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Spatial analysis of saturated hydraulic conductivity in a soil with macropores

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Abstract

Saturated hydraulic conductivity (K_S) is an important soil hydraulic parameter for it establishes a limit on the rate of water and solute transmission through soil. However, its determination in the laboratory has been shown to be much influenced by column size. We evaluated the spatial variability of laboratory K_S measurements using three different column sizes: firstly, sixty 5.1 cm long columns of 5 cm diameter were used (type-I), next, thirty 20 cm long and 20 cm diameter columns were considered (type-II), and finally, thirty columns 100 cm long and of 30 cm diameter (type-III) were studied. All columns were collected along a transect in a sandy loam soil with macropores. Estimates of macroporosity at three depths (2.5, 12.5, and 16.5 cm) for twenty-four of the type-II columns were calculated from stained dye patterns obtained during ponded infiltration. The geometric mean of K_S decreased with increasing column size, i.e., from 2.24, 1.68 to 0.56 cm/h for type-I, -II, and -III columns, respectively. The coefficient of variation (CV) based on a log–normal distribution showed a similar trend: 619% for type-I, 217% for type-II, and 105% for type-III. Type-II and type-III columns were large enough to encompass a representative elementary volume (REV). The percentage of dye-staining (macropore cross-sectional area) decreased from 3% at 2.5 cm to 1.7% and 1.6% at 12.5 and 16.5 cm, respectively. Percentage of depth-averaged macropore area was moderately variable with CV = 51%. A geostatistical analysis revealed that a weak spatial structure existed for type-I K_S measurements whereas type-II and type-III columns displayed better spatial correlation with a range of approximately 14 m and 11 m, respectively. Spatial correlation was also observed for depth-averaged macropore area with a range of 12 m. The cross-semivariogram calculated between type-II K_S values and depth-aver-

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aged macropore area obtained from the same columns indicated positive spatial cross-correlation for all lags.

Keywords: Spatial variability; Saturated hydraulic conductivity; Macroporosity

1. Introduction

Increased environmental awareness has led soil scientists, hydrogeologists and hydrologists to pay increased attention to the processes of water and solute redistribution in soils and aquifers. A proper characterization of a soil's hydrodynamic behavior is of paramount importance for addressing many environmental problems, such as the study of the effects of irrigation and drainage on the salinity level of soils, for analyzing impacts of ground water drawdown on agricultural production, or for investigating possible effects of leakage from hazardous waste disposals located in the unsaturated soil zone. The accurate quantification of soil hydraulic properties is also needed in order to predict recharge of water and agrochemicals to both shallow and deeper aquifers.

In view of such problems, the property of the saturated hydraulic conductivity (K_S) plays a key role, for it determines the maximum capacity of saturated soil to transmit water. Also, it is commonly used in formulas to 'match' unsaturated conductivity predictions based on the $\theta(\psi)$ relationship (e.g., Mualem, 1992). Problems associated with the determination of K_S in situ, or in the laboratory using undisturbed soil columns are mainly related to its high spatial variability (Russo and Bresler, 1981; Lauren et al., 1988; Mohanty et al., 1994a). The variability of K_S tends to decrease as the sampling volume increases and greater integration occurs (Anderson and Bouma, 1973; Baker and Bouma, 1976; Baker, 1977; Lauren et al., 1988).

Water flow near saturation is significantly influenced by the presence of macropores (Bouma et al., 1977; Bouma, 1982). Networks of macropores facilitate the more rapid downward movement of water and solutes to greater depths allowing bypass of much of the soil matrix. Macropores also tend to increase the variability of K_S measurements when small sample sizes are used (Mohanty et al., 1994a).

Studying the variability of soil hydraulic properties such as K_S, or infiltration rate, has been accomplished using conventional statistical techniques (Mohanty et al., 1994a), although more sophisticated geostatistical methods can be used (Vieira et al., 1981; Byers and Stephens, 1983; Lauren et al., 1988; Ünlü et al., 1990; Mohanty et al., 1991; Mohanty et al., 1994b). The former method assumes that the data for a particular property collected at different spatial locations are independent of each other, regardless of whether they are close to or far away from one another. This allows frequency distributions to be used for the calculation of the required sample size for estimating the mean within some specified confidence intervals. However, it does not provide insight into the variability of the property in terms of its spatial location, the so-called spatial structure. Therefore, spatial statistics have been adopted to measure the correlation between neighboring points. Use of geostatistics is of particular importance if sampling networks have to be designed, or if prediction of values of a regionalized variable at unsampled locations is of concern, or if stochastic flow and transport models are being implemented (Yeh et al., 1985; Binley et al., 1989). Furthermore, Sharma et al. (1987) showed that an increased subsurface flow occurs with increased spatial dependence in the soil hydraulic properties. A key step in these applications is the derivation of the semivariogram and its parameters. However, the dependency of laboratory K_S measurements on core size, especially in structured or macroporous soil, also has implications for the derived semivariogram. Therefore, more accurate quantification of the relationship between K_S variability and core size is needed to make reliable predictions of water flow and chemical transport processes at field-scale.

