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ERRATA

page 183:	Figure 1	read: dots in stead of crosses
189:	line 9	read: difference is with the evaporation rate
190:	line 5	read: mistakes which were made

Capillary conductivity data estimated by a simple method

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ABSTRACT: For the determination of capillary conductivity much rather tedious laboratory work is needed. Many people are materially or mentally not equipped for such kind of work but nevertheless need the data.

A less laborious, simple technique is described which can give good results. A vertical column of soil is allowed to evaporate at the top; all other sides are completely closed. Every day the total weight of the column is read and determinations are made of the moisture content and moisture tension at a number of depths.

The velocity of flow for different depths can be calculated from the changes in moisture content and weight. The potential gradient can be read from the moisture tension readings, making it possible to calculate the capillary conductivity.

A difficulty is that a pF-curve is needed when moisture content or moisture tension is determined. In the latter case, used in this paper, the total amount of moisture in the column determined from tension data and the pF-curve does not agree with the amount determined from the total weight. This means the flow velocity cannot be calculated exactly. The reason is that the pF-curves used lack sufficient reproducibility. They can be fitted to the soil column used by the iteration technique described.

The capillary conductivity values, determined with the aid of Bouyoucos' electrical nylon units, are fairly accurate at moisture tensions between 0.1 to 20 atmospheres. Below 0.1 atmosphere they lack accuracy.

An advantage of this method is, that it is a true imitation of some moisture flow processes which occur in nature and to which knowledge of the capillary conductivity has to be applied.

RÉSUMÉ : Le travail de laboratoire nécessité pour la détermination de la conductivité capillaire peut être considéré comme assez fatigant. Beaucoup de gens ne sont pas équipés, matériellement et mentalement, pour un tel travail et cependant doivent posséder ces données.
Une technique moins laborieuse, plus simple est ici décrite : elle peut donner de bons résultats.

On laisse évaporer à son sommet un prisme vertical de sol; tous les autres côtés sont soigneusement clos. Chaque jour, on lit le poids total du prisme et l'on détermine la teneur en humidité et la tension de l'humidité à différentes profondeurs.

La vitesse de l'écoulement pour différentes profondeurs peut être calculée en partant des changements de la teneur en humidité et des poids. Le gradient du potentiel peut être déduit des lectures de la tension d'humidité rendant possible le calcul de la conductivité capillaire.

Une difficulté se rencontre dans le fait qu'une courbe pF est nécessaire quand la teneur en humidité ou sa tension est déterminée. Dans le dernier cas qui est utilisé dans cette communication, le montant total d'humidité dans le prisme déterminé par les mesures de tension et la courbe pF ne concorde pas avec le montant déterminé par le poids total. Ceci signifie que la vitesse de l'écoulement ne peut pas être calculée exactement. La raison en est que les courbes pF utilisées ne sont pas superposables. Elles peuvent être applicables au prisme utilisé par une technique d'itération décrite.

Les valeurs de la conductivité capillaire déterminées à l'aide des dispositifs en nylon de Bouyoucos sont bien précises pour des tensions d'humidité de 0,1 à 20 atmosphères. Elles manquent d'exactitude en dessous de 0,1 atmosphère.

Un avantage de la méthode est qu'elle est une imitation de certains processus de mouvement d'humidité du sol qui se produisent dans la nature et auxquels la connaissance de la conductivité capillaire doit être appliquée.

I. INTRODUCTION

The measurement of capillary conductivity is difficult. The readings of both moisture flow and potential gradient often pose problems. Therefore a very well equipped laboratory is needed in which a skilled experimenter can thoroughly control all disturbing factors. However, a simpler method is given in this paper. It was inspired by the work of Richards and Weeks (1953) and by the good results of field measurements by Wind (1955).

The convenience gained in technique causes but little loss in accuracy. On the other hand, this method gives conductivity data over a wide range of moisture content from 0.05 to 100 atmospheres. The calculation of the conductivity data is somewhat more laborious than with other methods.

II. METHOD

A vertical cylinder filled with undisturbed soil and saturated with moisture, is allowed to evaporate only from the top. The weight of the total cylinder is determined, the moisture content or the tension or both are read daily at a number of depths. For every day, at every depth the velocity of flow is known; it equals the amount of moisture lost by the soil below. The potential gradient belonging to this flow can be calculated from the tension data. So, the capillary conductivity K can be calculated with the formula

$$v = K\left(\frac{\mathrm{d}\Psi}{\mathrm{d}h} - 1\right)$$

where v is the velocity of flow in mm/day, and $\mathrm{d}\psi/\mathrm{d}h$ the potential gradient in cm/cm.

