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Unsaturated Hydraulic Conductivity determined by parameter estimation from One-step Outflow Experiments

Umættet hydraulisk ledningsevne bestemt ved parameter-estimering fra »one-step outflow«-eksperimenter

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Summary

A relatively simple method for determining the unsaturated hydraulic conductivity by parameter estimation from one-step outflow data and water retention data was used on 8 Danish soils chosen with regard to diversity in texture and geological origin. The van Genuchten parameters, α and θ_r, were determined from water retention data only, whereas n, θ_s and K_s were estimated from both water retention and outflow data. The unsaturated conductivities obtained were briefly compared to results from the hot air method used in another project. The conductivities estimated from the two methods agreed fairly well for most samples at pressure heads higher than approximately -200 cm H_2O. At pressure heads below -200 cm H_2O, the conductivities estimated from the hot air method were significantly higher than those estimated by the one-step outflow method. It is suggested how the parameter estimation method of *Kool et al.* (1985a) can be improved.

Key words: Unsaturated hydraulic conductivity, parameter estimation, one-step outflow, hot air method, van Genuchten model.

Resumé

En relativ simpel metode til at bestemme umættet hydraulisk ledningsevne ved parameterestimering ud fra »one-step outflow« og vandretentionsdata blev anvendt på prøver fra 8 danske jorde med spredning i såvel tekstur som geologisk oprindelse. Van Genuchten-parametrene, α og θ_r, blev bestemt alene ud fra vandretentionsdata, mens n, θ_s og K_s blev estimeret ud fra såvel »outflow«- som vandretentionsdata. De herved estimerede ledningsevner blev sammenlignet med resultater fra varmluftmetoden. Ledningsevner estimeret ved de to metoder stemte rimeligt overens ved vandpotentialer højere end ca. -200 cm. v.s.. Ved lavere potentialer var ledningsevnen bestemt ved varmluftmetoden betydelig højere end ved »one-step outflow«-metoden. Effektiviteten af parameteroptimeringsmetoden af *Kool et al.* (1985a) kan forbedres ved at øge udstrømningsperioden, at holde nogle af parametrene konstante i optimeringsproceduren, at bruge uafhængigt målte vandretentions-data, at bruge en stepvis sænkning af det pneumatiske tryk i stedet for en stor øjeblikkelig sænkning samt/eller at installere tensiometre i jordprøven.

Nøgleord: Umættet hydraulisk ledningsevne, parameterestimation, udstrømningsmetoden, varmluftmetoden, »van Genuchten«-model.

Introduction

In addition to the soil water retention characteristic, the hydraulic conductivity as a function of soil water content K(θ) is one of the most important relations for simulation of flow processes in the unsaturated zone such as infiltration, soil water redistribution, uptake of water by plants and evapotranspiration. Unsaturated hydraulic conductivity can be determined directly by laboratory or field methods from steady state flow experiments performed at several flow rates (e.g., *Nielsen et al.* 1960; *Bouma et al.* 1983). Transient flow experiments have also been employed for conductivity determinations using analytical or quasi-analytical solutions of the flow equation (e.g., *Arya et al.* 1975; *Dirksen* 1979). This will normally require restrictive initial and boundary conditions and give the hydraulic diffusivity as a result. Knowledge of the water retention characteristic for calculation of K(θ) is therefore needed.

Since such experimental procedures to determine the unsaturated hydraulic conductivity are quite laborious, several investigators have proposed models to compute the relative unsaturated hydraulic conductivity directly from the more easily measured soil water retention characteristic (*Childs* and *Collis-George* 1950; *Mualem* 1976). These models are based on the assumption of soil behaving as an equivalent capillary medium. Given a suitable functional relationship between the water content and the pressure head, closed-form expressions for K(θ) can be derived (e.g., *Brooks* and *Corey* 1966; *van Genuchten* 1980). A drawback of fitting such models to water retention data alone is that any error in the assumed model will be forced into the conductivity function.

Recently, attention has increased in the feasibility of determining the parameters in the hydraulic conductivity and the water retention functions simultaneously from transient flow measurements by parameter estimation techniques (*Zachmann et al.* 1982; *Hornung* and *Messing* 1982; *Dane* and *Hruska* 1983; *Kool et al.* 1985a; *Russo* 1988). The unknown parameters are estimated by minimizing deviations between observations and predictions. Such problems are usually stated as the inverse problem.

Kool et al. (1985a) have proposed a parameter estimation procedure involving measurements of cumulative outflow against time from an undisturbed soil core with a saturated porous plate at the bottom. The sample is subjected to a large "one-step" pneumatic pressure increase. The laboratory procedure is similar to the one-step outflow method by *Doering* (1965). The optimization method of *Kool et al.* (1985a) has shown problems with highly correlated parameters and non-uniqueness. Non-uniqueness occur when several local extrema exist for the optimization, and in this case the estimated parameters will depend on the initial guess of the parameters. It may therefore be necessary to fix some of the parameters in the optimization and to use more data in the fitting procedure.

In the present work parameter estimation is investigated for one-step outflow measurements combined with water retention data. The unsaturated conductivities obtained are briefly compared to results from the hot air method as used by *Jacobsen* (1989).

Theory

Direct problem

Water flow in a one-step outflow experiment can be described by Richards' equation

$$C\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial\psi}{\partial z} - 1\right)\right] \tag{1}$$

subjected to the following initial and boundary condition:

$$\psi = \psi_o + z \qquad t=0, \quad 0 \le z \le L \tag{2a}$$

$$\frac{\partial\psi}{\partial z} = 1 \qquad t>0, \quad z=0 \tag{2b}$$

$$\psi = \psi_L - \psi_{pn} \qquad t>0, \quad z=L \tag{2c}$$

$C \equiv d\theta/d\psi$ is the water capacity (L^{-1}), z is the vertical distance taken positive downward (L) with z = 0 at the top of the soil core and z = L at the bottom of the porous plate, t is time (T), ψ is the pressure head (L), ψ_o is the pressure head at the top of the soil core at the start of the experiment, ψ_L is the pressure head at the bottom of the porous plate, and ψ_{pn} =

$\Delta p/\rho g$, where Δp is the instantaneous increment in pneumatic pressure in the pressure chamber ($ML^{-1}T^{-2}$), ρ is the density of water (ML^{-3}), and g is the gravitational acceleration (LT^{-2}).

The initial condition (Eq. 2a) describes the start situation, where the soil core is drained to equilibrium with pressure head, ψ_o, at the top of the core, and with the pressure head increasing with depth due to the contribution of gravitaty. The boundary condition (Eq. 2b) describes a zero-flux condition at the upper boundary (e.g., insert Eq. (2b) in Eq. (1)). The pneumatic potential is assumed instantaneously to propagate through both the soil and porous plate and thereby to be effectively translated to the lower boundary condition, but with the total head adjusted for the pressure head at the bottom of the porous plate.

Eqs.(1-2) can be solved for the two-layer system (i.e., soil and plate) by numerical methods (*Kool et al.* 1985b). Since the porous plate remains saturated during the experiment, the flow in the plate will only depend of its saturated hydraulic conductivity and the gradient in pressure head.

Cumulative outflow, Q(t), can be calculated from the net change in the amount of water within the soil column after the increment in pneumatic pressure

$$Q(t) = A \left[\int_0^L \theta(z,0)\,dz - \int_0^L \theta(z,t)\,dz \right] \tag{3}$$

where A is the cross-sectional area of the core (L^2).

The water retention characteristic is assumed to be described by the model of *van Genuchten* (1980), Eq.(4), which inserted in the conductivity model of *Mualem* (1976) gives Eq.(5).

$$S_e = \begin{cases} \dfrac{1}{\left[1 + |\alpha\psi|^n\right]^{1-1/n}} & \psi < 0 \\ 1 & \psi \geq 0 \end{cases} \tag{4}$$

$$K = K_s\, S_e^{\gamma}\left[1-\left(1-S_e^{n/(n-1)}\right)^{1-1/n}\right]^2 \qquad (5)$$

and

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

where S_e is the effective saturation, θ_r and θ_s are residual and saturated volumetric water contents, respectively. K_s is the saturated hydraulic conductivity, and α, n and γ are empirical parameters. *Mualem* (1976) estimated γ to be approximately 0.5 for most soils. In this study this parameter is kept constant at that value. In practice, K_s, θ_r and θ_s must be considered somewhat empirical (*van Genuchten* and *Nielsen* 1985), and can only be used in the range of pressure heads significant for the experiment. The impact of changing α and n on the shape of the pF-curve is illustrated in Fig. 1. α is related to the air-entry tension and n to the width of the pore-size distribution (*Kool et al.* 1985a).

