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## Abstract

Accurate in situ determination of unsaturated soil hydraulic properties is often not feasible because of natural variability of most field soils, and because of instrumental limitations. Therefore the soil hydraulic properties are often measured in the laboratory, or derived by computer models using simple standard laboratory methods.

This paper analyses problems in describing field hydraulic properties of a Ap horizon of a silty loam, basing on data from different laboratory methods: (i) A standard pressure plate apparatus and (ii) a constant-head permeameter were used to measure the static retention characteristics and the saturated hydraulic conductivity independently. (iii) An instantaneous profile method was applied to measure water retention and conductivity simultanously. Relatively new technics involving "undisturbed" soil samples instrumented with mini tensiometers and Time Domain Reflectometry (TDR) mini probes characterise the experiment. The models by Mualem and van Genuchten (MvG) were used to describe the soil hydraulic functions. The different laboratory results were then compared with the hydraulic field properties measured in instantaneous profile manner.

The laboratory method allows a high spatial and temporal resolution; this facilitates an investigation of some of the assumptions made, when fitting the MvG models to hydraulic data. A reasonably good description of the hydraulic data was obtained when setting the residual water content, $\theta_r$, to 0 and the pore connectivity factor, $l$, to 0.5 because $\theta_r$ and $l$ were not sensitive. However, a poor fit resulted when the saturated water content, $\theta_s$, was equated to the porosity, and the saturated hydraulic conductivity, $k_s$, to its independently measured value. Values for $\theta_s$ and $k_s$ derived from field measurements were somewhat higher than those obtained from laboratory samples.

To demonstrate the influence of the different input data on a water balance, the cumulative drainage from an initially saturated soil column was simulated with different sets of hydraulic parameters estimated from field and laboratory data. Parameters derived from the laboratory results consistently yielded lower predictions of cumulative drainage compared to hydraulic parameters derived from field measurements. The differences were relatively small when an initial water content corresponding to 60 cm suction (field capacity) was used.

'Dedicated to Prof. Dr. K. Bohne on the occasion of his 60th birthday



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## 1. Introduction

Our ability to mathematically model water and solute movement in the subsurface seems to be well ahead of our ability to accurately quantify the flow and transport properties of soils. This is particularly true for the unsaturated hydraulic properties involving the soil water retention, $\theta(h)$, and hydraulic conductivity, k(h), functions, where $\theta$ is the volumetric water content ( $cm^3 cm^{-3}$), $h$ is the soil water pressure head (hPa), and $k$ is the hydraulic conductivity (cm $day^{-1}$). In situ field measurements of the soil hydraulic properties are time consuming and costly. Moreover, the results are often unreliable because of experimental shortcomings and high spatial and temporal variability. Because of these problems, the unsaturated hydraulic properties are frequently determined in the laboratory, or estimated indirectly from other soil properties which can be measured more easily and accurately. A drawback of such alternative methods is, that they may yield values which are not representative for field conditions. Still, for many purposes, laboratory-measured data are helpful as a complement or substitute for field data since in situ measurements are usually not available at relatively low water contents, and ordinarily do not allow for the same spatial and temporal resolution as laboratory measurements.

The primary objective of this paper is to analyse problems in describing field and laboratory measured soil hydraulic properties using the RETC program. The laboratory data were obtained with an improved laboratory method for determining the unsaturated soil hydraulic properties. The 0(h) and *k(h)* curves were obtained on “undisturbed” samples from the Ap horizon of a silty loam instrumented with mini tensiometers and Time Domain Reflectometry (TDR) mini probes. The laboratory set-up is well-suited for accurately determining a large number of hydraulic data. Additionally, the water retention characteristic and the saturated hydraulic conductivity were obtained with pressure plate extractors and a constant-headpermeameter. The field hydraulic properties were determined in instantaneous profile manner, using neutron scattering and tensiometer with transducer.

Some of the advantages of closed-form analytical expressions for the hydraulic properties were summarized by Van Genuchten and Nielsen ( 1985) : (i) the ability to predict *k(h)* from (h) measurements; (ii) more convenient numerical simulations of flow and transport in the vadose zone; and (iii) comparisons, substitutions, or scaling of the hydraulic properties for different soils. The observed hydraulic properties in this paper are modeled with the expressions of Van Genuchten ( 1980). The program RETC (Van Genuchten et al., 1991) was used to obtain the hydraulic parameters by fitting the model parameters to observed field and laboratory data using different fitting conditions.

A secondary objective of this paper is to investigate the performance of the fitted hydraulic parameters in a numerical model for variably-saturated flow. The approach is somewhat similar to that used by Wösten et al. ( 1986) who evaluated the relative accuracy of hydraulic functions in terms of numerical predictions of such functional criteria as travel time, depth of water table, and downward water flux. In this paper we shall study the sensitivity of the predicted cumulative drainage to different parameter sets.

## 2. Materials and methods

### 2. 1. *Measurement of hydraulic properties*

A schematic of the experimental set-up for measuring the soil hydraulic properties in the laboratory is shown in Fig. 1. More detailed descriptions of the method are given by Malicki and Skierucha ( 1989) and Plagge ( 199 1) The laboratory procedure is based on a similar concept as the evaporation method by Wind ( 1966), modified by Boels et al. ( 1978) and Tamari et al. ( 1993). The improved technology provides a detailed description of $\theta$ and $h$ in time and space. The measuring cell consists of five pairs of sensors to measure $h$ and $\theta$ in 5 positions and time during the evaporation experiment. Each measuring cell consist of a 250 $cm^3$ core sampler, 10 cm high and 5.5 cm in diameter, to take undisturbed soil cores in the field. Table 1 provides some specifications of the tensiometers and the TDR equipment used as sensors for $h$ and $\theta$, respectively. The mini tensiometers are composed of a 2.8 mm diameter ceramic cell with an inner boring permitting quick response times, a brass tube, and a pressure transducer with a resolution of 0.2 hPa. Transducers are monitored by a real-time multitasking computer to control the measurement and collect data dependent to defined events. The used TDR system (EASY TEST Ltd.) is operating with a $2.0 \times 10^{-10}$ s rise-time needle pulse, supported by an Atari personal computer. The TDR mini probes consist of two 54 mm long stainless steel needles with a diameter of 0.8 mm, separated 5 mm from one another. The probes are connected by a 50 W cable to the TDR meter. For the experiments the standard deviation of the observed water content was about $\pm 0.006$ g $cm^{-3}$. The TDR probe and the tensiometer, aligned horizontally at an angle of 90°, are installed through a pair of trapped holes in standard sampling steel cylinders. Five pairs of sensors, vertical