For the determination of the moisture contents and tensions and thus the potential gradients, one can use tension readings, moisture readings or both. From the weight of the total cylinder one can compute the total moisture content.

In using moisture tension readings only, a moisture characteristic must be used to find the moisture contents. It is necessary to check the latter by the total weight. With the corrected moisture contents a new moisture characteristic can be made, with no errors on the moisture axis. There is no check on the tension readings.

In using moisture content readings only, these can be checked by the total moisture content of the cylinders. A moisture characteristic must be available for the determination of tension. Here too, there is no check on the tension data.

If one reads both moisture tension and moisture content, and a moisture characteristic is available, a mutual check of all data, including the tension readings is possible.

Although, this is the best way of getting the most reliable results, a lot of work has to be done, both in experimentation and in elaboration of the data. The other two methods are far more convenient; from them the reading of the tension is preferable to the moisture reading. The latter gives no check on the moisture characteristic from which the tension data must be derived.

The cylinders used were of steel, 40 cm high, and with a surface of 80 cm². The tension was read with Bouyoucos' (1948) nylon units installed at eight depths through holes in the wall.

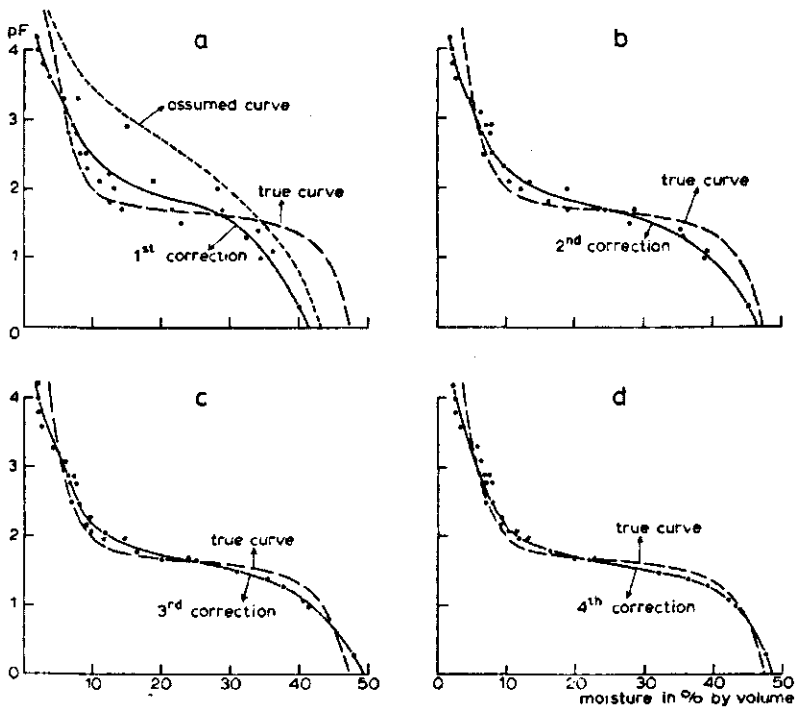

FIGURE 1. *Example of the reiteration method. The crosses are corrected values obtained from the former curve, assumed curve 1a first correction in 1b etc. Through the crosses a new line is drawn, which approach the true curve more and more. The true curve is given in every figure; in reality it is of course not known*

After filling the cylinder with undisturbed soil and installation of the nylon units with some gypsum, they are placed under water to saturate the soil. When the total weight of the cylinder and the electrical resistance of the nylon units have reached equilibrium it is placed in a dry environment. All apertures are thoroughly closed, except the top surface, where evaporation is allowed.

Every day the cylinder was weighed and the nylon units were read until the top 2 or 3 units have reached a moisture tension of more than 10 atmospheres. Then the moisture content at different depths and the total amount of dry matter of soil and cylinder are determined gravimetrically.