This paper compares K_S measurements on cores in the laboratory using three different sample volumes collected from a field-transect in the central part of Belgium. In this study we also analyse the effect of sample volume on the measured pattern of spatial variability in K_S in a soil with macropores. Furthermore, the spatial interdependence of K_S with macropore area obtained from dye experiments was investigated.

2. Materials and methods

2.1. Experimental design

Undisturbed soil cores were collected along a transect in a sandy loam soil (Udifluvent, Eutric Regosol), located in an orchard, approximately 15 km east of Leuven, Belgium. The plot within the orchard had a gentle slope of 5%, perpendicular to the direction of the transect. For the last forty years the soil has remained in grass. Three horizons were identified within the top one meter of the soil profile, i.e., Ap (0–25 cm), C1 (25–55 cm), and C2 (55–100 cm). Mallants et al. (1995b) found that clay percent increased from 12.7% in the Ap, to 16.6 and 21.8% in the C1 and C2, respectively. During soil sampling, we observed earth worm burrows and decayed root channels to be present throughout the soil profile. Soil structure was weak in the Ap and C1 horizons, but moderate in C2, being subangular blocky, medium to coarse, and friable to very friable (Soil Survey Staff, 1975).

Three different sample volumes (Table 1) were collected along the transect. In each horizon 60 undisturbed type-I soil cores were collected using a Uhland core sampler. An

Table 1
Dimensions, volumes, and number of undisturbed soil cores

Column type	Diameter (cm)	Length (cm)	Volume (cm^3)	No. of samples
I	5	5.1	100	60 [a]
II	20	20	6283	30 [b]
III	30	100	70684	30 [c]

[a] In each horizon. A total of 180 samples were analyzed in three horizons.
[b] In Ap horizon.
[c] Composite over Ap, C1, and C2 horizons.

alternating sampling distance of 0.1 and 0.9 m at the depths of 10, 50, and 90 cm was used. Type-II cores were collected only in the Ap. First, the soil surface was cleared of vegetation. Next, soil pedestals every 1 m were isolated by excavating the soil around them, and then 20 cm long and 20 cm diameter polyvinyl chloride (PVC) cylinders were pushed to enclose the pedestal. At a few sampling locations, the presence of large mole burrows necessitated taking samples at a larger spacing, simply because of difficulties to containing the soil into the partially filled cylinder. As a result, the total transect length for the type-II columns is slightly larger (36.5 m) than the transect lengths for the other two column types. The columns were cut-off at the bottom using a sharp spade, then both top and bottom were covered to prevent evaporation, and any loss of soil material. Sampling of the type-III columns was done by means of 30 cm diameter and 100 cm long PVC cylinders which were gently driven into the soil using a hydraulic jack. The bottom end was provided with a sharp-edged steel ring to facilitate intrusion of the column into the soil. The PVC cylinders also had the inner wall greased to have a close contact between the soil and the wall, avoiding the formation of 'insertion-created' macropores. Once the cylinder was completely filled with soil, the soil around it was excavated and the bottom end was cut off by means of a steel plate to isolate the column. Then, a PVC end cap was placed on both ends of the cylinder. Thirty undisturbed soil columns were collected in this way with a separation distance of 1 m. Type-III columns were collected in between the type-II sampling locations. At just one location along the transect a sampling distance of 2 m had to be used because of difficulties in driving the cylinder into a locally compacted layer.

Measurements of K_S for type-I columns were based on the constant-head permeameter method (Klute, 1965) by imposing a hydraulic head on top of the cores and measuring the resulting flux coming from the free-water outlet. Because of the presence of macropores that were continuous across the column, some cores exhibited direct piping. Type-II K_S values were determined using the technique described by Booltink et al. (1991). The saturated soil columns were put on a perforated PVC disk to which a filter cloth was attached to prevent the soil from falling out. This configuration was mounted on a funnel from which the flow was measured. At a depth of 10 cm, a tensiometer was installed and connected to a pressure transducer. While water was ponded on the soil to a depth of 1 cm, K_S measurements were performed by recording outflow with time when the pressure was zero. Prior to K_S measurements, soil samples were left to saturate from the bottom end. For each of the large columns (type-III), an end-cap assembly was attached to the bottom of the column together with an enclosed drainage system (Mallants et al., 1996b). Drainage water from this column could be collected in small sampling bottles via a polyethylene (PET) tube. The top boundary condition was established by allowing water to pond for a maximum depth of 0.01 m. Tensiometers were installed horizontally at six different depths, i.e., at 0.05, 0.15, 0.30, 0.45, 0.60, and 0.80 m below the soil surface. The pressure head was measured by pushing a hypodermic needle into a rubber membrane that was mounted on an air-filled reservoir. The needle was connected to a pressure transducer that converted the pressure to a digital value on a LCD screen (Thies-Clima, Germany). Once the soil was saturated from the bottom, water was then ponded on top of the soil surface and the water flux and pressure head were measured once a day for a period of approximately 20 days, when flow was at steady state. The average saturated conductivity for each column, K_S, was obtained from:

$$K_S = J_w L/(b+L) \tag{1}$$

where J_w is water flux (cm/h), L is column length (cm), and b (cm) is the height of water maintained on the top of the soil surface. Based on the observed pressure gradient between soil surface and any of the six tensiometer locations, saturated hydraulic conductivities can be calculated for any of the intermediate layers. Because of the purpose of the study, the comparison of K_S values for the Ap horizon using three different column sizes, we present here only K_S measured for the 0–0.15 m layer.