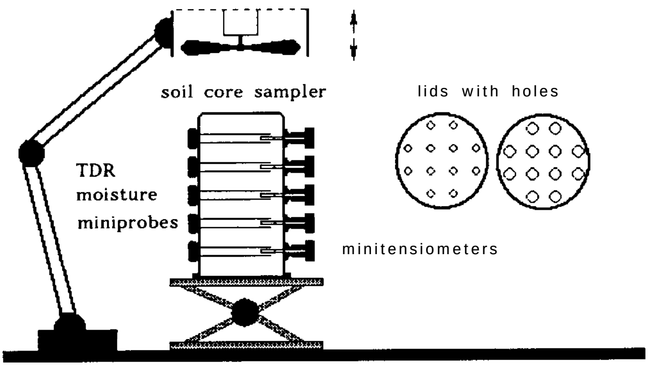


Fig. 1 Schematic diagram of the experimental apparatus for simultaneously measuring the hydraulic conductivity and soil water retention curves

Table 1
Properties of the tensiometers and TDR equipment

| | Tensiometry | TDR |
|---|---|---|
| Parameter | $h$ (hPa) | $\theta$ (%) |
| Measuring range | O-850 hPa | 0-100% |
| Resolution | 0.2 hPa | 0.6% |
| Spacial resolution | 2.8 mm x 15 mm | 7mm X 54mm |
| Contact surface or measured volume | 1.38 cm’ | 2.1 $cm^3$ |
| Total volume for equipment” | 0.13 cm’ | 0.03 $cm^3$ |

“Soil core volume 250 $cm^3$.

arranged, leads to five 2 cm thick soil layers. More technical details of the tensiometer and TDR system are given by Plagge ( 199 l), Malicki and Skierucha ( 1989) and Malicki et al. ( 1992). The volume occupied by all sensors was < 0.1% of the whole soil core volume. Fig. 2 shows a cross section of the measuring cell. The used TDR technique is applicable for soils with a salt content < 1 mS.

Undisturbed soil samples were taken at a mean depth of 1.5 cm from the Ap horizon of a silty loam from Ohlendorf, Germany. Some basic soil properties are listed in Table 2. The soil cores were water-saturated from the bottom during 3 weeks and then subsequently sealed at both ends before the sensors were carefully inserted from the sides. After the tensiometer and TDR readings indicated that the cores were in hydraulic equilibrium, the measuring cells were placed on a balance ( $\pm$ 0.01 g) to monitor the evaporation rate. The

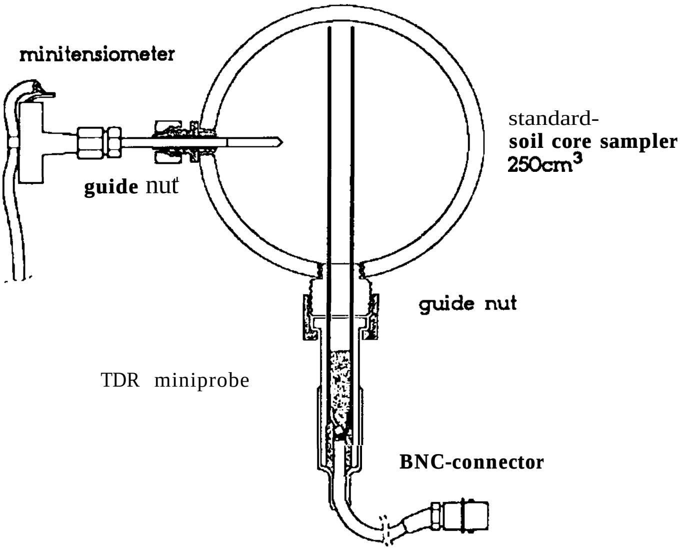


Fig. 2. Cross section of a measurement cell showing a TDR probe and a minitensiometer at a particular depth.

Table 2
Chemical and physical properties of the Ap horizon of a silt loam

| Parameter | Value |
|---|---|
| Depth | O-30 cm |
| *Particle size* | |
| < 2 $\mu$m | 9.2% |
| 2-6.3 $\mu$m | 81.2% |
| >63 $\mu$m | 3.6% |
| Bulk density | 1.37 g $cm^{-3}$ |
| Porosity | 0.487 $cm^3 cm^{-3}$ |
| $k_s$ | 35.0 cm $day^{-1}$ |
| Organic matter | 1 .0% c |
| pH ($CaCl_2$) | 6.3 |
| CEC | 11.2meq/l00g |

upper seal was subsequently removed and the soil subjected to controlled evaporation from the top using small ventilators. The experiment was terminated when the uppermost tensiometer in the soil core reached a suction of approximately 850 hPa. The measurements were conducted in a room with a controlled air temperature of 20°C. Unsaturated hydraulic conductivity values, k(h), were obtained from the transient head profiles and calculated water fluxes using Bezier fitting procedures for data smoothing (Sobczuk et al., 1992). The saturated hydraulic conductivity, $k_s$ was obtained from the geometric average of 20 replications measured with a constant-head permeameter (Hartge and Horn, 1989). The hydraulic properties in the field were determined previously by Duynisveld and Strebel ( 1983) according to the instantaneous profile method, using neutron scattering and tensiometers connected to pressure transducers.