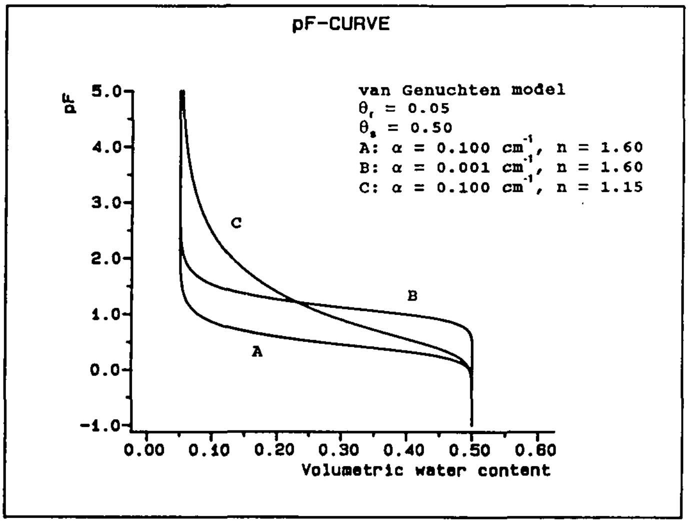

Fig. 1. pF-curves calculated by the van Genuchten model for various values of α and n.

The unsaturated hydraulic conductivity, $K(\theta)$, can be expressed as a function of pressure head if Eq.(4) is substituted into Eq.(5). An expression for $C(\psi)$ is obtained by differentiating Eq.(4). Eqs. (4-6) therefore define the relationships necessary for solution of Eqs.(1-3) in terms of the parameters α, n, θ_r, θ_s, and K_s.

Inverse problem

Solving the inverse problem for this case implies finding the best combination of the parameter estimates in the direct problem for a given set of experimental data. In this study, the soil hydraulic properties were determined by an iterative optimization procedure proposed by *Kool* and *Parker* (1987b). The best combination of parameter estimates was found by minimizing the objective function:

$$E(b) = \sum_{i=1}^{N} \left[w_i \left\{ Q(t_i) - \hat{Q}(b,t_i) \right\} \right]^2 + \sum_{j=1}^{M} \left[v_j \left\{ \theta(\psi_j) - \hat{\theta}(b,\psi_j) \right\} \right]^2 \tag{7}$$

where $Q(t_i)$ is the cumulative outflow measured at time t_i, $\hat{Q}(b,t_i)$ is the cumulative outflow calculated from Eqs.(3-5) corresponding to the trial parameter vector b = (α, n, θ_r, θ_s, K_s). $\theta(\psi_j)$ is the measured water retention data, $\hat{\theta}(b,\psi_j)$ represents the water content for the trial parameter vector b calculated from Eq.(4), and w_i and v_j are weighting factors. Using w_i = 1 for all i, the difference $\theta(\psi_j)$-$\hat{\theta}(b,\psi_j)$ can be weighted by

$$v_j = \frac{\left(\dfrac{\sum_{i=1}^{N} Q(t_i)}{N} \right)}{\left(\dfrac{\sum_{j=1}^{M} \theta(\psi_j)}{M} \right)} \tag{8}$$

for all j, which gives the $\theta(\psi_j)$-values nearly the same weight as the $Q(t_i)$-observations (*Kool* and *Parker* 1987b). For more details, see *Kool* and *Parker* (1987b; 1988).

Eqs.(7-8) are solved by adjusting the parameters until the weighted sum of squares is minimized. These parameters can then be substituted into Eqs.(4-6) to give the $\theta(\psi)$ and $K(\theta)$ relations for the soil.

When parameters are highly correlated, a change in one is balanced by a corresponding change in the other(s). The result is that neither can be determined accurately. Therefore it can be necessary to fix some parameters in the optimization and to use more data in the fitting procedure.

Parameters, in this study were estimated using the computer program SFIT by *Kool* and *Parker* (1987b). SFIT is a flexible program for determination of hydraulic properties from one-dimensional transient flow experiments. It may take into account hysteresis and air entrapment (*Kool* and *Parker* 1987a), and a variety of initial and boundary condition can be specified in the input file. Experimental input may consist of measured water contents and/or pressure heads at different times and depths and/or cumulative infiltration or drainage with time. In addition, input may include equilibrium water retention data.

Method and materials

Eight Danish soils were chosen with regard to diversity in texture and geological origin. The soils from Kalø, Rønhave, Årslev, Ødum and Foulum are developed from moraine deposits, Højer and Tylstrup from marine deposits, and Jyndevad from glaciofluvial deposits. Geological description of most of the soils are given by *Nielsen* and *Møberg* (1984, 1985). Textural composition is shown in Appendix A. Bulk density and particle density are reported by *Jacobsen* (1989). Undisturbed soil samples (6.10 cm diameter, 3.42 cm length) were taken at depths of 10, 30, 50, 70, 90 cm using steel cylinders. For Jyndevad the upper two depths were 5 and 15 cm. For details in the sampling programme, see *Jacobsen* (1989). The water retention characteristics were determined by using sandbox equipment and pressure chambers as described by *Schjønning* (1985). Saturated hydraulic conductivity was determined in the laboratory applying the constant head method as described by *Rasmussen* (1976).

For the unsaturated hydraulic conductivity determination by the one-step outflow method, undisturbed soil samples (not the same as used for the water retention and saturated conductivity determination) were brought to water saturation and then drained to -20 cm H_20

(middle of the sample) by using sandbox equipment. The samples were placed in a pressure chamber (Model 1250, Soilmoisture Equipment Corp.) on a saturated ceramic plate with an air-entry value of 2000 cm H_20 and with a saturated hydraulic conductivity measured to be 4.69×10^{-9} m/s. Figure 2 shows the experimental setup.

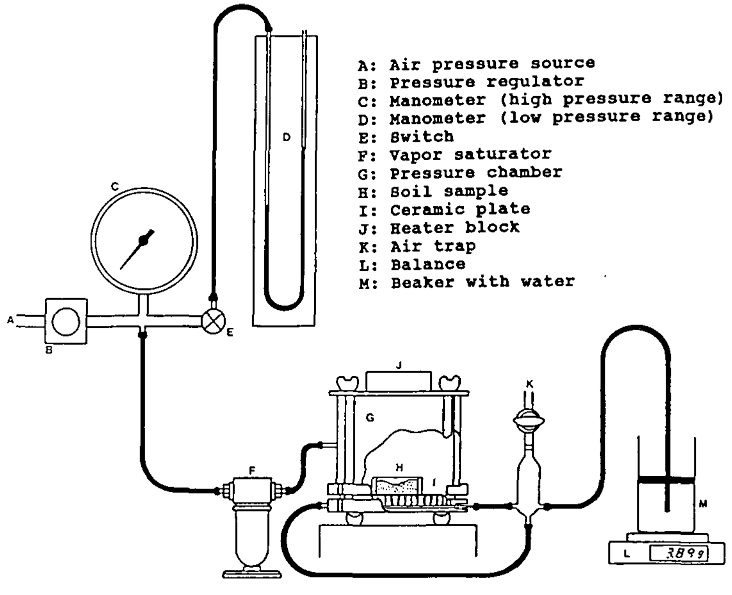

Fig. 2. Schematic diagram of the experimental setup.