Type-II and type-III columns were also used for dye-staining and transport experiments (Mallants et al., 1994; Mallants et al., 1995a, Mallants et al., 1995b, Mallants et al., 1996c). After finishing the transport experiment for the type-II columns, a 2 L methylene blue (MB) solution (1 g/L) was applied under ponding conditions to a subset of 24 of the samples. After complete penetration of the dye solution, the soil column was drained to equilibrium for 24 h, with the top end covered to prevent evaporation. Next, the soil was removed sequentially to the depths of 2.5, 12.5, and 16.5 cm below the soil surface. Photographs were taken of each cross section. The photos were digitized using a color digital scanner, and subsequently the digitized images were analysed using image analysis software. On the basis of color, each pixel was classified as belonging either to the matrix or the macropore space, so that the total area occupied by stained macropores was calculated. A total of seventy photographs were analysed for this purpose.

2.2. Geostatistical procedures

Spatial variability in K_S and macropore area was investigated using the semivariogram estimator, $\gamma^*(h)$, as proposed by Matheron (1963):

$$\gamma^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i+h) - z(x_i)]^2 \tag{2}$$

where $N(h)$ the number of pairs separated by the lag distance h, and $z(x_1)$, $z(x_2), \ldots$, $z(x_n)$ are data values measured at spatial locations x_1, $x_2, \ldots$, x_n. If two or more regionalized variables, Z_1 and Z_2, are spatially inter-correlated, the cross variances are given by (Vauclin et al., 1983):

$$\gamma_{12} = \gamma_{21} = (1/2)E[Z_1(x) - Z_1(x+h)][Z_2(x) - Z_2(x+h)] \tag{3}$$

which can be estimated by

$$\gamma^*(h)_{12} = \gamma^*(h)_{21} = \frac{1}{2N(h)} \left\{ \sum_{i=1}^{N(h)} [z_1(x_i) - z_1(x_i+h)] \times [z_2(x_i) - z_2(x_i+h)] \right\} \tag{4}$$

where z_1 corresponds to K_S measurements and z_2 is macropore area. The cross semivariogram becomes useful when, for instance, two or more variables that are cross correlated have to be estimated using co-kriging at unsampled locations, where the primary variable is undersampled (because of higher level of difficulty and/or the cost involved) whereas the secondary variable (covariable) is far more easy to determine or has been routinely assembled during surveys (Yates and Warrick, 1987). In the present study we will investigate how saturated conductivity and macropore area are spatially cross-correlated. The outcome of such an analysis may be used to improve the quality of estimates of K_S in the field by using co-kriging with macropore area as the auxiliary random function.

3. Results and discussion

3.1. K_S variability

Spatial distributions of $\ln(K_S)$ for all three column types are shown in Fig. 1. Type-I and type-II represent detached column experiments, whereas conductivity measurements based on the type-III columns may be considered as attached column experiments because the effect of the underlying soil profile is included. Differences in the spatial variability in K_S between the three horizons for type-I columns have been discussed by

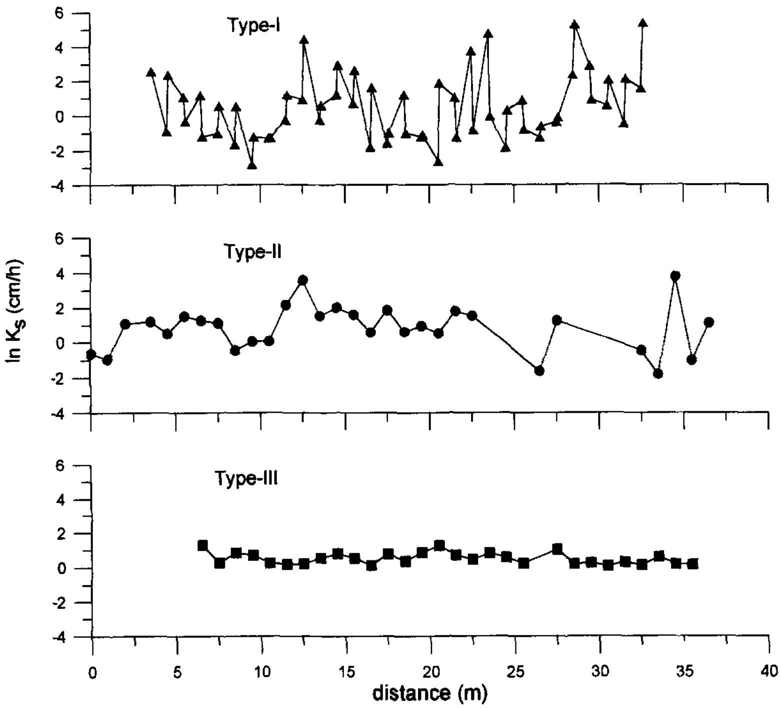

Fig. 1. Distribution of $\ln(K_S)$ for three sample volumes along the transect.