### 2.2. *Mathematical description of hydraulic properties*

The water retention and hydraulic conductivity curves were described using the respective models (Van Genuchten, 1980) :

$$\theta(h)=\theta_r+\frac{\theta_s-\theta_r}{[1+(\alpha h)^n]^m} \tag{1}$$

$$k(h)=k_s\times\frac{\{1-(\alpha h)^{n-1}[1+(\alpha h)^n]^{1-m}\}^2}{[1+(\alpha h)^n]^m} \tag{2}$$

where $\theta_r$ and $\theta_s$ are the residual and saturated water contents ( $cm^3$ cm-‘), respectively; $\alpha$ is an empirical parameter ($cm^{-1}$) whose inverse is sometimes referred to as the air entry value, $n$ is a fitting constant reflecting the steepness of the retention curves, $m = 1 - 1/n$, and *1* is an empirical pore connectivity factor frequently set to 0.5 following Mualem ( 1976). For notational convenience, $h$ and $\alpha$ are assumed to be positive in this study (i.e., $h$ denotes suction).

Eqs. ( 1) and (2) contain up to six independent coefficients, represented by the parameter vector $b = \{\theta_r, \theta_s, a, n, 1, k_s\}^T$. We adopt the view by Van Genuchten and Nielsen ( 1985) and Luckner et al. ( 1989) that the different parameters are essentially empirical coefficients without much physical significance. Their values were estimated by fitting the retention and conductivity models to the observed data using the parameter optimisation program RETC of Van Genuchten et al. ( 199 1) . This program uses Marquardt’s maximum neighborhood method (Marquardt, 1963; Daniel and Wood, 1971) to minimize the objective function, *O(b):*

$$\min_b O(\boldsymbol{b})=\sum_{i=1}^{N}\left[\left(\theta_i-\hat{\theta}_i(b)\right)\right]^2+\sum_{i=N+1}^{M}\left[W_1W_2\left(k_i-\hat{k}_i(b)\right)\right]^2 \tag{3}$$

where $\theta_i$ and $\hat{\theta}_i$ are the observed and fitted water contents, respectively, $k$ and $\hat{k}_i$ are the observed and fitted conductivity data, N is the number of retention data, and $M$ is the total number of observed data points. The parameter $W_2$ is set by the optimization program to account for differences in the number of measurements and the adopted units of $\theta$ and $K$. The input parameter $W_1$ may be used to change the weight of the conductivity data in their entirety with respect to the retention data.

The parameters can be fixed at their initial estimates, or adjusted for a “best” fit during program execution. Better results are generally obtained when the number of unknown parameters can be limited by using independently determined parameters, or by carrying out a sequential fit by fixing those parameters which are found to be highly correlated with other parameters. The maximum number of iterations was set to 30, the input parameter $W_1$ to 1 .0. With these considerations in mind, Eqs. (1) and (2) were fitted to the observed $\theta$ and calculated $k$, assuming the following fitting scenarios:

(i) 1 is fitted (Case 1) or set equal to 0.5 (Case 2))
(ii) $\theta_s$ is maximal and set equal to the mean porosity, $\varepsilon$, of 0.487 $cm^3\,cm^{-3}$ (Case 3),
(iii) $k_s$ is fixed at 35.0 cm day-’ measured independently by the constant-head permeameter in the laboratory (Case 4),
(iv) $\theta_s$ is fixed at 0.487 $cm^3\,cm^{-3}$ and $k_s$ at 35.0 cm $day^{-1}$ (Case 5),
(v) $\theta(h)$ is fitted and K(h) is predicted assuming $k_s$ = 35.0 cm $day^{-1}$ and $l$ = 0.5 (Case 6).

2.3. *Modeling cumulative drainage*

A simple flow problem was simulated numerically to assess the implications of the different fitting scenarios. We selected the example of cumulative drainage from an initially

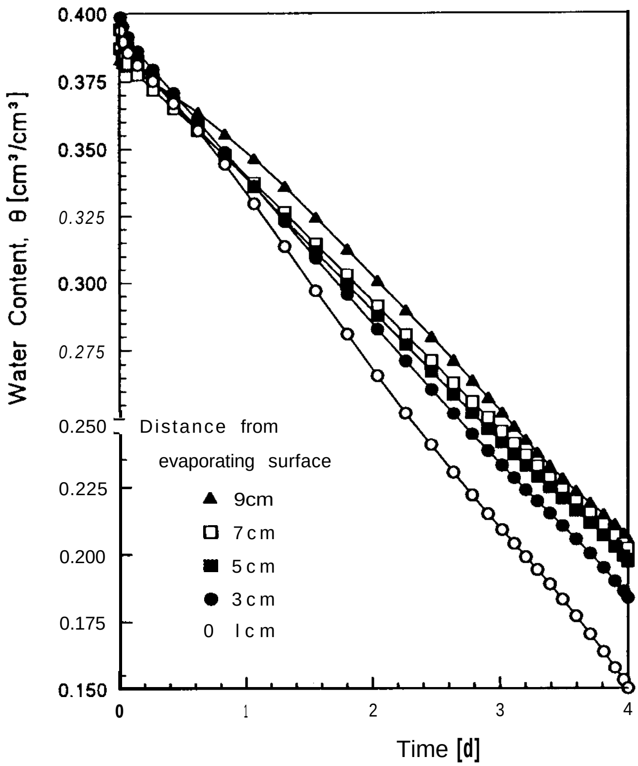


Fig. 3. Water content, measured with TDR at five positions in the soil column, versus time of evaporation.

