficient, we can say that K_{hom} and K_s are positively correlated to each other. However, K_s is on average by about a half order of magnitude less than K_{hom}. This trend in opposite to the one observed in Tisice (see above) where the double-ring infiltration tests gave the vertical field-saturated hydraulic conductivity K_{inf} about twice as high as the Guelph permeameter horizontal field-saturated hydraulic conductivity, K_{hom}. Some possible reasons for this paradoxical behaviour are discussed above in the section on the Guelph permeameter measurements in Tisice.

The infiltration measurements were accompanied by taking disturbed and undisturbed soil samples in the field in order to estimate moisture content, bulk density and other physical properties of the soil. Some of the undisturbed core samples were taken directly from the infiltration area, immediately after the end of an experiment on a certain spot, i.e., after removal of the disc infiltrometer and the fine sand cake. Other cores were taken before a measurement from a spot which preserved the initial moisture content of the soil. All core samples were then processed in the laboratory. Among others, they were saturated by capillarity and weighed. The volumetric moisture content which they possessed at that instant is sometimes referred to as the 'maximum capillary soakability'. The total porosity was also determined on all core samples. Figs 24a and b provide some results of these analyses. The volumetric moisture content

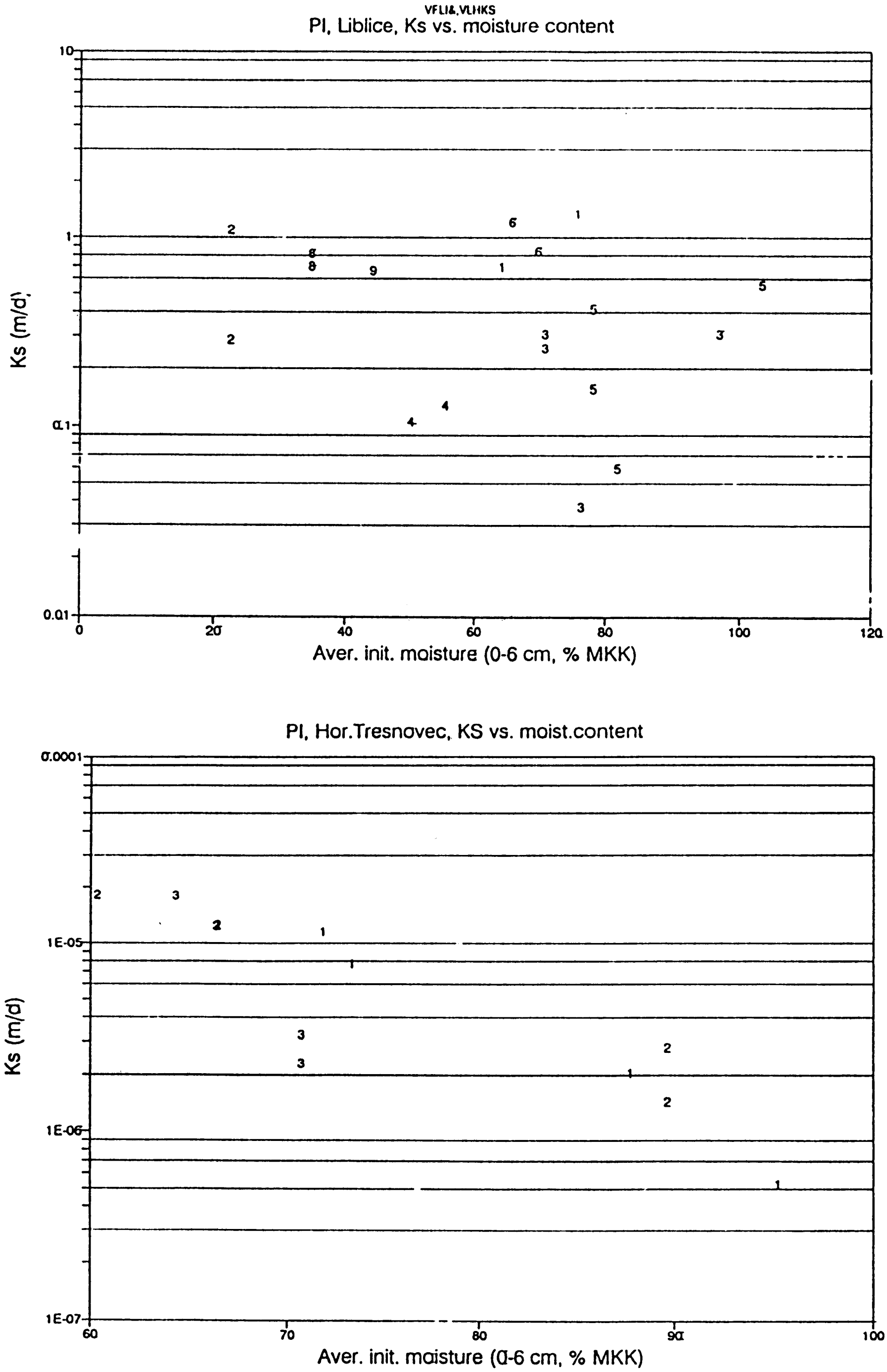
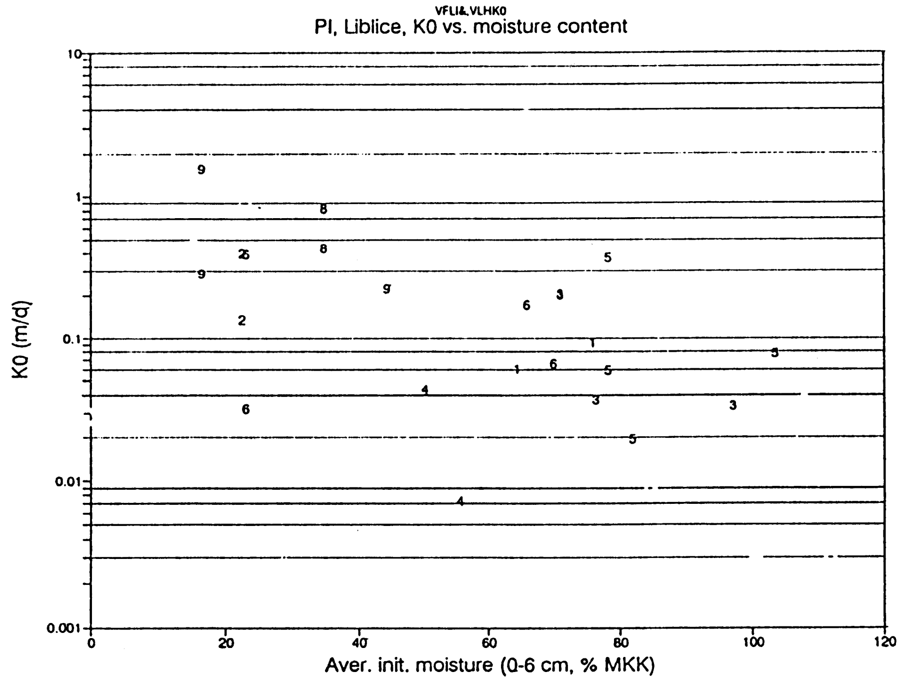