Table 2
Descriptive statistics of K_S (cm/h)

	Column type		
	I	II	III
Max.	217	43	1.27
Min.	0.06	0.16	0.04
Avg.	13.9	5.28	0.49
SD	41.2	9.50	0.34
Geometric mean [a]	2.24 A [b]	1.68 A	0.37 B
$\sigma^2 \ln(K_S)$	3.7	1.74	0.74
CV [c] (%)	619	217	105

[a] Geometric mean, $K_G = \exp(\mu(\ln K_S))$, was calculated because the distribution of K_S is log–normal.
[b] Values followed by the same capital letter are not significantly different at 0.05 probability level.
[c] $CV = (\exp(\sigma^2 \ln(K_S)) - 1)^{0.5}$.

Mallants et al. (1996a) and are not the point of the current paper, and so is not repeated. Although the volume of soil sampled by type-II columns is more than sixty times the volume for type-I columns, their geometric means are not significantly different (Table 2). Type-III columns had a significantly smaller geometric mean in comparison with the other two column types. Difference in K_S for the three column types indicates that the size of the columns significantly affects the spatial variability in K_S. With increasing sample size, both the variability and the mean of K_S decrease (Table 2). This behavior is mainly the effect of the increased vertical dimension of the cores, for the large mean and variability in K_S using type-I and to a lesser extend also type-II cores is determined by direct macropores. Especially the type-I cores exhibited a large coefficient of variation (CV = 619%) indicating that several cores might have more open-ended macropores than others. The term macropores here refers to pores without capillarity (Kutilek and Nielsen, 1994, p. 20). On the contrary, small mean and CV (105%) in K_S for type-III columns might indicate discontinuous macropores across the columns. Measurements on large columns such as used here will most likely produce K_S values more in agreement with in situ measurements. A similar relationship between column size and K_S measurements was reported by Lauren et al. (1988). Based on the method of Shapiro and Wilk (1965), the distribution of K_S was found to be better described with a log–normal than a normal probability density function (pdf) in all cases. For instance, for column type II, $W_{normal} = 0.964$ (Prob. $< W = 0.43$) for a log–normal distribution versus $W_{normal} = 0.492$ (Prob.$W < 0.0001$) for a normal distribution. The better agreement between ln-transformed data and a log–normal pdf is further exemplified by the fractile diagram shown in Fig. 2. Similar results were found for column size I and III (not shown here).

The relationship between sample volume and K_S measurement variability is an example of the REV (representative elementary volume) concept (Hubbert, 1956; Bear, 1972). The REV concept is defined as the smallest possible quasi-homogeneous domain for which a variable is invariant with respect to sample size. In soil science, the appropriate sample size varies from a fraction of a cm^3 (Greenwood and Goodman, 1967) to a m^3 (Helfesrieder et al., 1989). We evaluated the relationship between sample

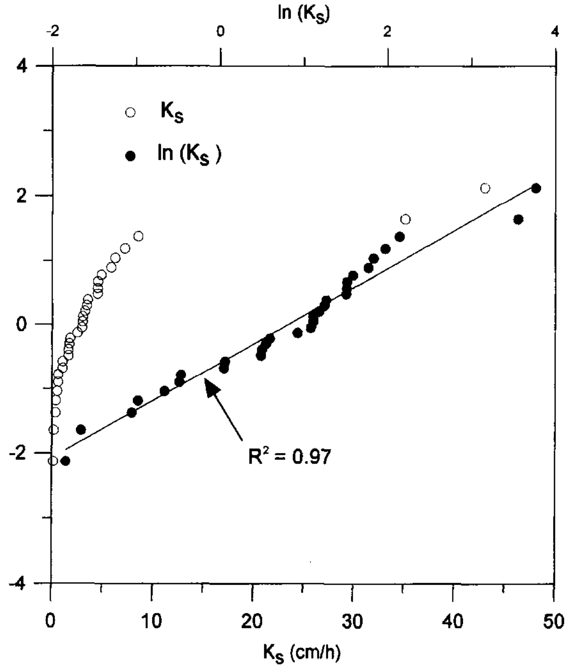

Fig. 2. Fractile diagram of K_S measured on type-II cores for raw and ln-transformed data.