The sample and ceramic plate were brought in to capillary contact by wetting the plate with a small amount of water. Afterwards the added water was quickly removed. After re-equilibrating the sample at -20 cm H_20, the pneumatic pressure was increased instantaneously to 1000 cm H_20, and cumulative outflow was recorded periodically for about 20 hours. Due to uniqueness problems in calculation when using this relatively short outflow time, additional samples from two locations (Jyndevad and Rønhave) were investigated using outflow time of approximately one week. The outflow was measured by a precision balance (Fig. 2). The vapor saturator (Fig. 2) saturates incoming air so that there is no drying effect on the sample being tested. The heater block (Fig. 2) delivers a small source of heat to maintain the walls of the extractor at a slightly higher temperature than the soil sample to eliminate condensation on the inside walls of the extractor. To prevent evaporation from the beaker during the experiment an oil film was placed on the water. A water density of 1.00 g/cm^3 was used in calculations. The weight of water was adjusted for the buoyancy on the tube from the outflowing water in the beaker.

In general, two samples from each depth were investigated. For Kalø only samples from a depth of 70 cm were investigated. Due to layering in the subsoil only samples from 10 and 30 cm depth were used from Højer. For Rønhave and Jyndevad, additional about two samples from each depth were investigated at about one week of outflow time. All samples were controlled for a smooth surface to ensure a good contact with the ceramic plate for the entire surface. Because of this two additional samples were not left for all depth. A few of the samples were not used in the calculation because the outflow were unrealistic compared to the porosity of the samples. It was believed to be due to experimental or data collecting error.

In the same sampling programme samples were collected for determination of the unsaturated hydraulic conductivity by the hot air method (HAM) (*Arya et al.* 1975) as reported by *Jacobsen* (1989). The calculation procedure as proposed by van *Grinsven et al.* (1985) using the conductivity function of *Wind* (1955) (Eq. 9) was used in that study.

$$K(\psi) = a\,|\Psi|^{-b} \tag{9}$$

For further details about procedure and results, see *Jacobsen* (1989).

Results and discussion

Figure 3 shows an example of the cumulative outflow curves for Rønhave and Jyndevad. Water is released more readily from the Jyndevad sample at the start of the experiment as compared to the sample from Rønhave. Later on, nearly all of the water is released from the samples. However, after a week some outflow does still occur, but at a much lower rate. This reflects both a lower unsaturated hydraulic conductivity at lower water contents and lower pressure head gradients.

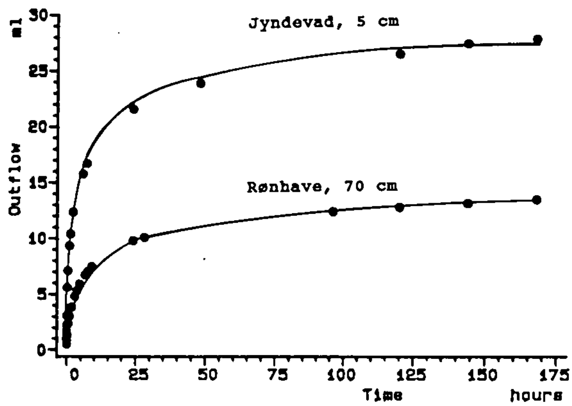

Fig. 3. Measured cumulative outflow (•) and predicted outflow by parameter estimation (——) for a coarse sand (Jyndevad) and a sandy loam (Rønhave).

As a first approach only the outflow data was used in the fitting procedure. But the resolution of the outflow curves were too small and often the optimization broke down due to uniqueness problems or because the parameters were too highly correlated. Even with several parameters fixed, the correlation coefficient could still be more than 95% between some of the parameters. Independently measured equilibrium water retention data were therefore included in the input data.

The following approach was used. First, the parameters in Eq. (4) (α, n, θ_r and θ_s) were fitted to the water retention data. Then α and θ_r were fixed and n, θ_s and K_s were obtained by a simultaneously fit to outflow data and water retention data. θ_r was fixed since it is quite insensitive to this kind of outflow data (*Kool et al.* 1985a). α was fixed due to an often very high correlation coefficient between α and K_s. This high correlation was not found for the experimental data from Jyndevad, and α was not fixed in the estimation procedure for the samples from this coarse sandy soil. Saturated hydraulic conductivity of the soil samples was measured but not used as a fixed parameter, since it is very sensitive to the macro structure of the soil sample. It may therefore not reflect the properties of the soil matrix, which determine the unsaturated hydraulic conductivity.

It could be argued, that the above approach is close to predicting the unsaturated conductivity from equilibrium water retention data only. But it is important to remember, that when the parameters are highly correlated, different sets of parameters can give a good model description when fitting to the water retention characteristic only. Any error in the assumed model will be forced into the conductivity function. Therefore, using transient flow data in the fitting procedure will significantly improve the reliability of the estimated parameters.

In Fig. 4a the estimated hydraulic conductivity is shown as a function of the pressure head for 10, 30 and 70 cm depth in Rønhave. The corresponding pF-curves are shown in Fig. 4b. The similar graphs for Jyndevad are shown in Fig. 5. Measured saturated hydraulic conductivity is shown in the figures, but was not used in the fitting procedure. Results from other locations and estimated parameters for all locations and depths are shown in appendix C and B, respectively. At the pF-curves in Fig. 4b and 5b circles represent the measured points, and the dashed lines are calculated by the van Genuchten model (Eq. 4) with parameters obtained by the simultaneous fit to the outflow data and the water retention data. Total porosity as calculated from measured dry bulk density and particle density is shown at a pF-value of -1.0 but was not used in the fitting procedure, because it will usually be higher than the saturated water content due to, among other things, air entrapment (*Kool & Parker* 1987a).

For Rønhave the hydraulic conductivity at -20 cm H_20 pressure head is in most cases around 10^{-7} m/s in 10 cm while it is around 10^{-8} m/s in 30 and 70 cm (Fig. 4a). This difference can be explained by the lower content of clay and higher content of organic matter in the upper soil, which gives a higher proportion of larger pores with easier water transport at relatively high water content. This is also reflected in the pF curves (Fig. 4b). In addition, the effect of soil tillage that loosens the soil and gives relatively a higher amount of larger