III. REITERATION PROCEDURE

Generally the moisture contents determined by weighing do not fully agree with those calculated from the tension readings. As the first are fairly exact, the errors are in the tension readings and in the pF-curve used. Making the assumption that the tension readings are accurate, the pF-curve is corrected in the following way. Every moisture content determined from the tension readings is multiplied by the quotient of the real and the calculated total moisture content. These corrected moisture contents are plotted against the tension; through these points a new line is drawn: the first correction of the pF-curve. The moisture contents are again calculated, now with the aid of the new pF-curve. For every date they are added and their sum is divided by the real total moisture content. They are multiplied by this quotient and again plotted against the tension. Through those points the second corrected pF-curve is drawn. One can repeat these corrections and each time the deviations of the points will be less.

An example of this iteration procedure is given in table 1 and fig. 1. For the sake of demonstration this is a fictitious example where the real pF-curve was known and the used pF-curve was made to differ extensively from the real curve.

Table 1 shows that the corrected moisture contents at every step come nearer to the true moisture contents. In fig. 1 the difference between the true and the corrected curve becomes smaller after every iteration.

In reality the true curve of course is not known; the iterations should be continued until the deviations of the points from the smooth line through them are not greater than one per cent of moisture. Generally this is achieved in 4 or 5 iterations. Only curves of sandy soils, which have a very flat part, need some more, as fig. 1 shows.

Thus it appears possible to find a pF-curve which nicely fits the soil column. Fig. 2 gives a pF-curve of a sandy soil made in 4 iterations from 29 tension observations with nylon units at 8 depths in a 40 cm cylinder.

IV. OBSERVATION OF TENSION AND GRADIENT

First the cylinder of soil is placed in water, the top surface covered, so no evaporation is possible. Through the bottom surface the soil is in contact with the surrounding water. After some time the total weight of the cylinder as well as the tension readings have reached equilibrium. At that state deviations of the nylon units can be noted, repaired or corrected.

Then the bottom surface is closed and the top surface opened. By evaporation the top layers become drier than the lower parts; so a gradient comes into being. This is shown in figures 3 and 4. Not always does the gradient (logarithmic scale) increase with time. Often the evaporation strongly decreases when the soil becomes drier; and then there is only a small increase in tension gradient.

The tension profiles obtained are typical for the soil type. An advantage of this method is, that they are approximately natural tension profiles. There is no large difference between the drying of a soil in the field and in a soil cylinder in the laboratory. The same drying patterns as seen in the laboratory will occur in the field, influenced of course by the meteorological conditions and sometimes by a groundwater table.

Figures 3 and 4 give a picture of the variance in the tension observations with nylon units.

In dry conditions these differences are not too bad, but where the soil is moist there are rather large deviations. This method therefore generally gives the best results above a tension of 100 cm (pF 2).

TABLE 1. Iteration procedure for the correction of the pF-curve of a drying soil in which tensions are read at 4 depths and moisture content is only known as a mean for the whole column