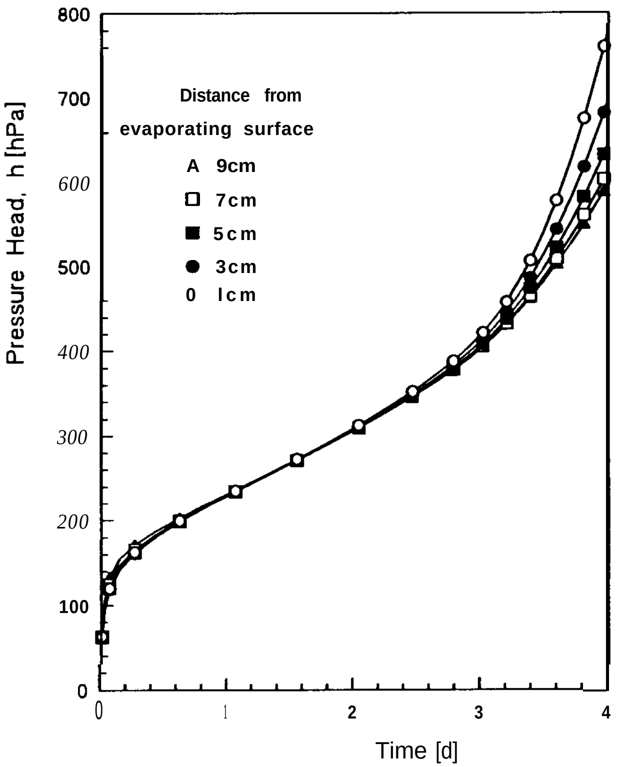


Fig. 4. Soil water pressure head, measured with tensiometers at five positions in the soil column, as a function of

saturated soil column (silt loam). Drainage was simulated numerically using the linear finite element code HYDRUS described by Kool and Van Genuchten ( 199 1) Two different initial soil water contents were used: (i) the water content at saturation, $\theta=\theta_s$, and (ii) the water content at a suction of 60 hPa, which we designate as field capacity ( $\theta=$ 0.33 cm $cm^{-3}$). The simulation involved cumulative drainage from a 30 cm long column over a 100 day period assuming a zero flux condition (no evaporation or infiltration) at the soil surface, and a zero pressure head condition (gravity drainage) at the bottom of the finite column. Cumulative drainage was predicted with parameter sets $\{\theta_r, \theta_s, a, n, l, k_s\}$ obtained by fitting the field or laboratory data using RETC assuming the aforementioned five fitting scenarios.

## 3. **Results and discussion**

### **3.1.** *Measurement of hydraulic properties*

As an example of the type of results obtained with the TDR mini probes, Fig. 3 shows a plot of the measured water content versus time for all five TDR positions in the 10 cm long

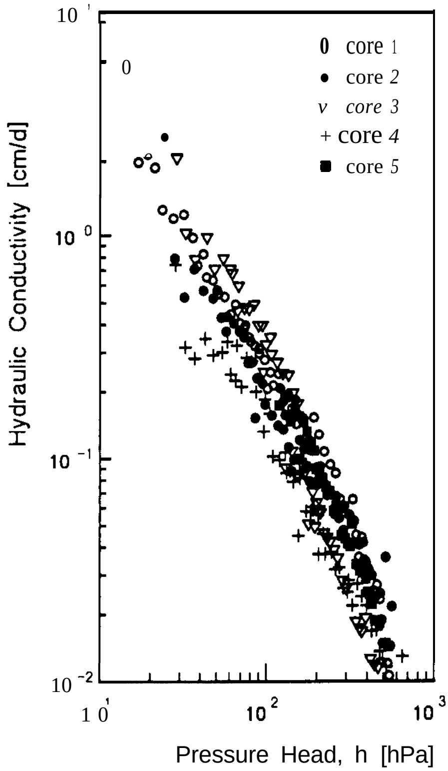


Fig. 5. Laboratory-measured hydraulic conductivity data as a function of pressure head for five samples

soil core. As expected, the largest decrease in water content occurred closest to the evaporating surface. Differences in pressure head at the various locations in the core become noticeable 2.5 days after the experiment started (Fig. 4).

The hydraulic conductivity was computed according to the instantaneous profile or unsteady drainage-flux method as outlined by Green et al. (1986). The evaporative flux was estimated from the overall column weight. Fig. 5 shows the measured K( h) determined on five different soil samples. The symbols in Fig. 5 represent results for five different cores over time and depth using averaging. The K(h) values appear to follow an approximately linear K-log h relationship for all samples. The considerable variability among the samples, especially in the wet range correspond to bulk density differences between the single samples.

### 3.2. *Hydraulic data analysis*

Figs. 6 and 7 show the observed and fitted water retention and hydraulic conductivity curves, respectively, for both the field and laboratory data. Because of the large number of data points measured in the laboratory, only average values of the variables h and $K$ for any particular value of $\theta$ and $h$, respectively, were plotted. Figs. 6 and 7 indicate a fairly close match between the observed and fitted data. The fitted curves were obtained by allowing all coefficients, except *1*, to vary in the parameter optimization process. Their values can be found under Case 1 in Table 3, which lists the fitted parameter values along with the correlation coefficient, $r^2$, and the objective function O(b) for all fitting scenarios. The field retention data exhibited more scatter than the laboratory data. The increased scatter may be attributed to the increased variability at the field scale, and to differences in accuracy and resolution in the observed $\theta$ and $h$ data. Because two different techniques were used to determine the laboratory retention data, the $(h)$ curve in Fig. 6 exhibits a slight discontinuity between 800 and 1000 hPa. the hydraulic conductivity data, as well as the fitted curves, were fairly similar for the field and laboratory experiments (Fig. 7). Higher values for the saturated water content, $\theta_s$, and saturated hydraulic conductivity, $k_s$, were found for the field data compared to the laboratory data. Initial optimizations of the data with RETC indicated that no "residual" water was present in both the field and laboratory determined retention curves. In accordance with the studies by Greminger et al. ( 1985), Wösten and Van Genuchten ( 1988), and Nimmo ( 199 1) , we therefore decided to fix $\theta_r$, to zero in all subsequent runs.