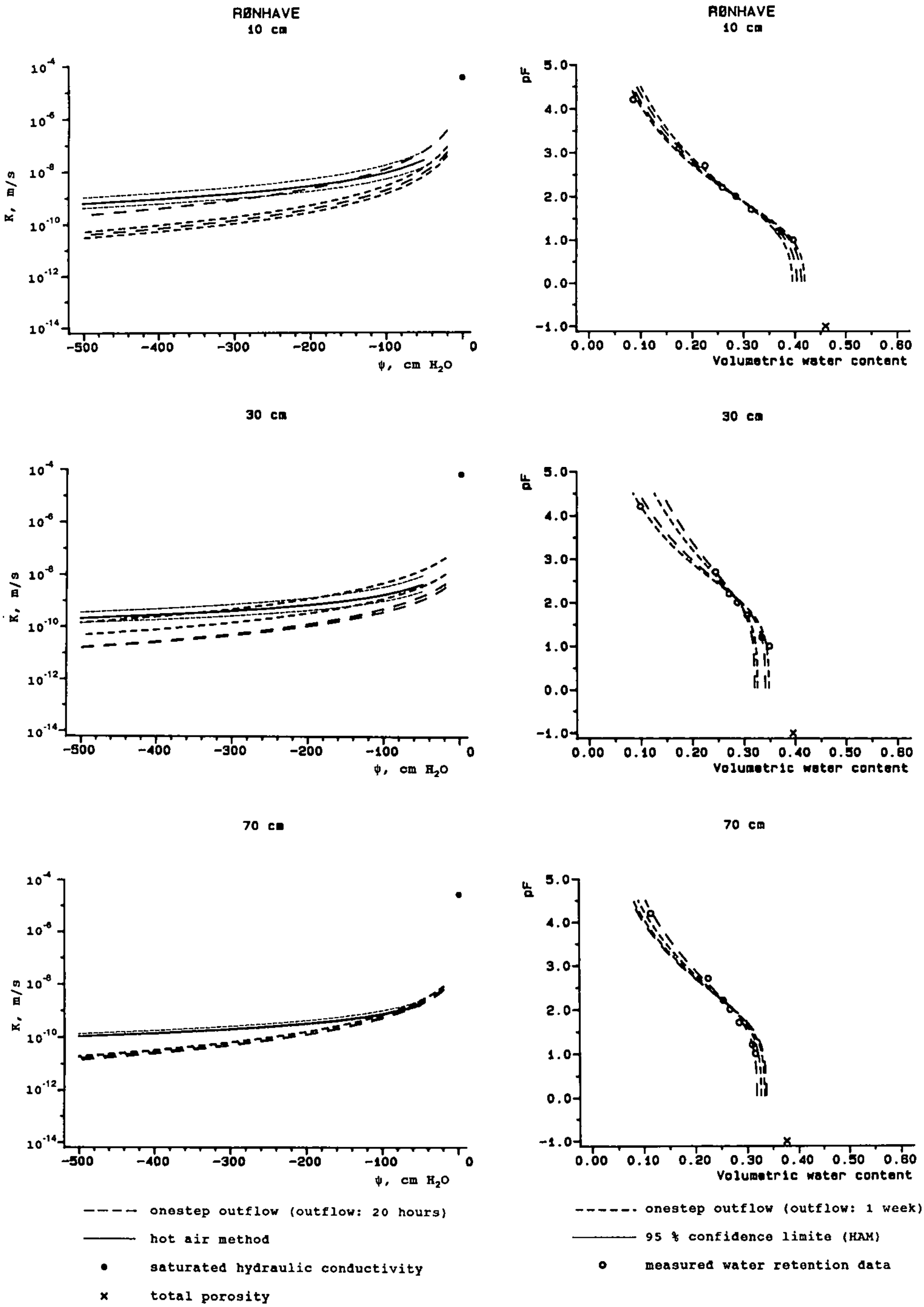

Fig. 4. Unsaturated hydraulic conductivity relations and water retention characteristics (pF-curves) for 3 depths in Rønhave.

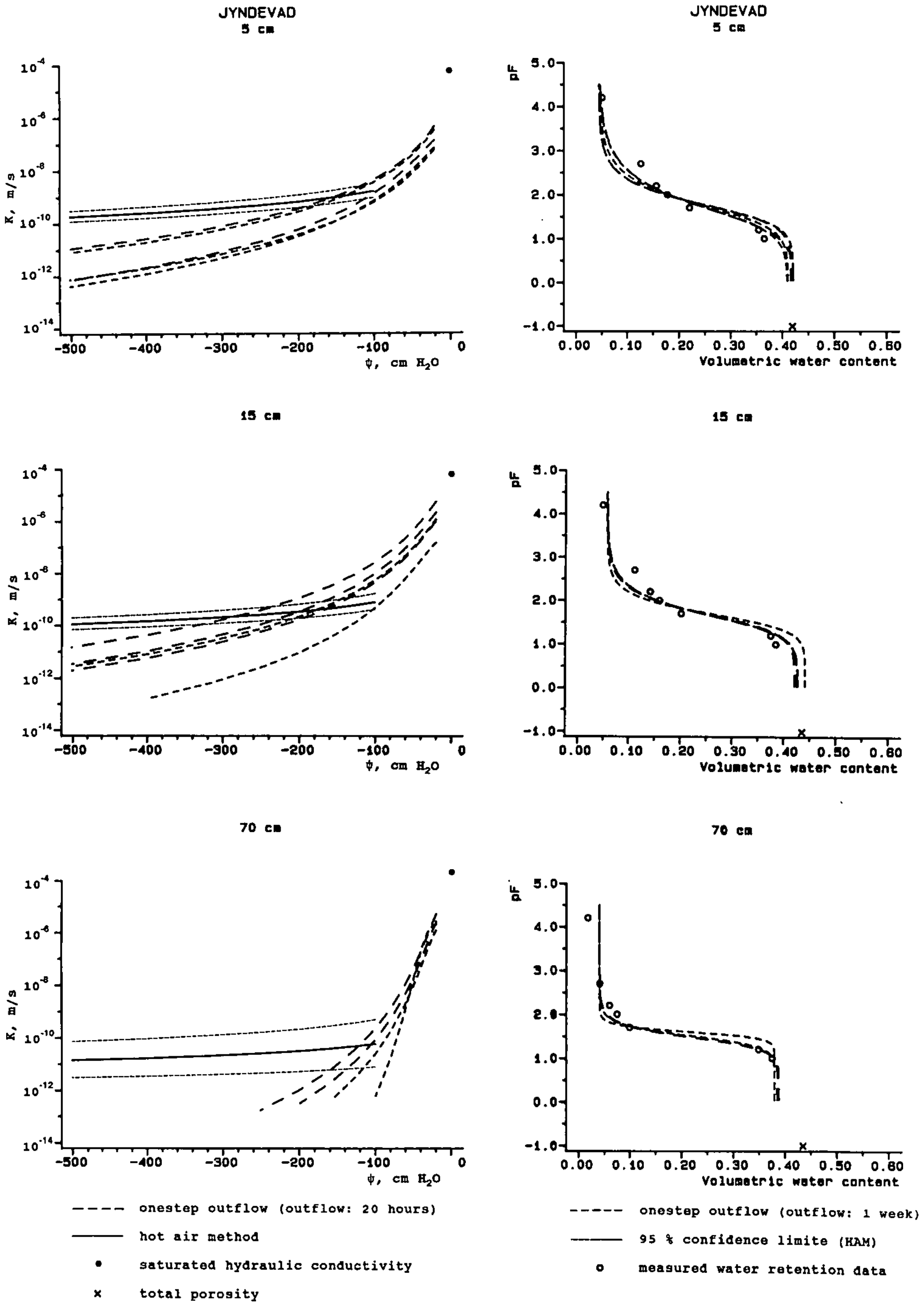

Fig. 5. Unsaturated hydraulic conductivity relations and water retention characteristics (pF-curves) for 3 depths in Jyndevad.

pores can result in higher conductivity in the top soil. In Jyndevad, the conductivity at -20 cm H_2O pressure head is higher in 70 cm than in 5 and 15 cm, probably due to the relatively coarser textured subsoil (Appendix A). But for all depths the conductivities in Jyndevad are higher than for Rønhave at high water content. For example in 70 cm the difference in conductivity at -20 cm H_2O is more than two orders of magnitude.

Another typical difference between Rønhave and Jyndevad is the rapid decrease in conductivity for Jyndevad at relatively high water contents. This is caused by the considerable emptying of the water filled pores already at pressure heads near saturation (Fig. 3 and 5b). This is clearly illustrated when the conductivity is shown as a function of water content (Fig. 6).

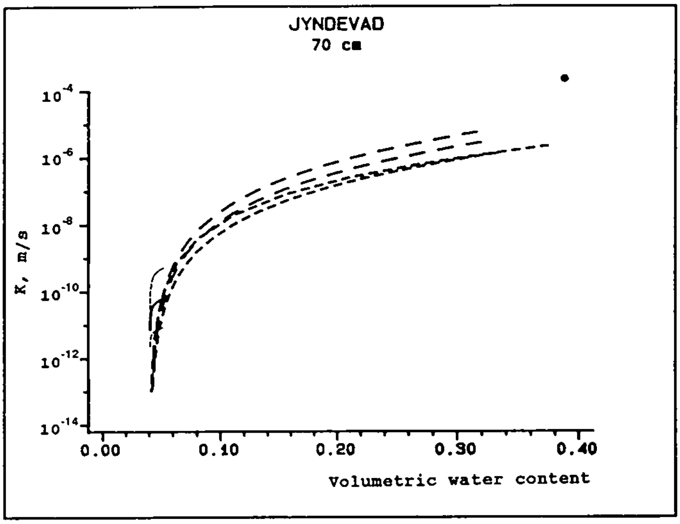

Fig. 6. Unsaturated hydraulic conductivity as a function of water content for Jyndevad, 70 cm. (— — —) onestep outflow (outflow: 20 hours); (– – – –) onestep outflow (outflow: 1 week); (———) hot air method; (———) 95 % confidence limit (HAM); • saturated hydraulic conductivity.

The conductivities estimated from the one-step outflow experiments were compared to the averaged conductivity for that particular depth as determined by the hot air method for several replicates. 95% confidence limits for the hot air results are shown in Fig. 4 and 5 as thin dashed lines. Two problems make this comparison difficult. First, two different conductivity functions are used to represent the results. For the hot air method, the Wind model (Eq.9) is used, whereas the van Genuchten model (Eqs.(4-6)) is used for the one-step outflow method. It is not easy to argue whether differences between the methods are caused by the experimental method or the conductivity function used. The other problem is the lack of prior knowledge of which method gives the best results. However, a comparison like this can give information about differences in the level and variation of results determined by the two methods.