Date		Logarithms of tension (cm)							Real moisture content (% by vol.)							
		1	3	9	19	23	31	37	1	3	9	19	23	31	37	
Depth (cm)	5	2.0	2.9	3.3	3.6	3.8	4.0	4.2	10.0	6.7	5.9	5.2	5.0	4.4	4.0	
	15	1.4	1.7	2.1	2.2	2.5	2.8	3.1	39.4	20.0	9.4	8.8	7.5	6.9	6.3	
	25	1.1	1.3	1.7	2.0	2.1	2.5	2.9	43.2	40.8	20.0	10.0	9.4	7.5	6.7	
	35	0.3	1.0	1.5	1.7	1.8	2.3	2.8	46.7	44.0	36.5	20.0	14.5	8.4	6.9	
									139.3	111.5	71.8	44.0	36.4	27.2	23.9	sum (real)
		Moisture content according to pF-curve							Corrected moisture contents							
Used pF-curve	5	30.0	17.3	11.9	9.0	7.5	6.3	5.2	28.5	15.3	7.8	4.0	3.0	2.3	2.2	
	15	36.0	33.0	28.8	27.6	23.3	19.0	14.6	34.2	29.1	19.0	12.6	9.3	6.9	6.2	1st
	25	38.5	36.9	33.0	30.0	28.8	23.3	17.3	36.1	32.5	21.8	13.3	11.4	8.5	7.4	correction
	35	42.3	39.2	35.0	33.0	32.0	26.2	19.0	40.1	34.6	23.1	14.6	12.7	9.5	8.1	
	sum	146.8	126.4	108.7	99.6	91.6	74.8	56.1								
First corrected pF-curve	5	17.0	7.5	5.5	4.0	3.4	2.7	2.1	19.1	8.1	5.1	2.9	2.4	2.3	2.1	
	15	31.6	26.5	15.0	13.0	10.0	8.0	6.6	35.5	28.8	13.9	9.5	7.1	6.7	6.5	2nd
	25	35.0	33.0	26.5	17.0	15.0	9.8	7.5	39.3	35.8	24.5	12.4	10.6	8.2	7.4	correction
	35	40.3	35.8	30.5	26.5	23.0	12.0	8.2	45.3	38.8	28.2	19.3	16.3	10.0	8.0	
	sum	123.9	102.8	77.5	60.5	51.4	32.5	24.4								
Second corrected pF-curve	5	14.0	6.5	4.5	3.4	2.9	2.5	2.0	14.8	6.8	4.5	2.9	2.4	2.4	2.3	
	15	37.5	24.0	12.0	10.8	8.6	6.9	5.5	35.5	25.2	12.0	9.1	7.2	6.7	6.3	3rd
	25	38.5	36.0	24.0	14.0	12.0	8.6	6.5	40.7	37.8	24.1	11.8	10.0	8.4	7.4	correction
	35	45.3	39.7	31.0	24.0	20.0	10.0	6.9	48.0	41.6	31.1	20.2	16.7	9.7	7.9	
	sum	131.3	106.2	71.5	52.2	43.5	28.0	20.9								
Third corrected pF-curve	5	13.0	6.6	5.8	3.7	3.0	2.5	2.0	13.3	6.8	5.9	3.3	2.7	2.6	2.3	
	15	35.5	22.0	11.3	10.0	7.9	7.0	5.6	36.4	22.5	11.5	9.0	7.1	7.2	6.3	4th
	25	41.1	38.2	22.0	13.0	11.3	7.9	6.6	42.1	39.1	22.4	11.8	10.2	8.1	7.4	correction
	35	46.4	42.1	31.6	22.0	18.2	9.0	7.0	47.6	43.1	32.1	19.9	16.4	9.3	7.9	

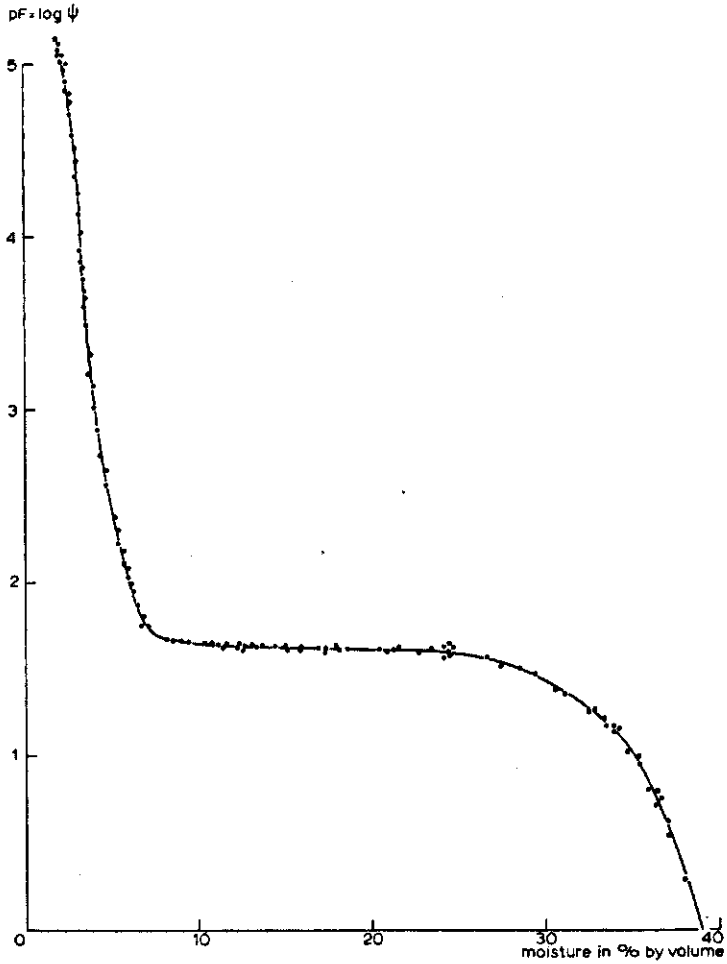

FIGURE 2. pF-*curve of a pure sand determined in a* 40 cm, *high evaporating cylinder by tension measurements at 8 depths*