Fig. 17. Dependence of the vertical saturated hydraulic conductivity K_s of the soil surface layer, measured by the disc infiltrometer in Liblice and Horni Tresnovec upon the average moisture content before the measurement. The soil moisture content is averaged over the depth interval 0-6 cm and is expressed in per cent of the maximum capillary capacity (MKK), approximately equal to the field capacity. The figures at the points of the graph denote the measurement sites.



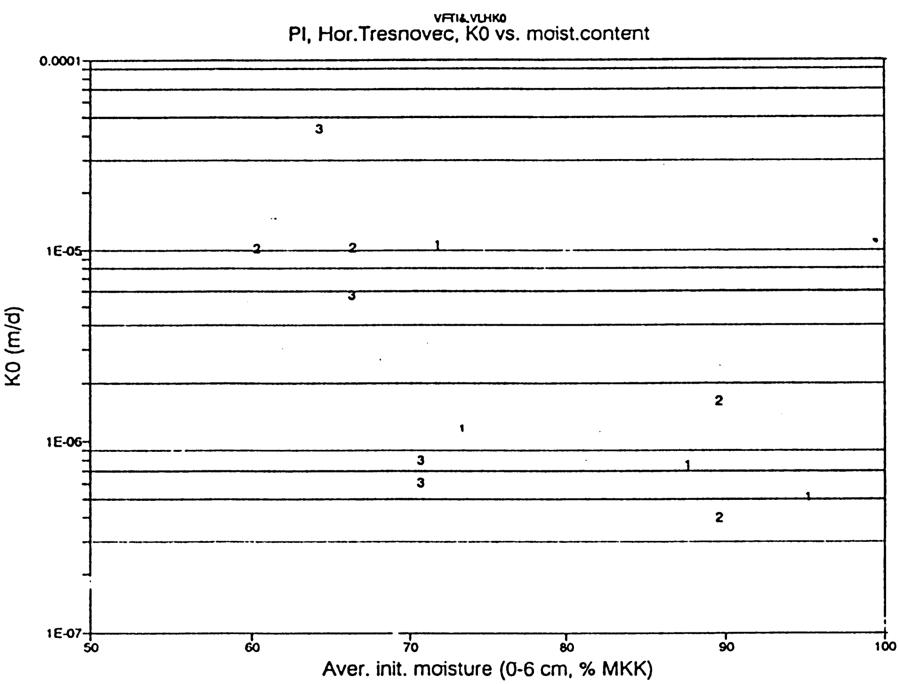


Fig. 18. Dependence of the upper limit of vertical unsaturated hydraulic conductivity of the soil surface layer K_o, measured by the disc infiltrometer in Liblice and Horni Tresnovec upon the average soil moisture content before the measurement. The soil moisture content is averaged over the depth interval 0-6 cm and is expressed in per cent of the maximum capillary capacity (MKK), approximately equal to the field capacity. The figures at the points of the graph denote the measurement sites.