To fulfil the boundary conditions, samples used for the hot air method had to be drained to lower pressure heads (-50 cm H_20 for Rønhave and -100 cm H_20 for Jyndevad) than samples used for the one-step outflow method. This makes a comparison between methods only possible in the range of potentials used for the hot air method. The agreement between the two methods is fairly good for pressure heads higher than about -200 cm H_20 (Fig. 4. and 5.). The deviation is generally within one order of magnitude. The same is the case for other soil types (Appendix B), even though a few samples seem to give poorer results. For the samples from Jyndevad in 70 cm, the agreement was only good around -100 cm H_20. However, at pressure heads lower than -100 cm H_20 this soil is already drained for most of the water (Fig. 5b), which also is clearly illustrated in Fig. 6.

Systematically, the conductivity is lower measured by the one-step outflow method as compared to the hot air method for pressure head lower than -200 cm H_20. It is not possible from this study to argue which method gives the best description of the conductivities at low pressure head (low water content).

The conductivities measured by the one-step outflow method show higher variation than conductivities measured by the hot air method, which can be seen by comparing the 95% confidence limits for the hot air method results with the variation in the conductivity curves from each single sample used in the one-step outflow method. This can be explained by the higher initial water content in the samples used in the one-step outflow method. This makes these measurements more sensitive to variation in macro structure which result in higher variation between samples similar to what is found for saturated hydraulic conductivity (*Hansen et al.* 1986). This deviation also can originate from sources implicit in the methods.

At Rønhave, there is no sign of difference between using long versus short outflow time, while in Jyndevad, there is some indication that long outflow time results in smaller conductivities. But due to the large variation and the few replicates, it is difficult to generalize. However, a long term outflow experiment enhances the resolution of the outflow data which makes the optimization procedure less subject to uniqueness problems.

As mentioned before, parameter estimation used on one-step outflow data may cause some problems with uniqueness and convergence in the optimization procedure. During the present studies, I have had contact to several scientists having problems of this kind with the one-step outflow method. Several suggestions for improving the method have been given in this connection.

One way to improve the uniqueness of the inverse problem is to independently measure some of the parameters in the van Genuchten model (e.g., K_s, θ_s and θ_r). As mentioned earlier these measurements may not be representative. Another approach is to include independently measured water retention data in the optimization procedure as used in this paper. The method can also be improved by performing a multi-step outflow experiment as suggested by *P.J. Wierenga,* University of Arizona, Tucson (1991, pers. comm.), in which the soil sample is subjected to a stepwise decrease in pressure head instead of a large one-step decrease. This approach will result in a higher resolution in the input data to the optimization programme. Experimental time will of course increase too. Another possibility is to install one or several tensiometers in the sample and measure the development in pressure head during the transient flow event as suggested by *Hopmans,* University of California, Davies (1991, pers. comm.). This additional information can be used to make the inverse problem more unambiguous.

In fact, it may be necessary to combine several of these improvements to make the method work well.

Conclusion

A relatively simple method for determining the unsaturated hydraulic conductivity by parameter estimation from one-step outflow data and water retention data was found to work reasonably well for both sandy and loamy soils at relatively wet conditions. The agreement between conductivities obtained by the one-step outflow parameter estimation method and the hot air method were fairly good for pressure heads higher than -200 cm H_20, while for pressure heads below, conductivities determined by the hot air method as compared to the one-step outflow method showed to be significantly higher. The variation in results between replicates was higher for the one-step outflow as compared to the hot air method.

Acknowledgements

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Appendix A.

Texture.

Location	Depth	Clay	Silt	Coarse silt	Sand				Org. mat.	$CaCO_2$
	cm	µm: <2	2-20	20-63	63-125	125-200	200-500	>500		
Rønhave	10	14.2	15.3	26.9	22.3	10.8	7.2	1.2	2.1	0.0
	30	14.3	18.2	25.2	23.4	10.4	5.7	1.0	1.8	0.0
	50	19.5	16.4	25.0	23.1	9.5	4.8	1.2	0.5	0.0
	70	17.5	15.5	21.4	24.9	13.4	6.4	0.6	0.3	0.0
	90	17.5	16.5	24.8	25.3	10.4	4.8	0.4	0.3	0.0
Jyndevad	5	4.1	3.8	3.1	5.9	11.4	51.2	18.3	2.3	0.0
	15	3.6	4.7	2.8	6.7	12.5	52.4	14.8	2.3	0.0
	50	3.5	1.9	1.0	3.1	7.3	74.2	10.1	0.4	0.0
	70	2.6	1.4	1.0	3.1	7.3	74.2	10.1	0.4	0.0
	90	2.5	0.5	1.0	0.6	4.2	77.8	13.2	0.3	0.0
Tylstrup	10	3.6	4.8	16.8	51.8	16.8	3.4	0.6	2.2	0.0
	30	4.6	3.8	20.5	55.5	10.9	2.6	0.4	1.7	0.0
	50	3.1	2.4	12.7	76.1	4.5	0.4	0.3	0.5	0.0
	70	2.5	1.0	19.0	73.8	3.3	0.1	0.1	0.2	0.0
	90	2.6	2.0	37.3	56.1	1.7	0.2	0.0	0.2	0.0
Foulum	10	7.7	9.9	15.2	16.8	14.1	24.4	9.5	2.5	0.0
	30	7.7	10.4	15.6	16.9	13.7	24.7	8.8	2.1	0.0
	50	13.4	9.6	13.4	16.5	13.6	23.1	10.2	0.3	0.0
	70	10.3	9.7	13.3	17.3	14.6	24.7	9.9	0.2	0.0
	90	11.4	10.1	12.3	16.1	15.1	24.7	10.2	0.2	0.0
Ødum	10	9.8	15.1	19.7	20.0	13.1	14.8	5.0	2.5	0.0
	30	10.9	14.3	18.3	20.4	13.8	14.8	6.1	1.6	0.0
	50	16.5	12.6	16.4	19.5	13.0	15.0	6.8	0.3	0.0
	70	16.5	12.6	15.9	20.8	14.0	14.6	5.6	0.2	0.0
	90	17.5	11.6	15.3	20.2	14.8	15.2	5.4	0.1	0.0
Årslev	10	14.4	14.6	20.6	20.2	16.3	14.9	0.8	2.3	0.0
	30	11.9	14.2	18.3	19.8	16.7	16.1	1.3	1.7	0.0
	50	20.4	12.6	15.9	22.5	17.2	10.0	1.2	0.3	0.0
	70	19.5	13.5	17.7	25.1	15.2	8.2	0.6	0.2	0.0
	90	18.6	14.4	18.3	23.2	13.8	10.4	1.2	0.2	0.0
Højer	10	18.1	15.0	38.8	24.1	0.8	0.2	0.2	2.9	0.0
	30	12.2	14.8	49.9	18.9	0.3	0.1	0.1	1.9	1.8
Kalø	70	36.7	13.3	11.5	12.0	8.8	12.0	3.6	0.4	1.8

Appendix B.

Van Genuchten parameters for each sample.