The tension gradient is found from the slope of the curve log Ψ versus depth with the following formula:

$$\frac{\mathrm{d}\Psi}{\mathrm{d}h} = \frac{\mathrm{d}^e \log \Psi}{\mathrm{d}^{10} \log \Psi} \cdot \frac{\mathrm{d}\Psi}{\mathrm{d}^e \log \Psi} \cdot \frac{\mathrm{d}^{10} \log \Psi}{\mathrm{d}h} = 2{,}34\, \frac{\mathrm{d}^{10} \log \Psi}{\mathrm{d}h}$$

In the case of the left curve of figure 4, for example, the tension gradients are calculated as in table 2.

TABLE 2. Calculation of the tension gradient $\mathrm{d}\psi/\mathrm{d}h$

Depth (cm)	Log Ψ	$\frac{\mathrm{d}\log\Psi}{\mathrm{d}h}$	Ψ	$\frac{\mathrm{d}\Psi}{\mathrm{d}h}$	$\left(\frac{\mathrm{d}\Psi}{\mathrm{d}h} - 1\right)$
5	3.00	0.074	1000	170.0	169.0
15	2.32	0.064	209	30.8	29.8
25	1.80	0.037	63	5.4	4.4
35	1.52	0.021	33	1.6	0.6

For vertical upward flow the tension gradient has to be decreased by 1 to compensate for the increase in potential due to gravity. Where $d\Psi/dh$ is only small, the errors in it can be great as compared to the value of $(d\Psi/dh - 1)$. As small gradients moreover occur especially in the low tension range, where the tension observations are not that accurate, the total gradient $(d\Psi/dh - 1)$ will be fairly unreliable below $\Psi = 100$.

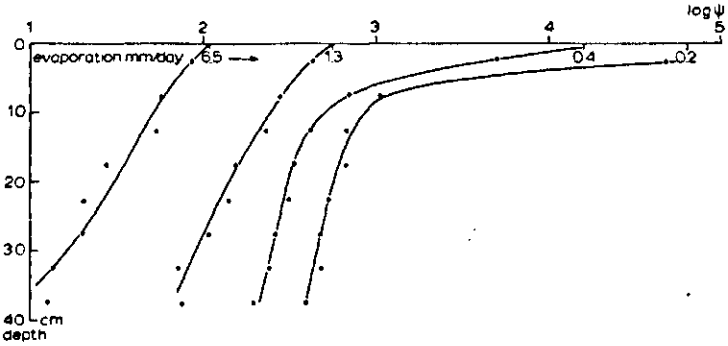

FIGURE 3. *Typical tension profiles of a drying soil with a high capillary conductivity in wet- and a low conductivity in dry conditions. This is a young moss peat. 95% organic matter*

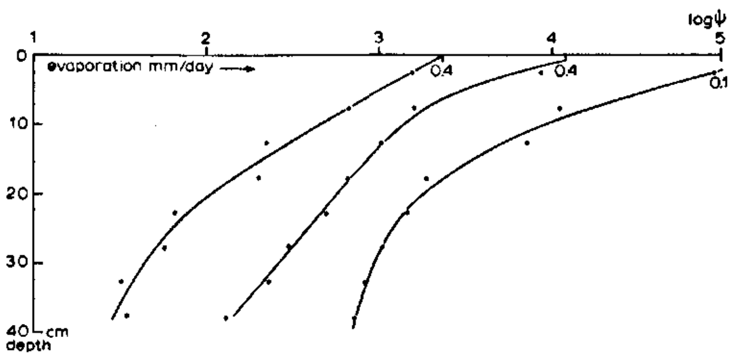

FIGURE 4. *Typical tension profiles of a drying soil with a low conductivity in wet- and a relatively high conductivity in dry conditions. This is a heavily compacted soil with 30% clay*

V. FLOW VELOCITIES

Evaporation begins when the soil cylinder is pulled from the water in which it was placed to obtain saturation, and the plastic cover is removed from the top surface. Initially the evaporation is very high but it rapidly decreases. Fig. 5 shows the relation between evaporation and time, and between evaporation and tension for two soils. The rate of evaporation and with it the flow velocity in the profile, depends on the laboratory atmosphere and the tension in the top layer. The latter is dependent on the total moisture content of the cylinder and the capillary conductivity of the soil.