To assess the importance of $l$ as a fitting parameter, the parameter sets $\{\theta_s, \alpha, n, l, k_s\}$ (Case 1) and $\{\theta_s, a, n, k_s\}$ (Case 2) were fitted to the data. Table 3 indicates that the fitting was relatively insensitive to the value for $l$. A wide range of values has been reported for 1. For example, Schuh and Cline ( 1990) found values ranging from – 8.73 to

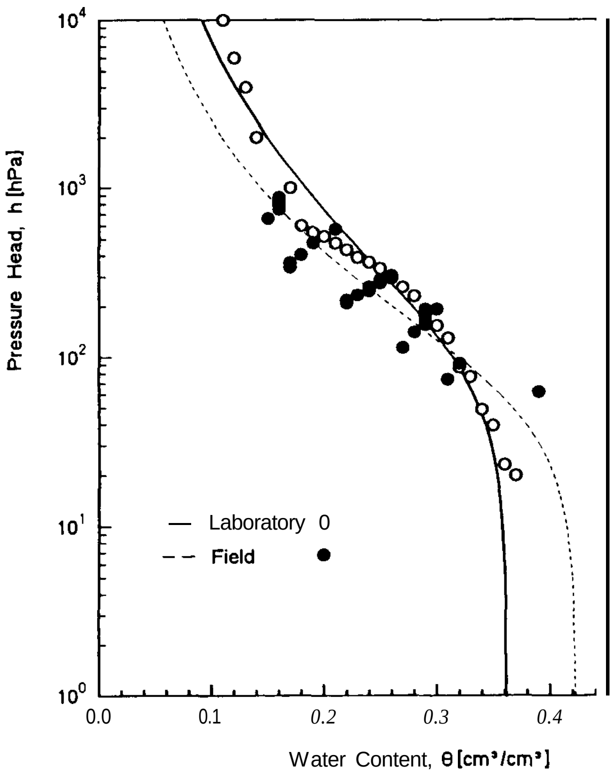


Fig. 6. Measured and fitted curves for the field and laboratory retention (Case 1; $\theta_r = 0$)

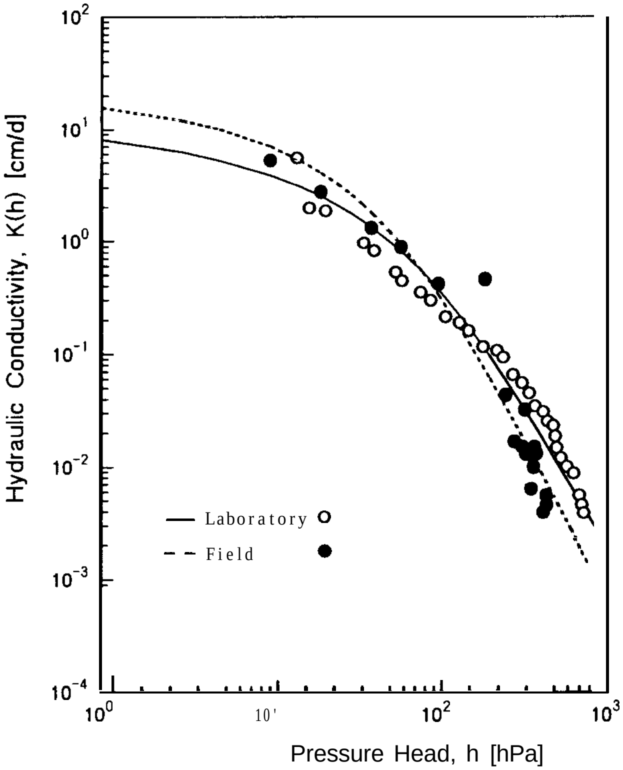


Fig. 7. Measured and fitted curves for the field and laboratory conductivity (Case 1; $\theta_r = 0$).

Table 3
Estimated hydraulic parameters for the Ohlendorf silt loam used in this study

| Case | | $\theta_s$ ($cm^3\,cm^{-3}$) | $\alpha$ (cm-‘) | $n$ | $k_s$ (cm $day^{-1}$) | $l$ | $r^2$ | $O(b) \times 10^3$ |
|---|---|---|---|---|---|---|---|---|
| 1 | Field | 0.386 | 0.010 | 1.42 | 18.0 | 1.87 | 0.980 | 4794 |
| | Lab | 0.353 | 0.007 | 1.31 | 12.2 | 1.07 | 0.981 | 5810 |
| 2 | Field | 0.422 | 0.014 | 1.40 | 22.9 | 0.50" | 0.978 | 4955 |
| | Lab | 0.362 | 0.008 | 1.31 | 13.7 | 0.50" | 0.981 | 5867 |
| 3 | Field | 0.487” | 0.017 | 1.45 | 33.8 | 0.50" | 0.976 | 5825 |
| | Lab | 0.487” | 0.014 | 1.36 | 36.2 | 0.50 | 0.972 | 15620 |
| 4 | Field | 0.446 | 0.018 | 1.38 | 35.0 | 0.50" | 0.858 | 1778 |
| | Lab | 0.364 | 0.012 | 1.25 | 35.0” | 0.50 | 0.978 | 6746 |
| 5 | Field | 0.487” | 0.017 | 1.45 | 35.0” | 0.50" | 0.976 | 5827 |
| | Lab | 0.487” | 0.014 | 1.36 | 35.0” | 0.50" | 0.972 | 15621 |
| 6 | Field | 0.446 | 0.018 | 1.38 | 35.0” | 0.50" | 0.954 | 4615 |
| [b] | Lab | 0.382 | 0.013 | 1.29 | 35.0” | 0.50" | 0.993 | 353 |

“Fixed parameters.
[b]Best fit for conductivity data only.

14.80, while Wösten and Van Genuchten ( 1988) reported values between – 16 and 2.2 for medium- and fine-textured soils. From these and other studies (e.g., Yates et al., 1992), it appears that the value of *1* has only a relatively small effect on the objective function, O(b). Therefore, as suggested by Mualem ( 1976), $l$ was fixed at 0.5 for the remaining cases.