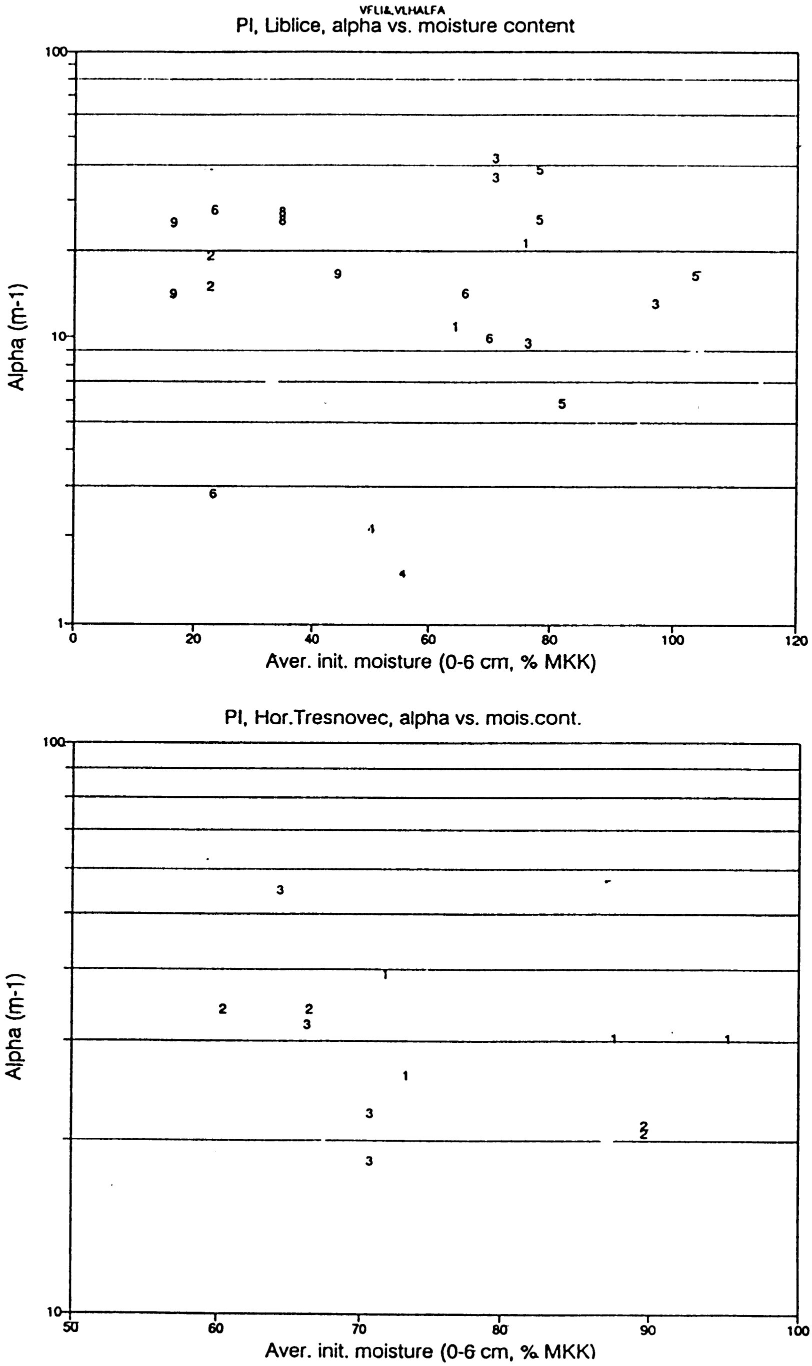
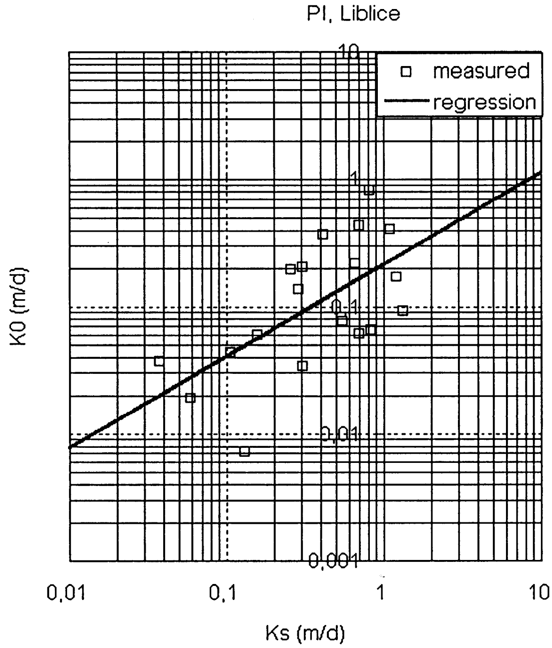


Fig. 19. Dependence of the exponential parameter α, expressing the speed of decline of vertical unsaturated hydraulic conductivity of the soil surface layer with the decrease of the soil water pressure head, upon the average soil moisture content before the measurement. The values of α were measured by the disc infiltrometer in Liblice and Horni Tresnovec. The soil moisture content is averaged over the depth interval 0-6 cm and is expressed in per cent of the maximum capillary capacity (MKK), approximately equal to the field capacity. The figures at the points of the graph denote the measurement sites.



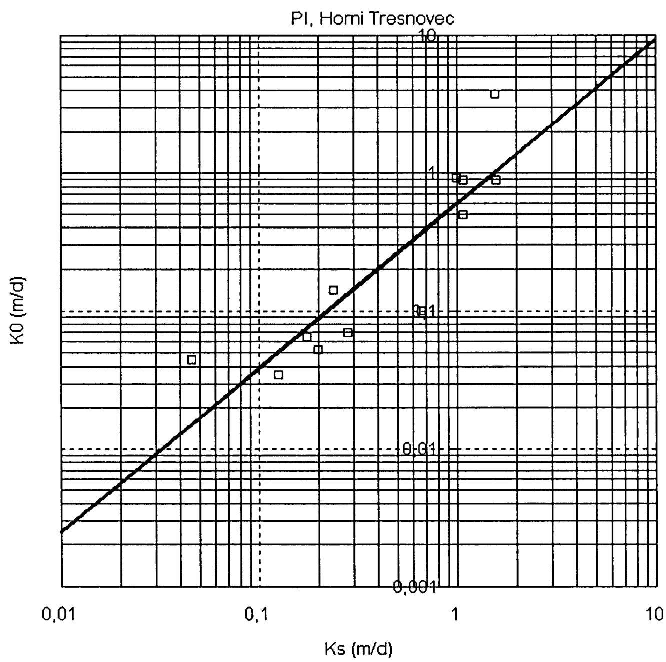


Fig. 20. Relation between the upper limit of vertical unsaturated hydraulic conductivity of the soil surface layer, K_o, measured by the disc infiltrometer in Liblice and Horni Tresnovec and the vertical saturated hydraulic conductivity of the soil surface layer, K_s, obtained from the same measurement. The straight line denotes the least squares regression.