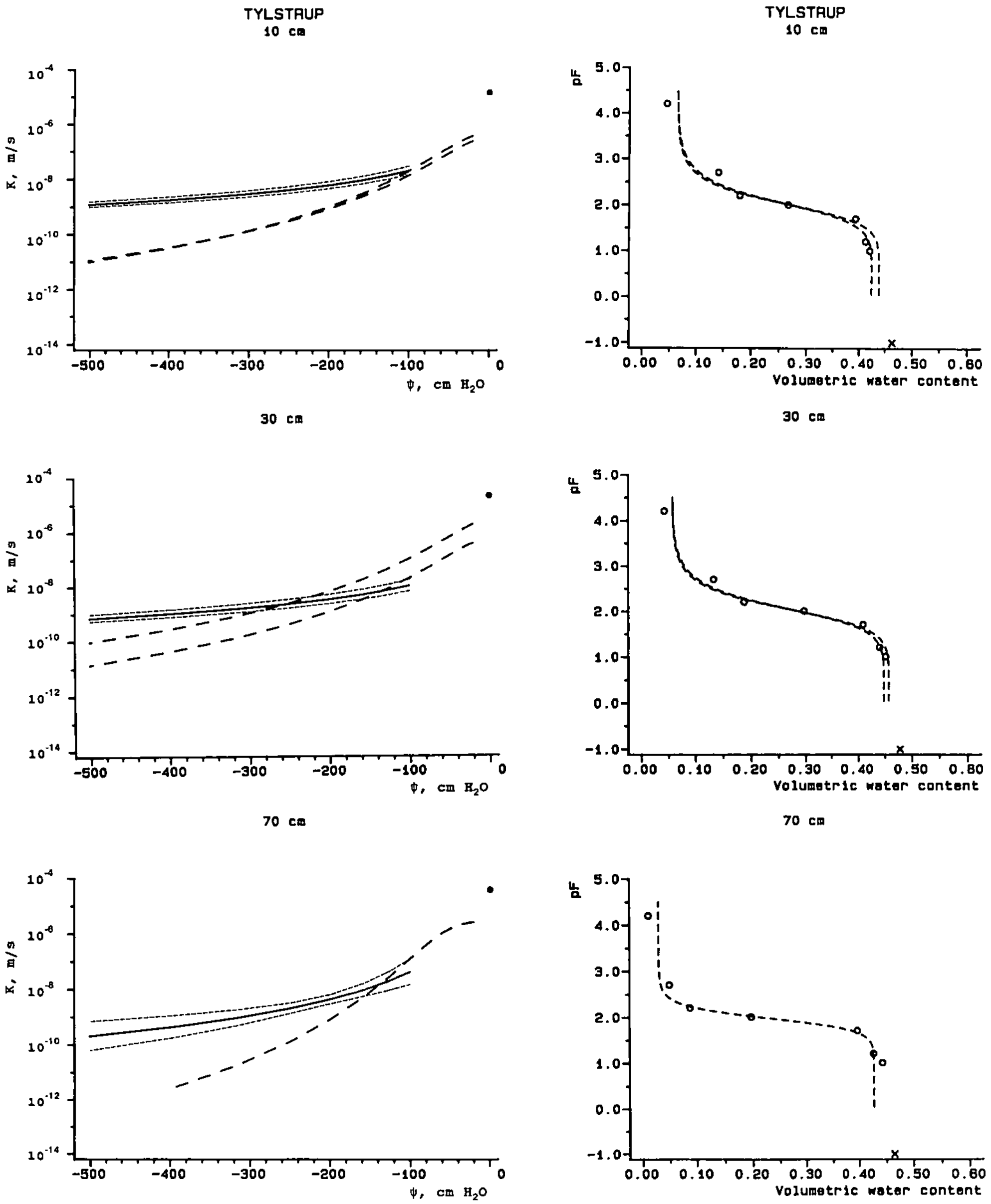
Location	sample no.	depth cm	α cm^{-1}	n	θ_r	θ_s	K_s 10^{-5} m/s	R^2
Rønhave	4805	10	0.052	1.22	0.000	0.414	28.306	0.999
	4868	10	0.052	1.20	0.000	0.405	4.889	0.999
	4875*	10	0.052	1.19	0.000	0.396	3.778	0.993
	4882*	10	0.052	1.23	0.000	0.421	6.472	0.986
	4808	30	0.013	1.14	0.000	0.320	0.094	0.985
	4815	30	0.013	1.21	0.000	0.340	0.067	0.998
	4878*	30	0.013	1.24	0.000	0.347	0.542	0.994
	4885*	30	0.013	1.16	0.000	0.325	0.247	0.989
	4835	50	0.029	1.18	0.000	0.357	0.797	0.999
	4836	50	0.029	1.17	0.000	0.349	0.319	0.998
	4848	70	0.017	1.18	0.000	0.318	0.139	0.995
	4849	70	0.017	1.24	0.000	0.337	0.103	0.995
	4846*	70	0.017	1.23	0.000	0.333	0.136	0.993
	4847*	70	0.017	1.21	0.000	0.327	0.150	0.994
	4864	90	0.012	1.17	0.000	0.310	0.033	0.992
Jyndevad	1319	5	0.039	1.71	0.044	0.422	4.819	0.999
	1326	5	0.024	2.12	0.044	0.416	0.392	0.997
	1375*	5	0.028	1.91	0.044	0.410	0.267	0.998
	1382*	5	0.024	2.10	0.044	0.421	0.206	0.997
	1389*	5	0.035	1.74	0.044	0.409	2.767	0.997
	1315	15	0.028	2.24	0.057	0.420	7.722	0.997
	1322	15	0.031	2.12	0.057	0.425	27.222	0.996
	1329	15	0.030	2.18	0.057	0.426	4.333	0.998
	1378*	15	0.031	2.14	0.057	0.426	5.728	0.997
	1385*	15	0.025	2.57	0.057	0.441	0.131	0.996
	1340	50	0.034	3.43	0.047	0.391	9.028	0.998
	1343	50	0.032	3.63	0.047	0.384	16.806	0.997
	1339*	50	0.031	3.86	0.047	0.382	7.975	0.987
	1355	70	0.037	3.47	0.040	0.385	8.028	0.998
	1356	70	0.038	3.35	0.040	0.388	18.472	0.998
	1353*	70	0.026	6.39	0.040	0.378	2.339	0.987
	1354*	70	0.034	3.78	0.040	0.379	2.831	0.998
	1367	90	0.029	6.39	0.036	0.369	2.536	0.995
	1368	90	0.035	4.25	0.036	0.384	7.028	0.995
Tylstrup	5057	10	0.013	2.29	0.064	0.437	0.556	0.995
	5064	10	0.013	2.17	0.064	0.423	0.392	0.996
	5060	30	0.013	2.12	0.056	0.448	2.731	0.996
	5067	30	0.013	2.20	0.056	0.457	0.542	0.998
	5086	50	0.013	3.74	0.041	0.426	5.667	0.997
	5087	50	0.013	3.71	0.041	0.424	1.994	0.996
	5101	70	0.012	3.59	0.029	0.426	2.806	0.995
	5114	90	0.010	3.36	0.032	0.416	0.814	0.998
	5115	90	0.010	3.50	0.032	0.428	6.472	0.997

Foulum	1144	10	0.009	1.30	0.000	0.366	0.042	0.999
	1158	10	0.009	1.36	0.000	0.375	0.433	0.994
	1147	30	0.024	1.29	0.000	0.400	6.194	0.997
	1161	30	0.024	1.28	0.000	0.395	2.086	0.999
	1174	50	0.112	1.18	0.000	0.341	34.111	0.998
	1175	50	0.112	1.22	0.000	0.369	7.028	0.998
	1188	70	0.014	1.24	0.000	0.272	0.086	0.993
	1189	70	0.014	1.28	0.000	0.279	0.586	0.997
	1202	90	0.007	1.20	0.000	0.267	0.189	0.983
	1203	90	0.007	1.26	0.000	0.276	0.013	0.992
Ødum	1242	10	0.006	1.27	0.000	0.372	0.067	0.997
	1231	30	0.013	1.25	0.000	0.368	0.725	0.997
	1245	30	0.013	1.39	0.000	0.402	0.825	0.994
	1258	50	0.018	1.22	0.000	0.323	0.142	0.994
	1259	50	0.018	1.31	0.000	0.350	0.044	0.983
	1272	70	0.008	1.17	0.000	0.298	0.070	0.978
	1273	70	0.008	1.19	0.000	0.298	0.019	0.988
Årslev	5141	10	0.027	1.20	0.000	0.367	1.972	0.996
	5155	10	0.027	1.21	0.000	0.375	0.078	0.980
	5214	30	0.019	1.20	0.000	0.335	1.692	0.998
	5221	30	0.019	1.25	0.000	0.352	1.633	0.998
	5171	50	0.025	1.16	0.000	0.358	0.550	0.993
	5172	50	0.025	1.15	0.000	0.356	0.369	0.994
	5185	70	0.010	1.17	0.000	0.325	0.023	0.995
	5186	70	0.010	1.21	0.000	0.336	0.075	0.986
	5199	90	0.012	1.19	0.000	0.347	0.133	0.995
	5200	90	0.012	1.17	0.000	0.338	0.064	0.993
Højer	4721	10	0.037	1.15	0.000	0.440	5.083	0.988
	4735	10	0.037	1.16	0.000	0.445	4.306	0.994
	4731	30	0.032	1.17	0.000	0.445	0.108	0.995
	4738	30	0.032	1.22	0.000	0.474	2.319	0.994
Kalø	1018	70	0.006	1.14	0.000	0.392	0.023	0.994
	1019	70	0.006	1.13	0.000	0.387	0.011	0.994
	1021	70	0.006	1.16	0.000	0.395	0.016	0.995

* outflow time about one week

Appendix C.