size and soil structure for hydraulic measurements. By using small soil cores such as type-I columns, any open-ended macropores will cause direct piping and lead to larger K_S values in comparison with cores containing only bulk soil. With larger columns, a larger number of macro- and mesopores is sampled and thus the variability between sampling locations becomes smaller. The optimal sample size in terms of an appropriate REV can be estimated from soil structure units (Bouma, 1985). According to Bouma (1985) a REV should contain approximately 20 elementary units of soil structure (ELUS). However, such an elementary unit of soil structure may be difficult to determine in the field. From soil survey information we estimated the size of soil structure units to be 10–50 mm (medium to coarse subangular blocky, Soil Survey Staff, 1975) in the Ap horizon. In this case, an individual soil aggregate or ped has an estimated maximum volume of 125 cm^3, considering a cube as the best approximation of the peds geometry, thus requiring a REV of approximately 2500 cm^3. This approximation does not consider any anisotropy in the structure of the macroporosity, which may well influence the size of the representative elementary area (REA). The latter is the equivalent of the REV on a surface (Hassanizadeh and Gray, 1979). In other words, the REA may have been different for the horizontal and vertical directions. The REV thus estimated is more than two times smaller than the volume of soil contained in our type-II columns. In a similar study, Lauren et al. (1988) estimated for their soil a REV should have approximately 14000–16000 cm^3 soil, for peds with sizes ranging from 700 to 800 cm^3. This is considerably larger than our type-I and type-II columns. In order to contain a representative number of macropores, our type-I column therefore may have

Table 3
Descriptive statistics for percentage macropore area for three depths and averaged for the three depths. Area sampled was 314 cm^2

Depth (cm)	Mean (%)	SD (%)	CV (%)	Skewness [a]	N
2.5	3.00 [A]	1.96	65	0.67 (−0.13)	24
12.5	1.66 [B]	1.78	107	2.64 (−0.24)	22
16.5	1.62 [B]	1.76	109	2.16 (0.02)	24
Avg. [b]	2.32 [C c]	1.17	51	4.00 (0.56)	24

[a] Values between parentheses are based on logarithmic transformation.
[b] Mean of depth-averaged macropore area.
[c] Values followed by the same capital letter are not significantly different at 0.05 probability level.

been too small. Whether or not type-II columns contained a sufficient number of macropores can be estimated from the variability in macroporosity as observed from stained dye patterns (Table 3, to be discussed later). For each column we calculated the macropore cross-sectional area by averaging over the three observation depths. This depth-averaged macropore area is used to give a pseudo-3D estimate of pore continuity across the soil columns. The arithmetic mean of depth-averaged macropore area using 24 columns was 2.32%. A relatively low CV of 51% was found for depth-averaged macropore area. Similar CV values were also found for planar and cylindrical macropores by Lauren et al. (1988), using a sampling area twice as large as ours. The fairly low variability of macropore area obtained here suggests that a volume of approximately 6000–7000 cm^3 may be large enough to contain a representative number of macropores. Hydraulic conductivity measurements using column III gave lowest mean and smallest variability in K_S. Based on the above finding, the volume of soil contained in type-III column ($\sim$ 70000 cm^3) is large enough to produce reliable estimates of K_S for the Ap horizon. However, from a practical point of view, the use of column III is less attractive because of the higher labor cost and the sampling difficulties involved. On the other hand, pore continuity across horizons necessitates taking type-III columns which include the natural layering of the soil profile. In addition to preserving natural pore structure, and thus flow boundary conditions, the high sample volume will be more representative of field-scale flow and transport processes.

The above findings illustrate that in situ K_S measurements may be preferred over laboratory measurements. The former technique most likely will give more representative results because of preservation of soil structure, in addition to avoiding the occurrence of direct piping phenomena. Different K_S field measurement methods have been evaluated by Bouma (1983) and Amoozegar and Warrick (1986). On the other hand, laboratory measurements may be more desired if they are combined with other type of laboratory measurements which are difficult to carry out in the field, such as the collection of drainage data from an initially saturated soil profile, as was the case for our soil (Mallants et al., 1996b).

We calculated the number of samples required to estimate the mean K_S for the type-II column within 20, 30 and 40% of the true mean for different probability levels

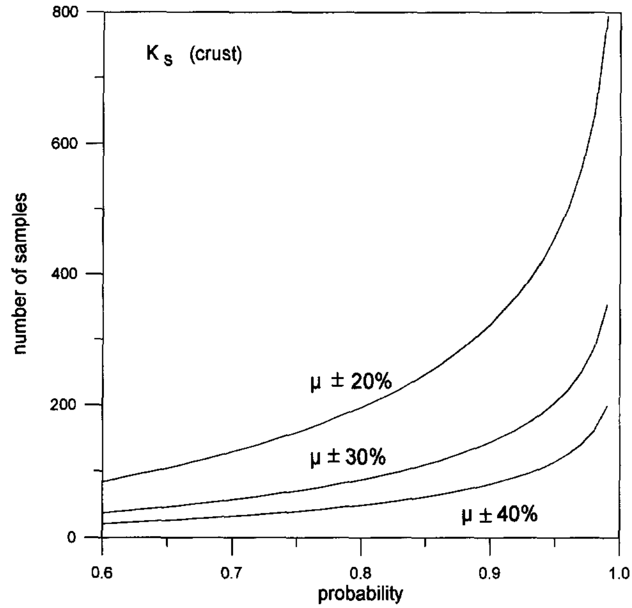

Fig. 3. Number of samples necessary to estimate the mean within 20, 30, or 40% of the true mean of K_s, for different probability levels.