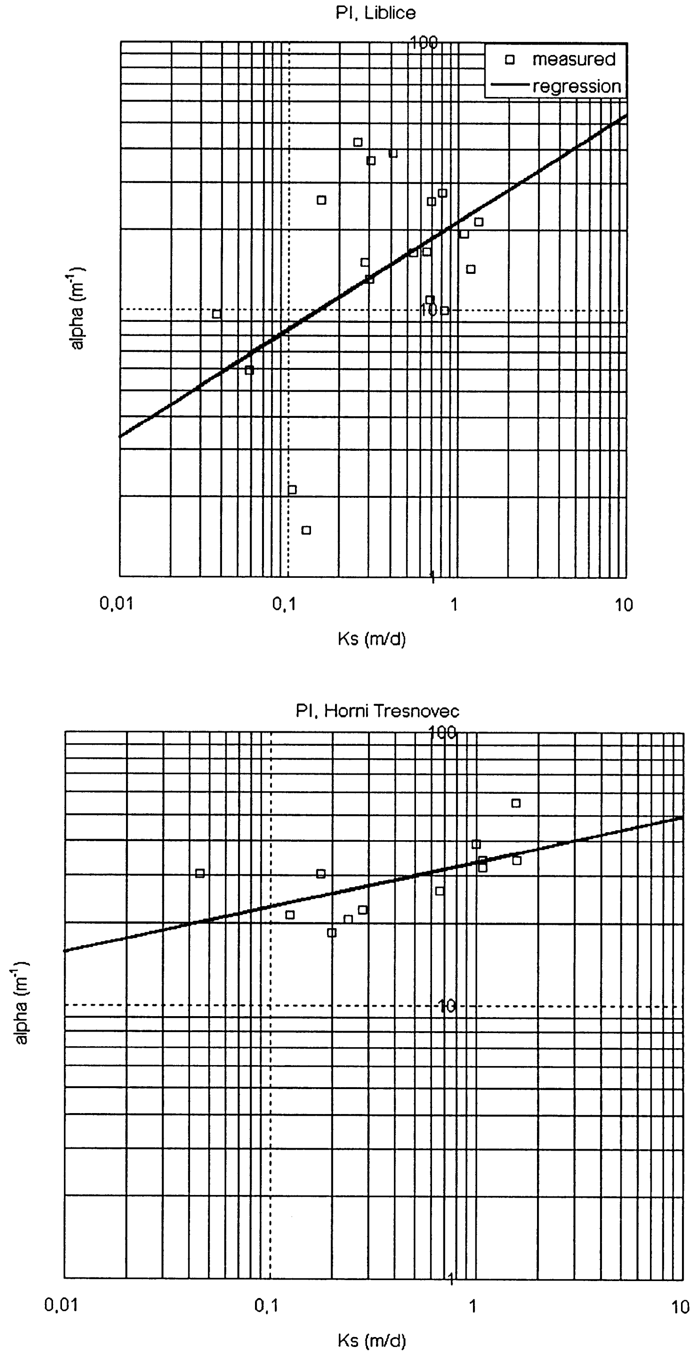
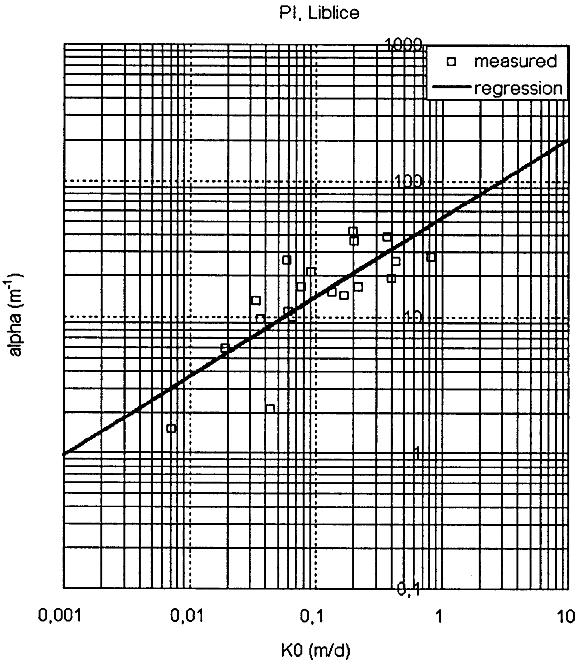


Fig. 21. Relation between the exponential parameter α, expressing the speed of decline of vertical unsaturated hydraulic conductivity of the soil surface layer with the decrease of the soil water pressure head, and the vertical saturated hydraulic conductivity of the soil surface layer, K_s, both obtained from the same disc infiltrometer measurement in Liblice and Horni Tresnovec. The straight line denotes the least squares regression.



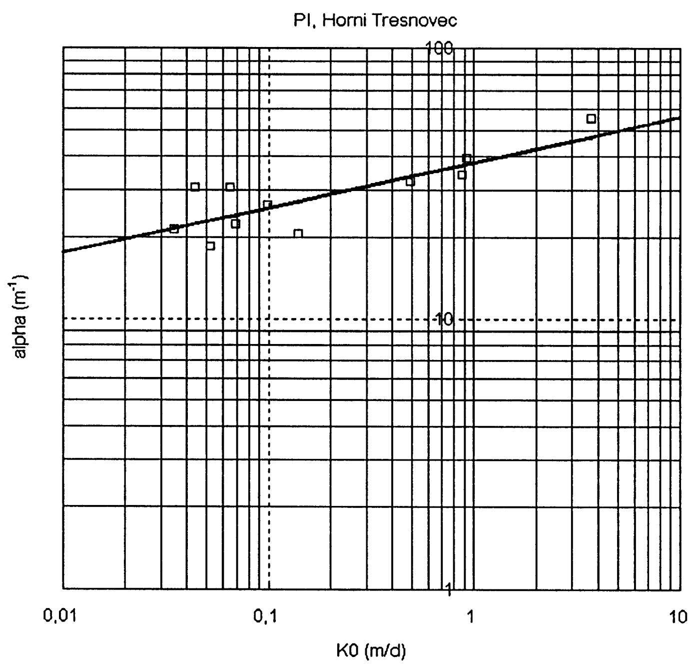
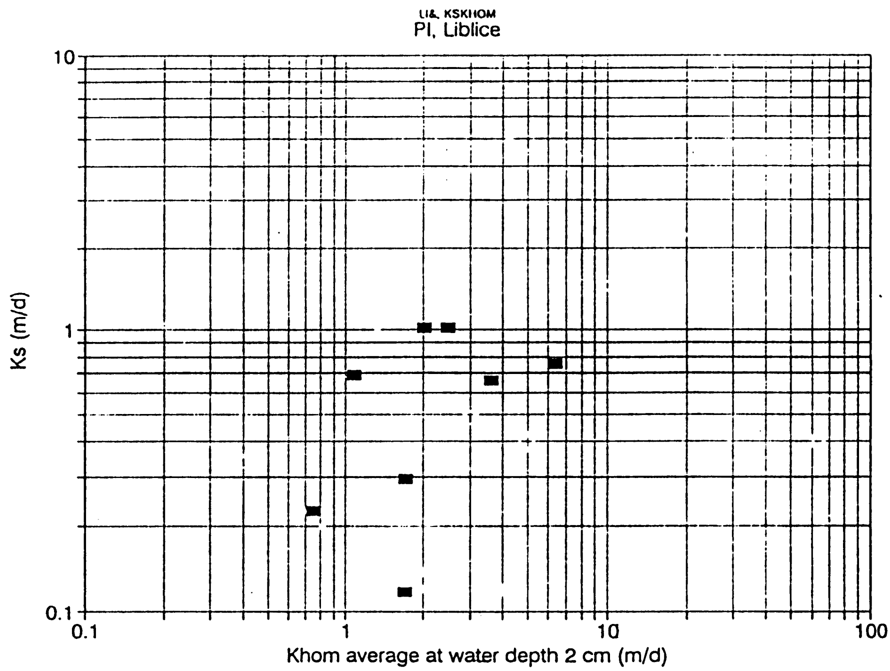