Therefore the time required when using this method is not the same for each kind of soil, as shown in table 3.

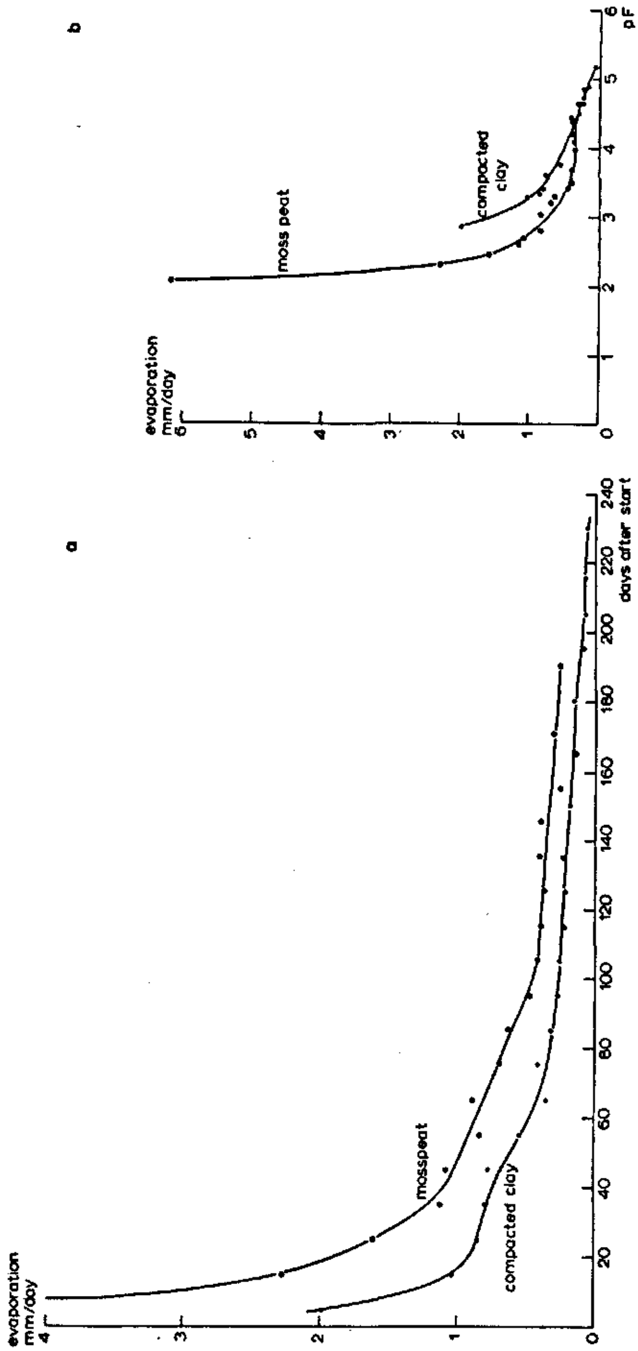

FIGURE 5. *Evaporation of two soils as a function of time (a) and tension (b)*

TABLE 3. Time in days until a certain moisture tension was obtained, for three soils

	Tension 1000 cm (pF 3) depth in cm			10,000 cm (pF 4) depth in cm		
	2.5	7.5	12.5	2.5	7.5	12.5
Compacted clay	7	13	30	74	77	150
Medium fine sand	23	51	73	30	61	97
Young moss peat	65	> 200	> 200	> 130	> 200	> 200

If one wants observations of capillary conductivity at high tensions at two depths in each cylinder, the time required will be at least two months. In a peat soil it will be about one year. So this method demands some patience from the investigator.

We used 40 cm cylinders, but it will be better to use columns not longer than 20 or 25 cm particularly when investigating peat soils.

The flow velocities at a certain depth equal the evaporation rate minus the moisture lost by the soil above that depth. The moisture losses are found from the last correction values from the reiteration procedure.

The errors in the flow velocities become the larger, the larger the difference is with F in the evaporation rate. This gives a third argument for the small reliability of this method at low tension values, for these are found in the bottom layers of the column, where the errors in the flow velocities are large.