(Fig. 3). All calculations are based on assuming a log–normal distribution for K_S. For estimates of K_S that are 20, 30, and 40% within the true mean for a probability of 90%, we need 324, 144, and 81 samples, respectively. Alternatively, if 50 samples were taken, the mean could be estimated within 40% of the true value, 80% of the time. When a similar analysis was made for the type-III columns assuming a log–normal distribution, it was found that 90% of the time, 74, 33, and 19 samples would be required to estimate the mean K_S within 20, 30, and 40% of the true value, respectively.

3.2. *Morphologic features*

A typical example of a digitized photograph of a horizontal 20 cm diameter section is given in Fig. 4. Evidently, the macropores are different in their size and shape. Both cylindrical and elongated pores were present. Fig. 5 shows the variability of the blue stained area with depth across the transect. The average macropore surface area decreased from 3% at 2.5 cm to 1.66% and 1.61% at 12.5 and 16.5 cm, respectively (Table 3). Probability density functions of macropore area were slightly better described with a log–normal than a normal distribution, as based on analysis of the skewness. This result may be due to the presence of horizontally oriented pores in some of the cross-sections, as in Fig. 4, which significantly increased the total macropore area. Our finding of log-normality of macroporosity differs from earlier findings of Lauren et al. (1988) who found a normal distribution for macropore populations. Relative variability

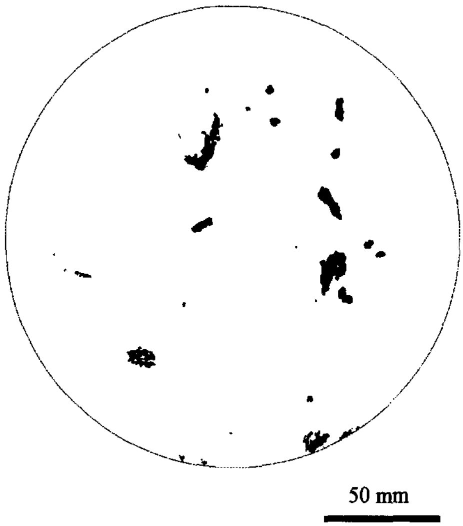

Fig. 4. Example of a digitized photograph of cross-sectional view of a soil column showing cylindrical and elongated macropores.

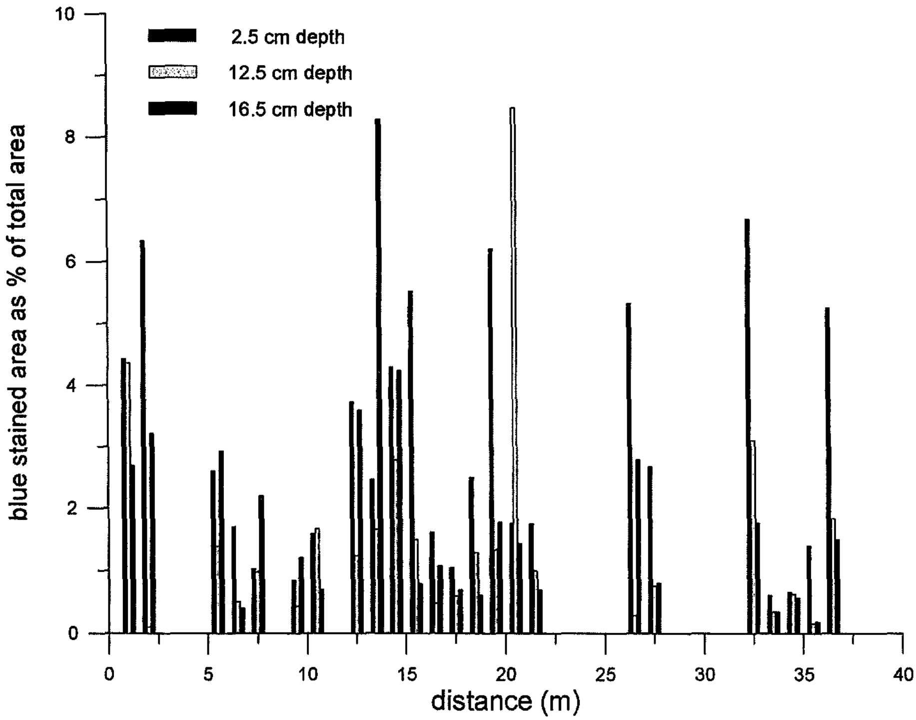

Fig. 5. Percentage blue-stained areas for three soil depths along the transect.