Unsaturated hydraulic conductivity relations and water retention characteristic (pF-curves) for three depths in Tylstrup, Foulum, Ødum and Årslev, and two dephts in Højer and one in Kalø.



- - - - onestep outflow (outflow: 20 hours)

——— hot air method

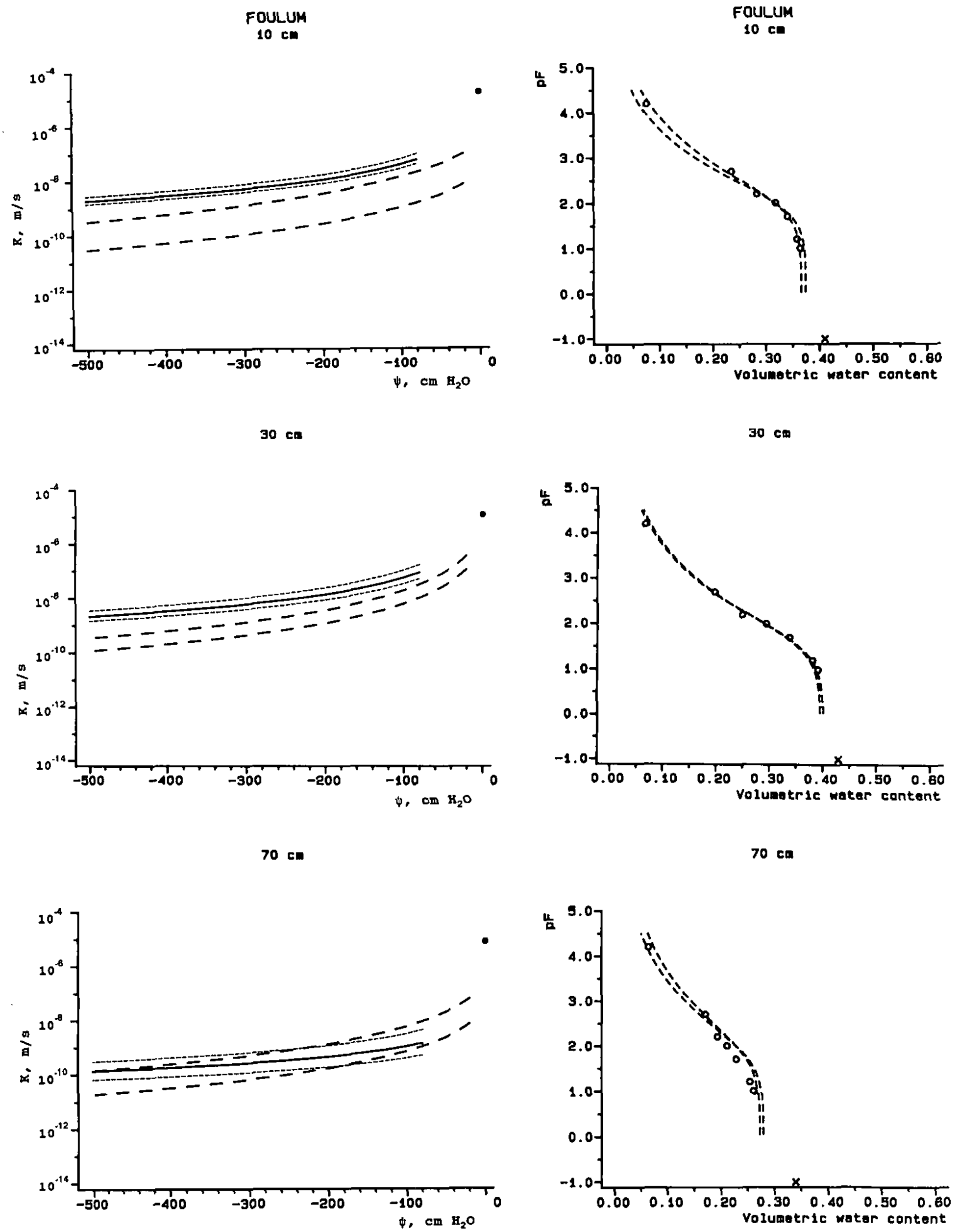
● saturated hydraulic conductivity

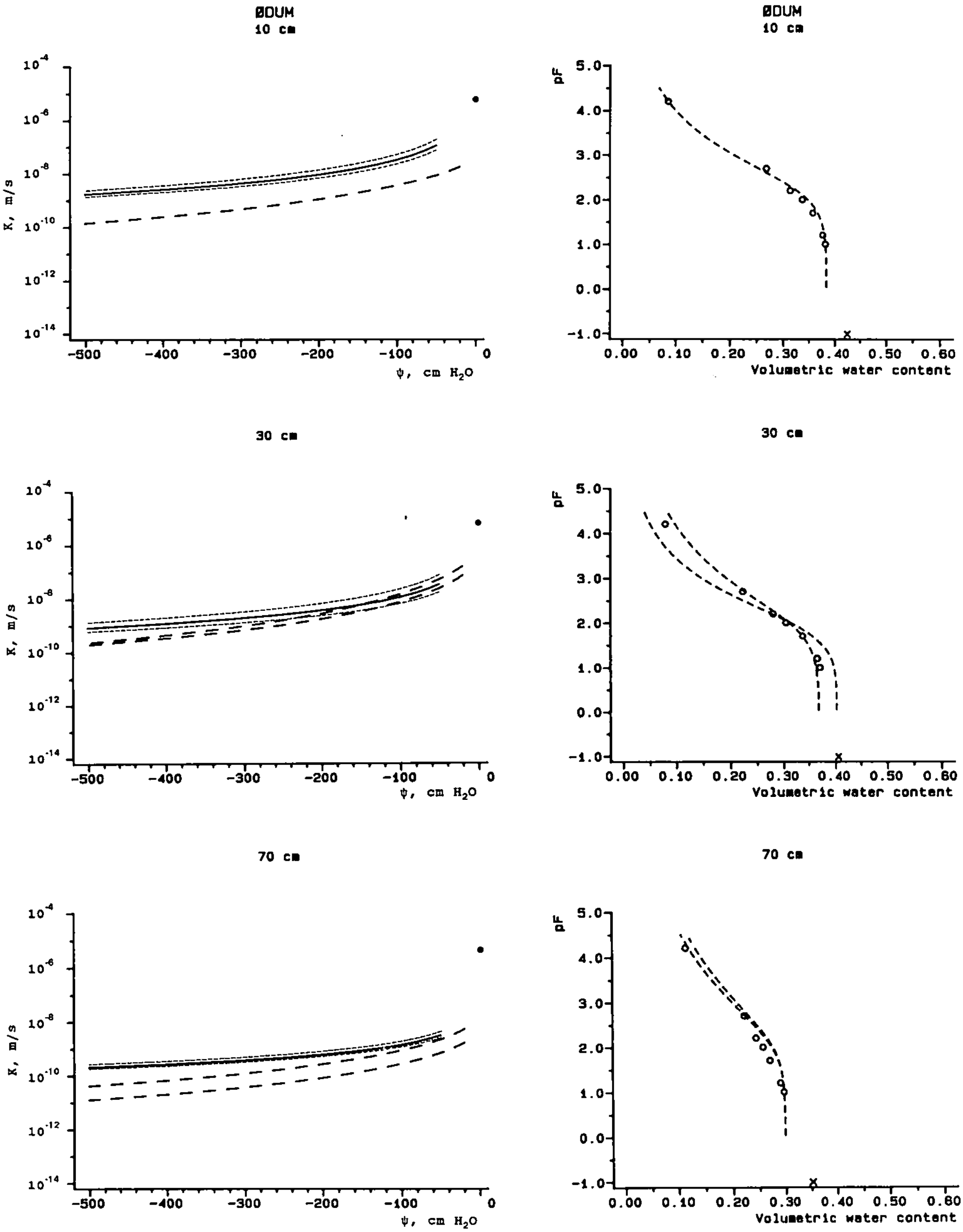
× total porosity

- - - - onestep outflow (outflow: 1 week)