For Case 3, the parameter $\theta_s$ was either fitted or fixed at a value equal to the porosity, $\varepsilon$, as measured on the same soil core for which the hydraulic properties were reported. When $\theta_s$ was set equal to $\varepsilon$, the fit resulted in a poor description of the retention curve. Fig. 8 shows that the retention curve is severely overpredicted in the wet range when $\theta_s$ was fixed to the measured porosity of 0.487 $cm^3\,cm^{-3}$. Fig. 9 demonstrates that the fitted K(h) curve, assuming $\theta_s$ to be equal to $\varepsilon$, also overpredicts the conductivity in the wet range, albeit less in comparison with the retention curve in Fig. 8. These results are consistent with the presumed presence of a "satiated" water content (e.g., Hillel, 1980) somewhat less than full saturation (or porosity, $\varepsilon$) because of entrapped or dissolved air. The relationship between $\varepsilon$ and $\theta_s$ depends on both soil type and the experimental procedure used for measuring $\theta_s$ For example, Ghosh ( 1976) used a value of $0.9\varepsilon$. It is our experience, however, that the hydraulic data are best described with a variable $\theta_s$ when a complete data set is available, rather than fixing $\theta_s$ at some arbitrary "field-satiated" value less than $\varepsilon$ or using a reduction factor.

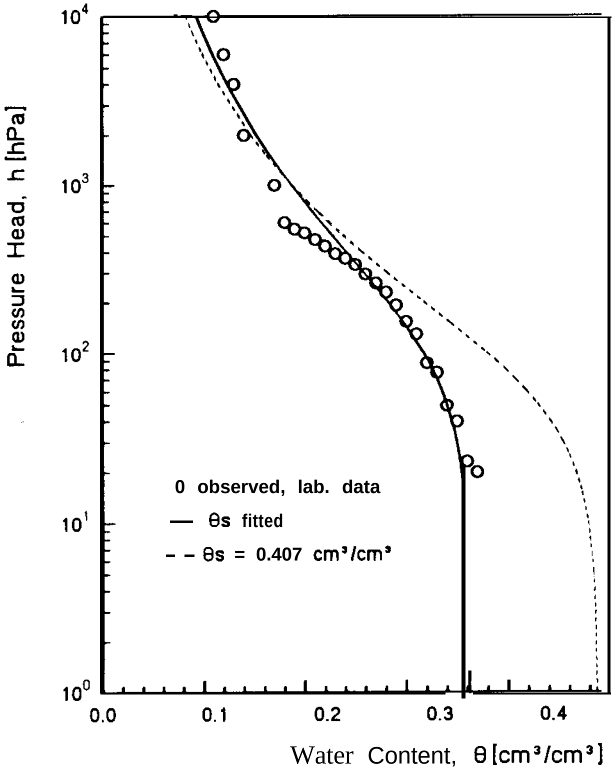


Fig. 8. Measured and fitted curves with $\theta_s$ fitted or fixed to the porosity for the laboratory retention (Case 3).

Statistical pore-size distribution or other theoretical models for predicting the hydraulic conductivity generally contain the saturated hydraulic conductivity, $k_s$, as a "matching" point (e.g., Mualem, 1986). Such an approach has become relatively standard, in part because $k_s$ is more easily measured than unsaturated K(h) values. Hence, the value for $k_s$ in the conductivity model is usually fixed during the optimization procedure. Case 4 involves the optimization of retention and conductivity data, where $k_s$ is either fitted or fixed to the value determined independently using the constant-head permeameter method. The results in Figs. 10 and 11 indicate a reasonably good fit for the laboratory data. However, the field data are relatively poorly described, as indicated by the low $r^2$ values in Table 3 (Case 4). This is in agreement with previous studies showing that $k_s$ should not be used as a matching point for the unsaturated conductivity curve (Van Genuchten and Nielsen, 1985; Vogel and Cislerova, 1988). Instead, and if available, a measured conductivity value at a water content somewhat less than saturation should be used as a matching point for the predicted curve. Such "matrix-K sat values" work much better than $k_s$ at, which is more an expression of structural porosity (Bouma, 1992).

In Case 5 we attempted to describe the hydraulic data with Eqs. ( 1) and (2) while fixing both $\theta_s$ and $k_s$ in the optimization process, i.e., fitting only $\alpha$ and $n$. The values of $\theta_s$ and $k_s$ were now both fixed to their independently measured values. Table 3 indicates that this Case resulted in a much poorer description of the data than if both were kept as unknowns

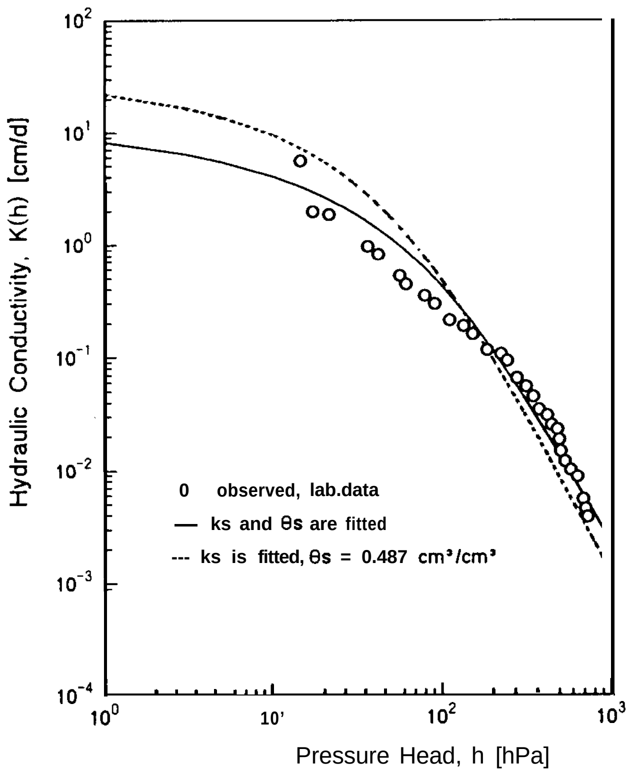


Fig. 9. Measured and fitted curves with $\theta_s$ fitted or fixed to the porosity for the laboratory conductivity (Case 3).