Fig. 22. Relation between the exponential parameter α, expressing the speed of decline of vertical unsaturated hydraulic conductivity of the soil surface layer with the decrease of the soil water pressure head, and the upper limit of vertical unsaturated hydraulic conductivity of the soil surface layer, K_o, both obtained from the same disc infiltrometer in Liblice and Horni Tresnovec. The straight line denotes the least squares regression.



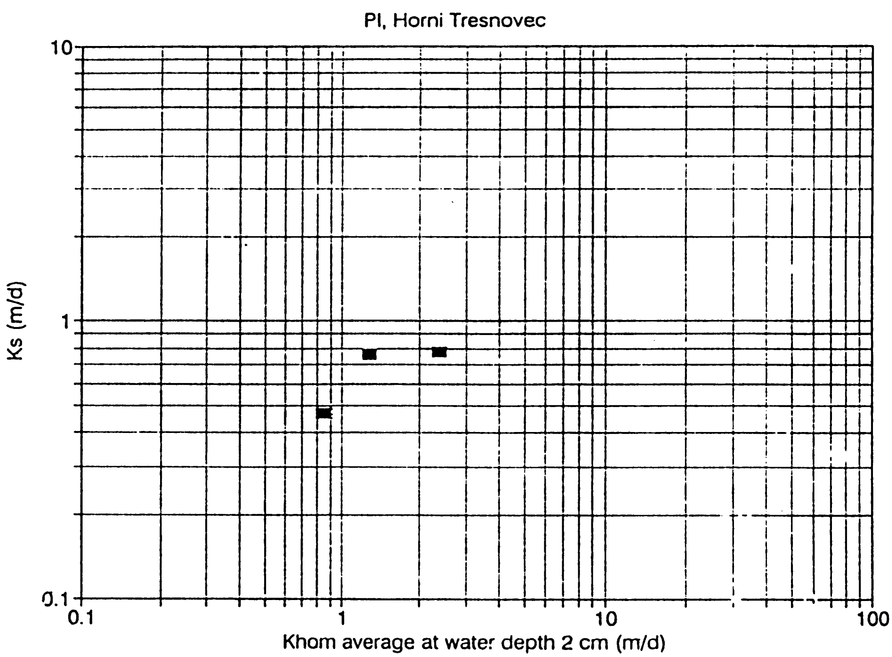
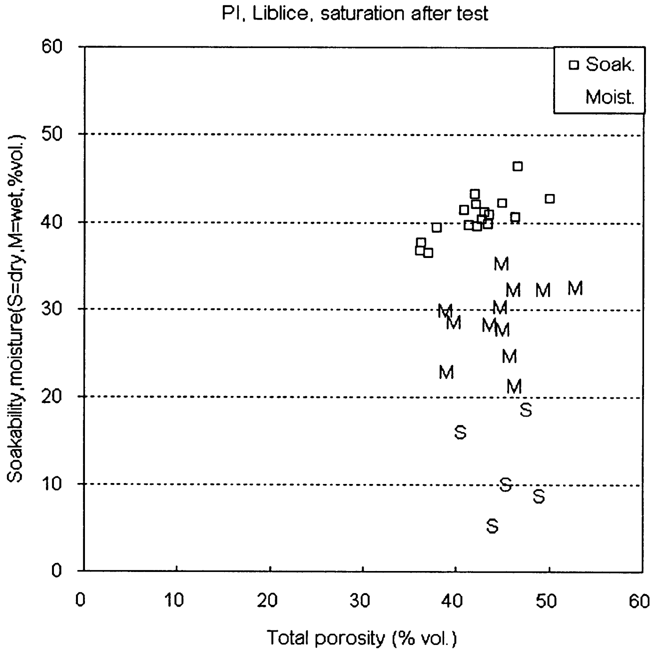


Fig. 23. Relation between the vertical saturated hydraulic conductivity of the soil surface layer, K_s, measured by the disc infiltrometer, and the horizontal field-saturated hydraulic conductivity K_{hom}, measured by the Guelph permeameter and characterizing average properties of the soil layer between 2 and 50 cm of depth, in Liblice and Horni Tresnovec. Each point represents the average values of K_s and K_{hom} for a single measurement site, with the averages being made over all boreholes or infitration spots and over all dates of measurement.



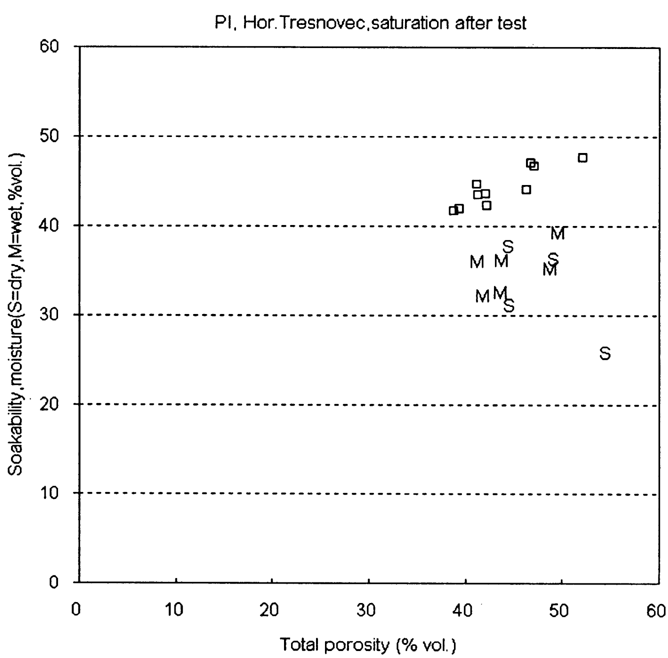


Fig. 24. Relation between the total porosity of the soil surface layer, its maximum capillary soakability (full squares) and its volumetric moisture content before (S) and after (M) the disc infiltrometer measurements in Liblice and Horni Tresnovec. All values were determined in laboratory on 100 cm^3 core samples taken from the depth of 1-5 cm. This graph illustrates the fact that the surface soil layer does not become saturated during the infiltration experiment.