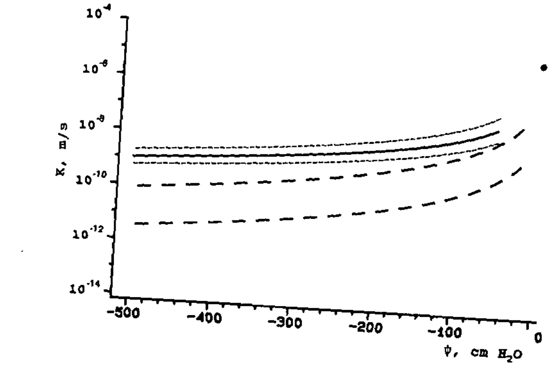
·········· 95 % confidence limite (HAM)

o measured water retention data

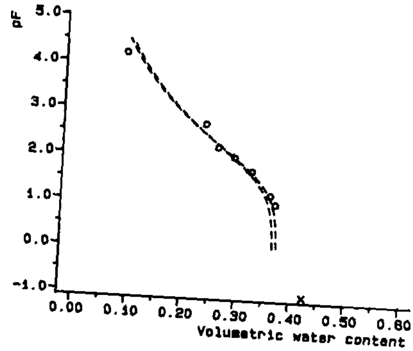

FOULUM
10 cm
K, m/s
ψ, cm H2O
FOULUM
10 cm
pF
Volumetric water content
30 cm
K, m/s
ψ, cm H2O
30 cm
pF
Volumetric water content
70 cm
K, m/s
ψ, cm H2O
70 cm
pF
Volumetric water content


ØDUM
10 cm
ØDUM
10 cm
K, m/s
ψ, cm H2O
pF
Volumetric water content
30 cm
30 cm
70 cm
70 cm

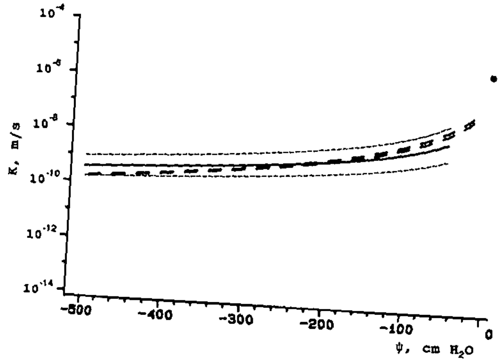
ÅRSLEV
10 cm



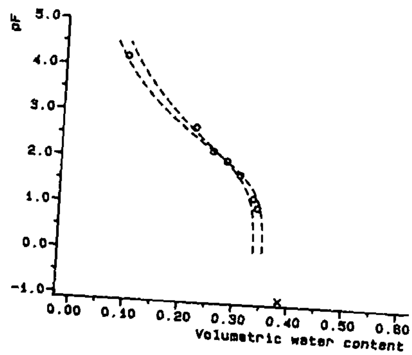
ÅRSLEV
10 cm



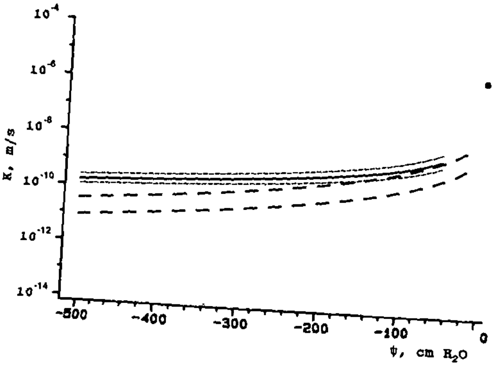
30 cm



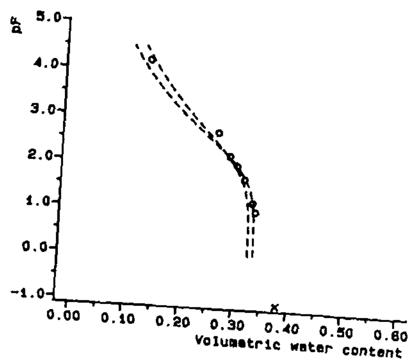
30 cm



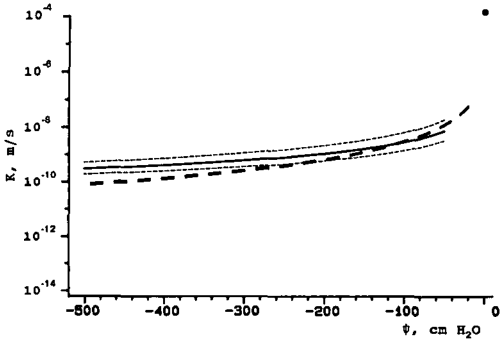
70 cm



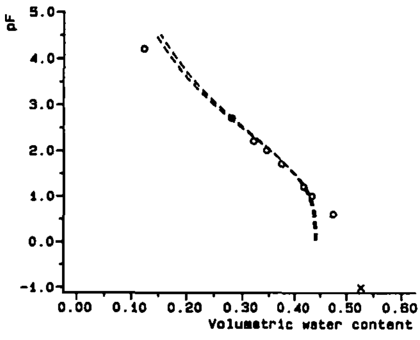
70 cm



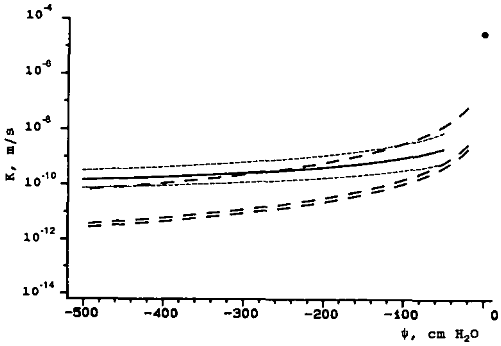
HØJER
10 cm



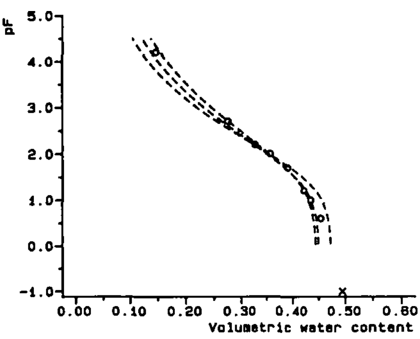
HØJER
10 cm



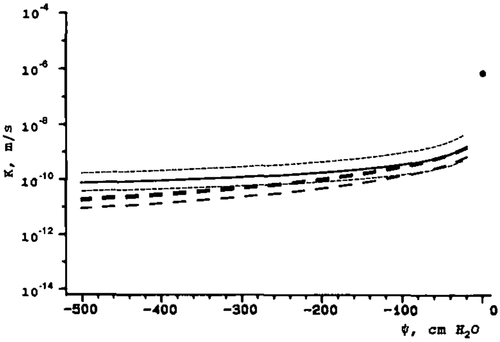
30 cm



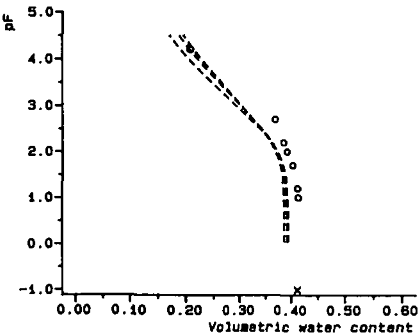
30 cm



KALØ
70 cm



KALØ
70 cm



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