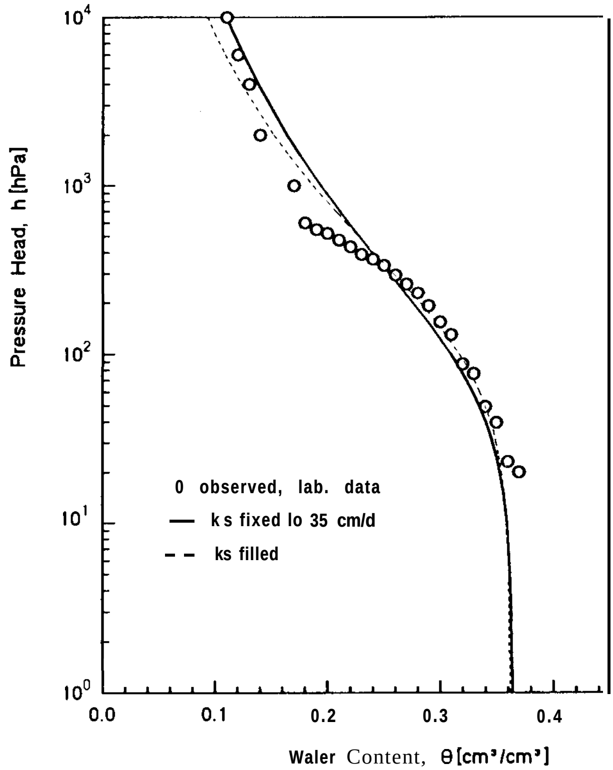


Fig. 10. Measured and fitted curves with $k$, fitted or fixed to the value measured with the constant-head permeameter for the laboratory retention (Case 4).

in the optimization (Case 2). This holds especially true for the laboratory data where the sum of squares given by Eq. (3) increases from 0.05867 to 0.15621. Relatively poor results should be expected when $k_s$ and especially $\theta_s$ are used as known parameters in the fitting process.

Finally, Case 6 in Table 3 involves the prediction of the K(h) function from measured $h$ and $k_s$ data, again assuming ***1= 0.5.*** This is a common approach since conductivity data are not widely available because they are more cumbersome to measure than retention data. The results in Table 3 indicate that the predicted ***K(h)*** describes the observed curve remarkably well, especially the laboratory data. In view of the previous results, the slight overprediction of the hydraulic conductivity using the independently measured $k_s$ value was to be expected.

### 3.3. *Drainage calculations*

The second objective of this study was to investigate the sensitivity of flow simulations to variations in the hydraulic parameter sets as obtained with the different optimization scenarios. Fig. 12 shows the simulated cumulative drainage from an initially saturated 30 cm long soil column using parameters from Cases I, 3, and 4. The numerical results for hydraulic parameters estimated from the field data (denoted by closed symbols in Fig. 12), yielded higher drainage rates than predictions made with parameters derived from the laboratory data. This difference is caused by the higher $k_s$ and $\theta_s$ values estimated from the field data. For the laboratory data the predicted cumulative outflow increased by 63 % when $\theta_s$ was set equal to the porosity (Case 3), and by 13% when $k_s$ was fixed at the measured value (Case 4), compared to the total drainage predicted using Case 1 parameters.

The drainage simulations assumed an initially completely saturated soil profile. Such conditions rarely occur in the field. For example, measurements by Duynisveld and Strebel ( 1983) for a similar soil as used in this study indicate that complete saturated conditions did not occur during a three-year period. Hence, the cumulative drainage simulations were repeated assuming an initial water content equivalent to an initial pressure head of – 60 hPa, or pF $\approx$ 1.8, which roughly corresponds to field capacity. Using the hydraulic parameters for Case 1, the simulated cumulative drainage amounts decreased significantly from those obtained when an initially saturated soil was assumed (Fig. 12). The differences between he laboratory and field-based predictions are also much smaller. This is to be expected since the water contents at – 60 cm for the field and laboratory cases are now very similar (Fig. 6). The results in Fig. 12, as well as those in Figs. 7-10, raise doubts about the usefulness of the parameters $k$,, and especially $\varepsilon$, to serve as matching or endpoints in

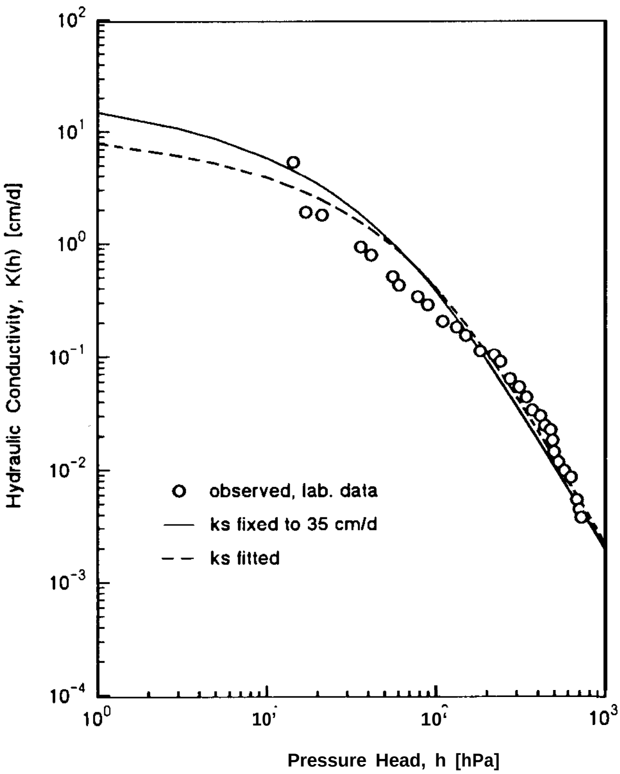


Fig. 11. Measured and fitted curves with $k_s$ fitted or fixed to the value measured with the constant-head permeameter for the laboratory conductivity (Case 4).