at the instant of sampling and the 'maximum capillary soakability' are plotted in these figures as functions of the total porosity. The moisture contents at sampling are denoted by the letter S (= dry) if the core was taken from a spot uninfluenced by the infiltration or by the letter M (= wet) if it was taken from the infiltration area immediately after the measurement. We can see that the 'maximum capillary soakability' is on average virtually equal to the porosity of the same sample, while the volumetric moisture contents at sampling, even for most of the M - cores (= wet cores), are considerably less. This demonstrates that the soil beneath a disc infiltrometer does not become saturated during the measurement, mainly because of preferential flow of water in the soil along more permeable zones and macropores, accompanied by the phenomenon of air entrapment in the soil pores.

A large rain simulator was used, only once, in Liblice, near to the measurement site 2, in autumn 1993. The infiltration area was about 16 m^2, the artificial rainfall intensity was about 20 mm h^{-1}. The surface runoff started at 7 minutes after the beginning of the rain. After an hour of (artificial) rainfall, the surface runoff rate was about 15 mm h^{-1}, i.e., the infiltration rate was approximately 5 mm h^{-1} or 0.12 m d^{-1}. This is less than the saturated hydraulic conductivities K_s provided by the disc infiltrometer on the same measurement site approximately at the same time (the values of 0.29 and 1.10 m d^{-1} were obtained from two parallel measurements). This may indicate that, probably, the disc infiltrometer values of K_s are not systematically biased downwards due to the hydraulic resistance of the sand cake.

CONCLUSIONS

We explored the possibility of using a complex simulation model of soil water, nutrients and plant growth, such as CERES, for investigating the interactions between the soil structure and other components of the environment, with the perspective of future exploitation of similar models for decision support in environmental control and sustainable agriculture.

The results of our effort show that, in principle, the complex simulation models could and should be used for this purpose. Some of the model input parameters can serve as indicators of the structural state of the soil. Hence, we are able to 'inform' the model about the structure of the soil. The model parameters relevant from this point are primarily the hydraulic and hydrological properties of the soil. Of course, one can expand the notion of soil structure to include also the physicochemical properties of the soil, such as the cation sorption capacity. This aspect is however beyond the scope of this study. It might be investigated in future.

In a particular case of the CERES model, the input parameters capable of carrying certain information about the soil structure comprise a) the properties of the soil surface, such as the bare soil albedo, the SCS curve number or the parameters of the Ritchie's bare soil evaporation theory, and b) the properties of the soil interior. Within the latter group, one can distinguish the static parameters (such as wilting point, field capacity or saturation moisture contents of individual soil layers) and the dynamic parameters, which govern the movement of water in the soil and out of the soil. These are, in particular, the soil water drainage constant (SWCON), playing in the CERES series of models a role similar to that of the saturated hydraulic conductivity, and the soil moisture diffusivity function, which is however hard-wired in the CERES program code.

Unfortunately, most of these parameters are not directly measurable. Therefore, it seems useful to investigate the ways in which these parameters could be derived or estimated from the basic, directly measurable soil properties such as the retention curve, the hydraulic conductivity function, the grain size distribution, etc. In this study, we suggested a method of estimating the Ritchie's bare soil evaporation parameters from the retention curve and from the hydraulic conductivity function. In addition, it was found that the Ritchie's parameters depend upon the potential evaporation rate. This dependence should be incorporated into future versions of CERES.

We also carried out a set of example calculations demonstrating how the hydrostatic soil parameters (the wilting point, the field capacity and the saturation moisture content) influence the soil water and nitrogen balance and the crop growth. Rather surprisingly, we found that a soil with higher retention capacity for water (believed to exemplify a soil in a good structural state) may produce lower yields than a comparable soil of which the available water capacity is low. The simulation results suggest that this may occur if the water supply (due to rainfall and irrigation) is insufficient and the nitrogen fertilizers are applied on the surface or into the shallow surface layer of the soil. Under these conditions, the plant roots in the deeper soil layers may suffer from shortage of both water and nitrogen if these have been retained in the upper layers. These simulation results must however be handled with caution. One should always realize that the amount of input information processed by a simulation model is limited and that the model only takes into account a limited number of factors and processes, namely those which were regarded as most relevant by the authors of model. Other factors, ignored by the model, may be relevant or even dominant in reality. Despite of this reservation, we think that the complex simulation models can predict real phenomena with an accuracy and complexity inaccessible to the common human sense. This is particularly true if the situations to be predicted are unusual. We even think that the results of our particular set of simulations as described above may be correct and should be proved or disproved by experiments.

The soil hydraulic and hydrological properties which are needed as inputs to the complex simulation models or from which the model input parameters can be derived have to be measured systematically and reliably. For this purpose, we investigated the feasibility of using the Guelph permeameter and the disc infiltrometer.