between samples was highest at the deepest depth (CV = 109% at 16.5 cm) and lowest at the shallowest depth (CV = 65% at 2.5 cm). This relatively low CV at the shallowest depth is due to the larger mean macropore area compared with the other depths. Variability of macropore area expressed in terms of the standard deviation (SD) decreases with depth (Table 3). Averaging the macropore area with depth significantly reduced the variability (CV = 51%). Similar results were reported by Lauren et al. (1988) for their silty clay loam soil. Regression analysis indicated a poor correlation ($r = 0.31$, not significant at 10% probability level) between $\ln(K_S)$ and percent macropore area at 16.5 cm depth. Using depth-averaged macroporosity values slightly increased the correlation with $\ln(K_S)$ to 0.37 (significant at 10% probability level). Separating the macropore area into vertical or horizontal oriented channels based on shape factors such as the ratio of pore area to the square of the pore perimeter (Bouma et al., 1977) may result in better K_S predictions. However, predictions of K_S based on morphological information will remain problematic, unless in some fashion, the three-dimensional pore continuity can be accounted for.

It is attractive to seek soil properties which can be used to predict K_S values, such as particle size distribution, or morphological parameters. These parameters could be cross-correlated to K_S and subsequently used in co-kriging in an attempt to better predict the spatial distribution of K_S in cases where only few K_S measurements are available but many observations of the co-variable (e.g., Lauren et al., 1988; Vauclin et al., 1983). The advantage of using macropore information in such an analysis is that it is relatively easy to determine. Measurements of staining patterns may also be obtained under field conditions (Lauren et al., 1988; Van Ommen et al., 1988) during soil surveys. They provide unique information on preferential flow paths under field conditions with only limited experimental effort. Our analysis suggests that macroporosity may be such a co-variable, although for this soil a low correlation was observed, presumably because of the inadequate representation of pore continuity. Other potential applications of macropore information are related to pedotransfer function development, for instance predicting the time of initial breakthrough in structured soil (Booltink et al., 1993).

3.3. Spatial analysis

Conventional geostatistical methods were used to analyse the spatial correlation of K_S for all three sampling volumes. Experimental semivariograms for $\ln(K_S)$ are given in Fig. 6. Weak spatial structure is observed for column I with an estimated range of 3.5 m, whereas columns II and III showed spatial correlation up to approximately 14 and 11 m, respectively. The pseudo periodicity in the type-I semivariogram, also referred to as hole-type function (Journel and Huijbregts, 1978, p. 248), indicates that zones of approximately 3.5 to 4 m wide repeatedly appear along the transect. The mean distance between these zones is 8 m, which corresponds to the abscissa of the minimum of the hole effect. This cyclic behavior is presumably the result of the specific history of the field, with large trees arranged in a regular configuration creating patterns of relatively higher macroporosity in a zone around the tree stem having plenty of tree roots. The

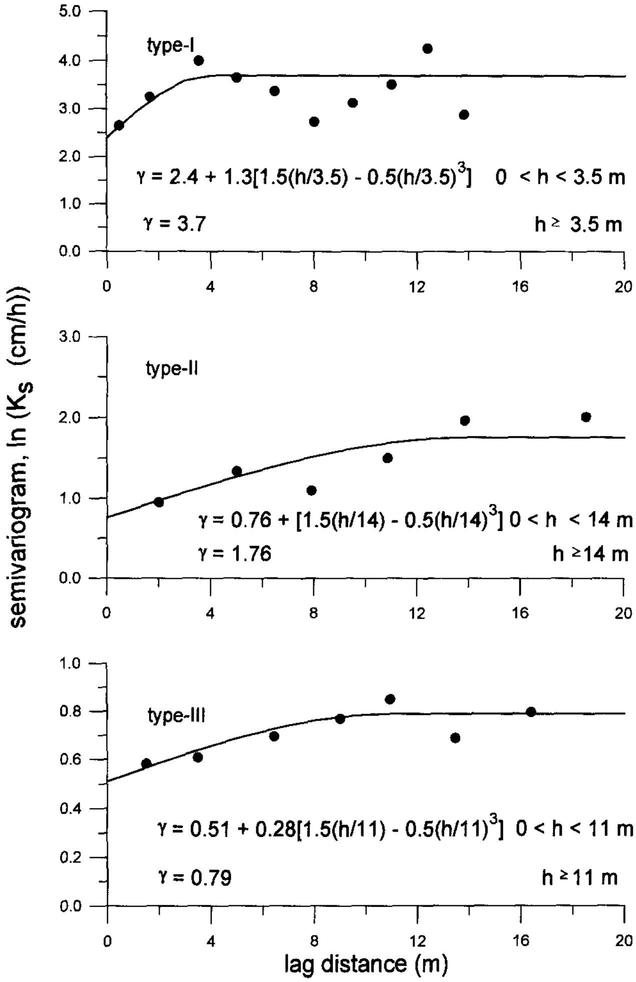

Fig. 6. Experimental and fitted theoretical semivariogram of ln(K_S) for sample type I, II, and III.