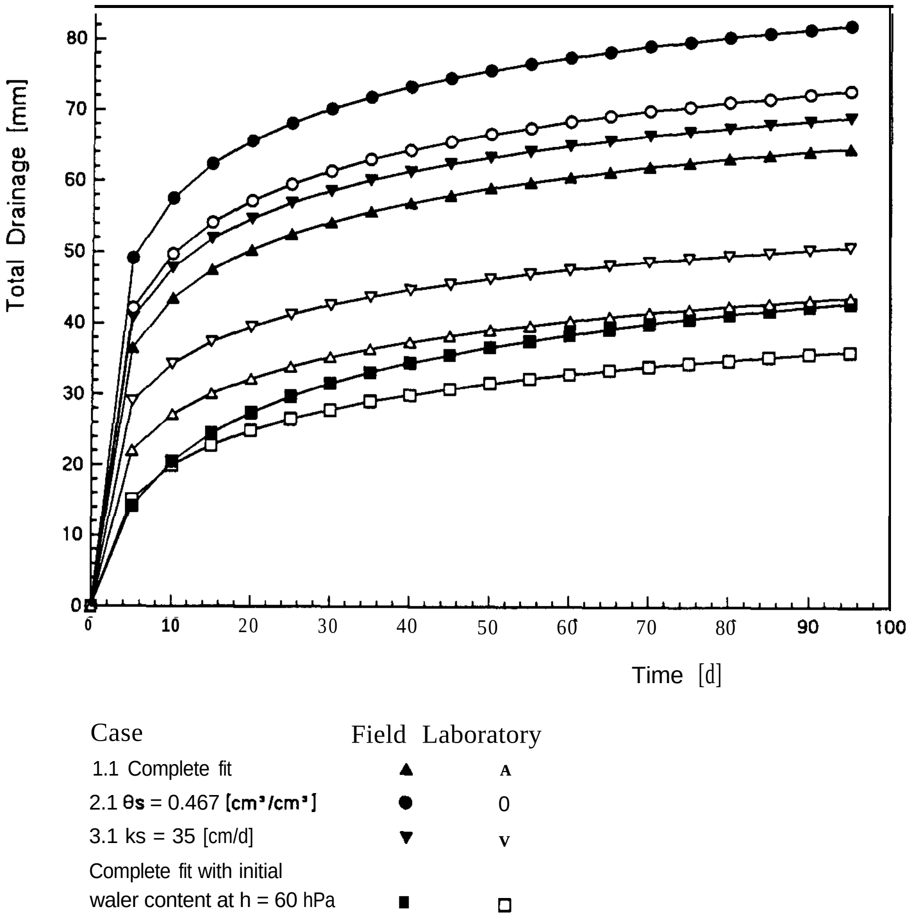


Fig. 12. Numerically predicted cumulative drainage assuming an initial water content at saturation or at field capacity, using parameter sets $\{\theta_s, \alpha, n, k_s\}$ obtained by fitting Eqs. (1) and (2) to laboratory data for various optimization scenarios.

the unsaturated hydraulic functions. Moreover, the great disparity of the simulated drainage curves in Fig. 12 shows that proper selection of the "saturated" conductivity and soil water retention values is not just a theoretical exercise, but can have important practical implications for simulating variably-saturated flow in the field.

## 4. Summary and conclusions

Soil water retention and hydraulic conductivity curves were determined by monitoring water contents and pressure heads with TDR and mini tensiometers, respectively, during forced evaporation from an "undisturbed" soil column. The method is relatively quick and provides hydraulic data with a high spatial and temporal resolution. Previously determined in situ field measurements of the hydraulic properties were included for comparison, The field data showed greater variability in the 13(h) and K( h) curves compared to the laboratory data. Still, the field- and laboratory-measured curves were reasonably similar over the range of measurements.

The program RETC was used to fit the model given by Eqs. ( 1) and (2) to the observed laboratory and field retention and conductivity data. Several fitting options were used to examine whether or not the number of fitting parameters could be reduced. Results were found to be relatively insensitive to the value for $l$, whereas good results were obtained when $\theta_r$ was set equal to zero. The best optimization resulted when $\theta_s$ and $k_s$ were fitted rather than fixed at independently measured laboratory values. A relatively good match with the conductivity data was also established when $K(h)$ was predicted from the measured $\theta(h)$, in conjunction with the measured $k_s$ value. However, for good results with RETC, the use of $\theta$ and $k$ near saturation (perhaps at $h \approx 10$ hPa) is the best way to avoid structural effects. However, for characterizing the flow regime, the flow through macropores should be separated from the one through the soil matrix (Bouma, 1982). Thus, additional measurements with other methods are needed.

The crust test by Boolting et al. ( 1991) may be one way to get these informations. Other methods to measure the matrix conductivity near saturation might be the use of a tension infiltrometer in the field. Nevertheless, our field experiences with the tension permeameter show that surface sealing and the use of a geometry parameter causes errors and in case of layered soils with stagnic horizons the interpretation of field data becomes difficult. In the laboratory, the use of the steady state evaporation method according to Plagge ( 1993) may be a better alternative to yield a $k(h)$ close saturation.

The fitted hydraulic properties were subsequently used as input in a numerical model simulating drainage from an initially saturated soil column. The simulated cumulative drainage from the column was higher for the field- than for the laboratory-derived hydraulic properties, primarily because of a higher estimated $\theta_s$ value for the field data. Using the porosity for $\theta_s$ significantly increased the predicted outflow. Similar drainage simulations with an initial water content roughly equivalent to field capacity resulted in much smaller differences in the predicted drainage for the laboratory and field hydraulic properties. The simulated drainage amounts in this case were also much less than those for the other cases with an initially saturated column.

The parameter estimation and drainage simulation results demonstrate again the necessity of new technics and methods to measure the soil hydraulic parameters near saturation in the field and laboratory.

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