The Guelph permeameter, i.e., the method of quasi-steady borehole infiltration into an unsaturated soil profile, appeared to be a versatile tool which can rapidly provide values of the field-saturated horizontal hydraulic conductivity of both topsoil and subsoil. However, assessing any meaningful information about the unsaturated soil hydraulic properties from the Guelph permeameter measurements alone seems impossible. The so-called matrix flux potential, which is sometimes suggested as being derivable from these measurements, does not in fact carry much new information, in addition to that contained in the field-saturated hydraulic conductivity. We therefore suggest that the Guelph permeameter is used as a tool for measuring the field-saturated hydraulic conductivity only. For this purpose, one can use the classical Glover (1953) formulae which, on one hand, express quite correctly the shape factor and, on the other hand, being predisposed to overestimate the hydraulic conductivity, are able to counterbalance the tendency of the borehole infiltration method to underestimate it (due to various physical reasons). The Guelph permeameter, beside its ability to produce large set of data useful as inputs to the complex or partial simulation models, can also be used to indicate directly the more permeable or less permeable zones in the soil profile. In this way, we can, for example, find out if the upper subsoil has been compacted by agricultural machinery, or, inversely, quantify the favourable effect of subsoiling and its duration in time.

The way in which we used the Guelph permeameter, measuring the quasi-steady discharge at several water table positions in the same borehole, suffers from the lack of proper theoretical background if the soil is systematically heterogeneous in the vertical direction. Therefore, it may be more advantageous, even if more laborious, to measure the discharges in several parallel boreholes of different depths, maintaining the height of water above the borehole bottom constant in all cases.

The disc infiltrometer is an instrument capable of giving to the observer an insight into the unsaturated hydraulic properties of the soil near saturation. We can also use the disc infiltrometer to specify, to some extent, the hydraulic role of soil macropores. Several measurements of the quasi-steady infiltration discharge have to be carried out on the same spot at different pressure heads maintained at the infiltrometer membrane. One of the measurements should be made with a small overpressure at the membrane. We also suggested a modified method for evaluation of the disc infiltrometer measurements, allowing to express the influence of soil macropores explicitly. In view of these findings, we can recommend the disc infiltrometer for use as one of the basic tools for testing the structural state of the topsoil. The disc infiltrometer can also be used on horizontal undisturbed bottoms of shallow pits in order to measure the hydraulic properties of deeper soil layers (we however did not yet test this procedure).

The theoretical background on which the Guelph permeameter and disc infiltrometer measurements are based is still insufficient and should be further developed, to be able to allow for soil heterogeneity and anisotropy, for the influence of macropores, for high and non-homogeneous initial moisture content, proximity of the groundwater table, etc. To decipher more complicated situations, one may need to supplement the Guelph permeameter or the disc infiltrometer by other instruments (e.g., tensiometers) providing additional information.

In general, we recommend that the field researchers do not confine themselves to using a single instrument or a single method for measuring the soil hydraulic properties or for testing the structural state of the soil. The comparisons of several methods, either made by ourselves or published in the literature, show that much more reliable information can be obtained if several methods are combined.

We found that in light and medium soils, especially those developed on the sedimentary rocks of the North-Bohemian Cretaceous (e.g., on the research site Liblice), the soil hydraulic properties are to a great extent texturally controlled. For such soils, we were also able to identify periods during which the hydraulic conductivity of the topsoil was at spontaneous minimum (without being influenced by artificial compaction). Particularly in this state of the soil the hydraulic properties are texturally controlled and, therefore, predictable and interpolable.

On the research sites of Liblice and Horni Tresnovec, we found that the three hydraulic parameters obtainable by our evaluation method from the disc infiltrometer measurements, i.e., the saturated hydraulic conductivity K_s, the upper limit of unsaturated hydraulic conductivity K_o and the Gardner's exponential parameter α, are correlated to each other. This contradicts to our previous preliminary conclusion, based on measurements in Tisice, that K_s is high and K_o is low if the soil structure is loose and vice versa.

REFERENCES

1. **Ankeny M.D., Kaspar T.C., Horton R.:** Characterization of tillage and traffic effects on unconfined infiltration measurements. Soil Sci. Soc. Am. J., 54: 837-840, 1990.
2. **Brutsaert W.**: Water infiltration in dry soil. Water Resour. Res., 12(2): 363-368, 1977.
3. **Childs E.C.:** An introduction to the physical basis of soil water phenomena. Wiley, London, 1969.
4. **Damaska J.:** The influence of fertilizer and lime application upon migration and cycling of nutrients and crop yields in agricultural soils of the Ústí nad Orlicí district (in Czech). Partial final report of the partial project VI-4-21-02, phase 03, 04, 05. Research Institute for Improvement of Agricultural Soils, Prague-Zbraslav, 34 p. + appendices, 1983.
5. **Doležal F., Lipavsky J., Kren J.**: Site evaluation using simulation models within a geographic information system for the purposes of land valuation, predictions and consultancy (in Czech and English). A project proposal submitted to the Grant Agency of the Czech Republic. Approved as project No. 502/94/1033, 1993.
6. **Doležal F., Lipavsky J., Kren J., Novak P., Šimon J., Kubat J., Pycha M., Cikanova S., Klímová P., Flasarova V., Pokorny E.:** The use of crop models for land valuation. In: Malama 'Aina 95 (Preserve the land). First international conference on multiple objective decision support systems for land, water and environmental management: Concepts, approaches and applications. University of Hawaii, Honolulu, Hawaii, USA. Abstract: Pre-conference Proc., pp. A-25 to A-26, full text: accepted for publication, 1995a.