trees were removed some ten years before our sampling. The spatial behavior of columns I, II, and III could be described with a spherical model. Differences in semivariograms for type-I, type-II, and type-III columns are due to the small sampling volume used (100 cm^3) for type-I in comparison with the appropriate REV for type II and III. Large-range spatial structures of K_S may therefore go undetected if the volume of soil sample is smaller than REV. Measurements with type-I columns can be considered point observations, which could be used to study microheterogeneity. In type-II and -III, K_S spatial structure is inclusive any microheterogeneity as that found in type-I. In other words, for larger cores, it is a combination of large-scale structure and small-scale structure, whereas for smaller cores it is only the small-scale structure. Type-I columns exhibited the highest, type-III columns exhibited the lowest, and type-II

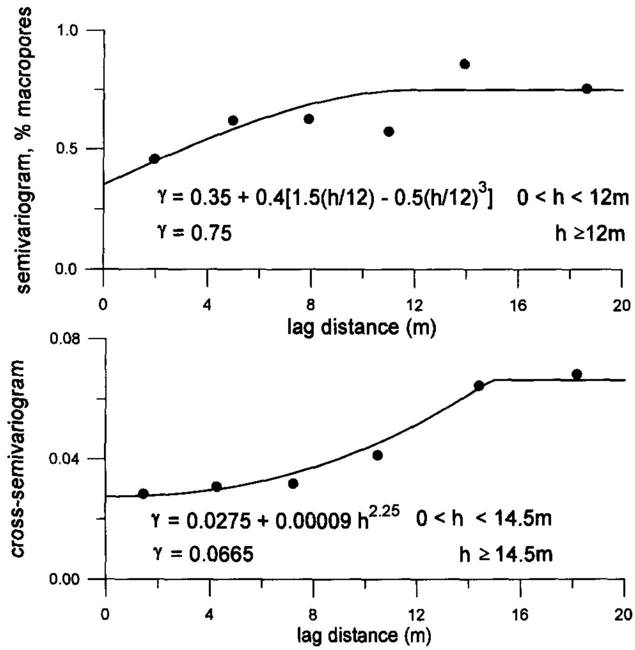

Fig. 7. Experimental and fitted theoretical semivariogram of ln-transformed depth-averaged blue stained area (in % of total area) (top), and cross-semivariogram between $\ln(K_S)$ and ln-transformed depth-averaged blue stained area (in % of total area) (bottom). Type-II columns were used for this purpose.

columns showed intermediate overall variance (sill value). For type-III columns, the nugget effect dominates, whereas for the type-II columns the structural component dominates the spatial variability. Because macropore variability is much more reduced in type-III columns, overall variability in K_S is smallest.

Fig. 7(top) shows the experimental semivariogram for ln-transformed depth-averaged macropore area, which could be described by means of a spherical model with a range of 12 m. Evidently, the range of spatial correlation for macroporosity is fairly similar to that for K_S measurements on the same cores (i.e., 14 m for type-II). Cross-semivariograms of K_S and depth-averaged macropore area, as in Fig. 7 (bottom) indicate positive spatial correlation between these two properties and can be described with a power model. This is in contrast to the earlier findings of Lauren et al. (1988) who found negative cross-semivariograms between the same properties. The difference in spatial behavior may be caused by the fact that we considered total macroporosity in the regression analysis. This includes staining patterns from horizontal ped faces and horizontally oriented macropores, which contribute only in a minor way to K_S, but their contribution to the total macroporosity was found to be high relative to the contribution of the circular pores (Timmerman et al., 1996). Using the same data set on staining patterns as discussed here, Timmerman et al. (1996) found that at the depths of 2.5, 12.5, and 16.5 cm, elongated pores accounted for, respectively, 64, 43, and 68% of total macropore area.

4. Conclusion

Measurements of K_S using type-I columns (5.1 cm long and 5 cm diameter) produced the largest variability because of the presence, or absence, of open-ended macropores in combination with a small sampling volume. This sampling volume may not have been large enough to encompass a REV. Type-II columns (20 cm long and 20 cm diameter) gave lower mean and variability for K_S compared with type-I columns. Because the macropore area of type-II columns still exhibited a moderate variability, and also because this column contained a sufficient number of elementary soil structure units, its size may have been close to encompassing sufficient ELUS to be a REV. The variability and the mean of K_S was further reduced for the type-III sample volume. Because of the increased sampling efforts involved, such columns may be impractical for routine investigations, making in situ measurements more attractive. However, if flow and transport studies across horizon boundaries are of concern, large columns that preserve the natural layering and macropore continuity are a prerequisite. In addition, laboratory soil columns allow the collection of data which may be difficult to obtain under field conditions, such as the spatial variability in the drainage process. Whether in situ measurements should be preferred over laboratory measurements thus depends on the purpose of the study.

Geostatistical analysis of K_S data revealed small range spatial structure or micro-heterogeneity for type-I columns whereas larger spatial structures were discovered in type-II and type-III columns. Spatial correlation existed between type-II K_S and depth-averaged macropore area. Soil structure parameters may be used as co-variable in the prediction of K_S for applications at field-scale, making the estimation of K_S more accurate and more efficient.

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