TABLE 4. Calculation of capillary conductivity for a young moss peat (see fig. 3)

Period no.	Period length (days)	Depth (cm)	Log Ψ	$\left(\frac{d\Psi}{dh} - 1\right)$	V mm/day	K mm/day
2	3	5	1.91	3.50	5.72	1.63
		10	1.81	1.68	4.79	2.85
		15	1.73	0.73	3.61	4.95
		20	1.66	0.68	2.43	3.57
6	13	5	2.50	19.4	1.05	0.054
		10	2.38	11.2	0.94	0.084
		15	2.29	6.2	0.84	0.135
		20	2.21	4.2	0.75	0.179
10	32	5	3.20	771.0	0.17	0.00022
		10	2.78	47.6	0.15	0.00315
		15	2.65	15.5	0.14	0.0090
		20	2.59	11.5	0.11	0.0096
12	17	5	3.56	2980.0	0.17	0.000057
		10	2.86	69.1	0.15	0.00217
		15	2.74	23.1	0.13	0.0057
		20	2.67	8.7	0.10	0.0115

VI. CALCULATIONS OF CAPILLARY CONDUCTIVITY

The quotient of the flow velocity and the gradient ($d\Psi/dh - 1$) is the capillary conductivity. Table 4 gives this for the four tension profiles of fig. 3.

Only the upper 20 cm were used here because the deeper layers gave less reliable results. The capillary conductivity sharply decreases with increasing tension, caused both by increasing gradients and decreasing flow velocities. Fig. 6*a* shows that the relation of capillary conductivity and moisture tension for a young moss peat soil appears to be a straight line from pF 1.5 to pF 3.5 when a logarithmic scale is used. The deviations from the mean line are rather small, as is also the case in the figures 6*b* and 6*c*. In fig. 6*d* the deviations are larger. These result from several mistakes which made the first time we used this method, of which an insufficient insulation of the bottom of the cylinder was the most important.

So it appears that this simple method can give very attractive results. As the process of drying which occurs in the cylinders is essentially the same as the drying process in the soil, practical application of the results of this measuring method will not be difficult.

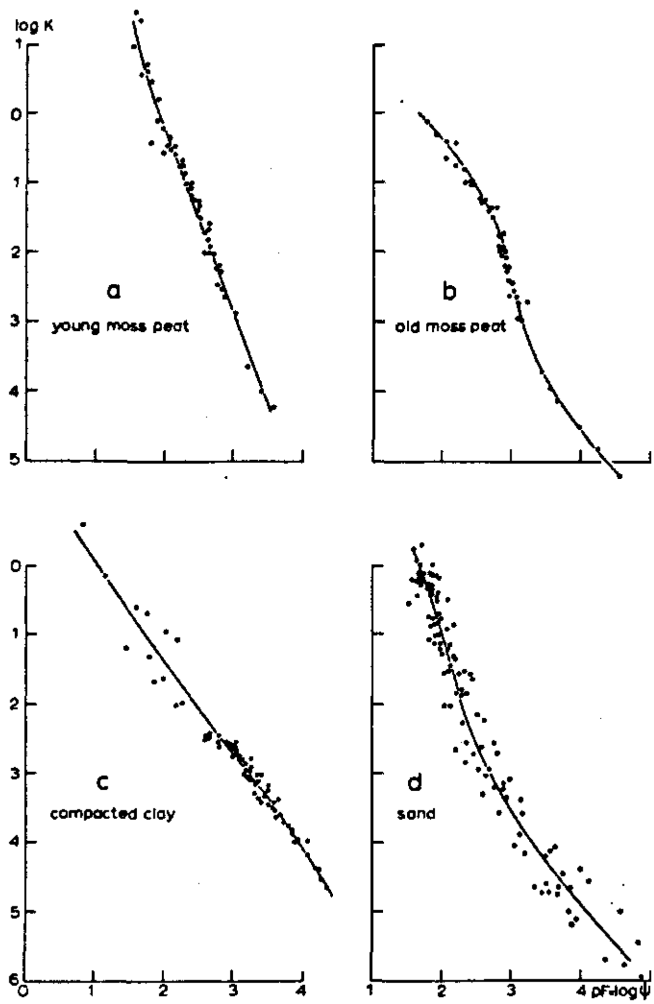

FIGURE 6. *Capillary conductivity of 4 soils as related to moisture tension*
a young moss peat, 95% organic matter, bulk density 0.15 g/ml
b old moss peat 93% organic matter, bulk density 0.19 g/ml
c heavily compacted clay soil, 30% clay
d pure sand, no organic matter, 1% clay

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