7. **Doležal F., Poruba M.**: A robust procedure for estimating the hydraulic parameters of the uppermost soil layer from the measurements made with a Guelph permeameter and a disc infiltrometer (in Czech). Submitted for publication to Vodní hospodárství, Prague, Czech Republic. Also available in Dole_al *et al.* (1995b), Supplement No. 3, 1996.
8. **Doležal F., Poruba M., Voplakal K., Soukup M.**: The infiltration and retention capacity of arable soils (in Czech). A supplement to the final report of the project RE 0930950004 'Revitalisation of the agricultural and forest catchment'. Research Institute for Soil and Water Conservation, Prague - Zbraslav, 159 p, 1995b.
9. FAO - UNESCO: Soil map of the world. Revised legend. World Soil Resources Report 60, FAO, Rome, 119, 1988.
10. **Gardner W.R.**: Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci., 85: 228-232, 1958.
11. **Godwin D., Ritchie J., Singh U., Hunt L.**: A user's guide to CERES Wheat - V2.10. Second edition. International Fertilizer Development Center, Muscle Shoals, Alabama, 94, 1990.
12. **Green W.H., Ampt G.A**: Studies on soil physics. I. The flow of air and water through soils. J. Agr. Sci., 4: 1-24, 1911.
13. **Gupta R.K., Rudra R.P., Dickinson W.T., Patni N.K., Wall G.J.**: Comparison of saturated hydraulic conductivity measured by various field methods. Trans. ASAE, 36: 51-55, 1993.
14. **Hrasko J., Linkes V., Nemecek J., Novak P., Šaly R., Šurina B.**: A morphogenetic classification system for the soils of CSFR (in Slovak). Research Institute of Soil Fertility, Bratislava, 108 p, 1991.
15. IBSNAT Project: Decision Support System for Agrotechnology Transfer V2.1. Dept. Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, 1989.
16. Int. Agrophysics, vol. 7, Nos 2-3, 1993.
17. **Jones C. A., Kiniry C.A.**: CERES - Maize. A simulation model of maize growth and development. Texas A + M University Press, College Station, Texas, 194 p, 1986.
18. **Kanwar R.S., Rizvi H.A., Ahmed M., Horton R., Marley S.J.**: Measurement of field-saturated hydraulic conductivity by using Guelph and velocity permeameters. Trans. ASAE, 32: 1885-1890, 1989.
19. **Krejca M., Kupcova J.**: Brutsaert infiltration equation (in Czech). Vodní hospodárství, series A, (10): 265-266, 1989.
20. **Lhotsky J.**: Complex agro-amelioration systems for overcompacted soils (in Czech). Guidebooks for introducing results of research into practice, No. 20/1991. Centre of Scientific and Technical Information for Agriculture, Prague, 35 p, 1991.
21. **Lhotsky J.**: Blueprints for the realisation output RV 06 A,B,C 'To introduce verified complex agro-amelioration systems for arable soils', of the partial research project P 06-32-813-04. Research Institute for Soil and Water Conservation, Prague, 1992.
22. **Lhotsky J.**: Agro-amelioration measures for arable soils and testing of their urgency and efficiency (in Czech). Summary final report of partial project P 06-329-813-04. Research Institute for Improvement of Agricultural Soils, Prague - Zbraslav, 75 s, 19990.
23. **Mohanty B.P., Kanwar R.S., Everts C.J.**: Comparison of saturated hydraulic conductivity measurement methods for a glacial-till soil. Soil Sci. Soc. Am. J., 58: 672-677, 1994.
24. **Otter-Nacke S., Ritchie J., Godwin D., Singh U.**: A user's guide to CERES-Barley - V2.10. International Fertilizer Development Center, Muscle Shoals, Alabama, 87 p, 1991.
25. **Paige G.B., Hillel D.**: Comparison of three methods for assessing soil hydraulic properties. Soil Sci., 155: 175-189, 1993.
26. **Perroux K.M., White I.**: Design for disc permeameters. Soil Sci. Soc. Am. J., 52: 1205-1215, 1988.
27. **Philip J.R.**: Approximate analysis of the borehole permeameter in unsaturated soil. Water Resour. Res., 21(7): 1025-1033, 22(7): 1162, 1985.
28. **Reynolds W.D., Elrick D.E.**: Measurement of field-saturated hydraulic conductivity, sorptivity and the conductivity - pressure head relationship using the 'Guelph permeameter'. In: Characterization and Monitoring of the Vadose (Unsaturated) Zone. Proc. Nat. Water Well Assoc. Conf., Denver, Colorado, 1985.
29. **Reynolds W.D., Elrick D.E.**: Ponded infiltration from a single ring: I. Analysis of steady flow. Soil Sci. Soc. Am. J., 54: 1233-1241, 1990.
30. **Reynolds W.D., Elrick D.E.**: Determination of hydraulic conductivity using a tension infiltrometer. Soil Sci. Soc. Am. J., 55(3): 633-639, 1991.
31. **Ritchie J.T.**: A model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res., 8: 1204-1213, 1972.
32. **Ritchie J., Singh U., Godwin D., Hunt L.**: A user's guide to CERES-Maize, V2.10. Second edition. International Fertilizer Development Center, Muscle Shoals, Alabama, 94 p, 1992.
33. **Saadalla W.M.**: The role of the bare soil evaporation in the soil water balance and maize crop growth and development - a comparative study using the CERES and S_1D simulation models. M.Sc. thesis. Department of Engineering Hydrology, University College Galway, Ireland, 332 p, 1995.
34. **Sharpley A.N., Williams J.R.**: (eds.), EPIC -Erosion/Productivity Impact Calculator. 1. Model documentation, 2. User's guide. U. S. Dept. Agric. Tech. Bull. No. 1768. USDA-ARS, Temple, Texas, 235 + 127 p, 1990.
35. **Soukup M., Doležal F., Poruba M.**: Revitalisation of the agricultural and forest catchment (in Czech). Final report of the project RE 0930950004. Research Institute for Soil and Water Conservation, Prague - Zbraslav, 1995.
36. **Tsuji G.Y., Uehara G., Balas S.**: (eds.) DSSAT (A Decision Support System for Agrotechnology Transfer), version 3. Vols. 1, 2 and 3, University of Hawaii, Honolulu, Hawaii, 164 + 284 + 244 p, 1995.

37. **Van Genuchten M.Th.**: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44: 892-898, 1980.

38. **Vogel T., Zhang R., van Genuchten M.Th.**: The S_1D software package for simulating water, solute and heat movement in variably-saturated porous media. Version 1.0, Research report No. 132, U. S. Salinity Laboratory, ARS, USDA, Riverside, California, 82 p, 1993.

39. **Wooding R.A.:** Steady infiltration from shallow circular pond. Water Resour. Res., 4: 1259-1273, 1968.

40. World Reference Base for Soil Resources. Preprint of a draft, ISSS + ISRIC + FAO, Wageningen/Rome, 162 p, 1994.

41. **Zochova D.:** Testing a Guelph permeameter for measuring hydraulic conductivity of light soils (in Czech). Ingénieur (M.Sc.) thesis. Department of Irrigation and Drainage, Faculty of Civil Engineering, Czech Technical University, Prague, 96 p, 1989.