A FIELD EXPERIMENT CONCERNING CAPILLARY RISE OF MOISTURE IN A HEAVY CLAY SOIL [1]

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SUMMARY

The rate of capillary rise of moisture in a heavy clay soil was calculated by means of a water balance. This moisture .movement was found to supply about 150 mm in 1953. Under favourable circumstances a delivery of 3 to 4 mm per day is possible. The calculated values appeared to be in conformity with the law of unsaturated moisture flow. A graph was compiled which gives the relation between height above the water-table, pF and capillary rise.

1   INTRODUCTION

In the Netherlands there are some regions of heavy river clay soil, agricultural production from which is small compared with the average for this country. These "basin clay soils" (EDELMAN, 1950) cover a total area of about 60,000 ha, the greater part of which is permanent grassland. Plans have been made to improve the soils in question, and the problem now arises : what is the best depth for the water-table ?

At present there are two opinions on this question. VISSER (1949) considers that a deep water-table is best. In that case, he says, aeration of the soil is better, and deeper root growth is possible. The large soil block which is then rooted contains enough water to enable the land to get through a dry period without grass yield being adversely affected. On the other hand, PONS (1949) states that in two very dry years grassland with high water-tables was found to remain green while grass on soils with low water-tables withered. MINDERHOUD (1953) found a negative correlation between the depth of the water-table and the summer yield of grassland on basin clay soils. He also found, from gypsum block observations, that the higher the water-table, the moister was the soil 10 cm below the surface.

It is not likely that evapotranspiration from moist soils is less than from dry soils, so it is probable that the soils with a high water-table get an extra supply of water from capillary rise.

2   EXPERIMENTAL PROCEDURE

An experiment was carried out on a basin clay soil near Zaltbommel, between the rivers Waal and Maas. The soil consists of 60 % clay and 40 % silt. Fig. 1 shows the moisture characteristics of this soil. The water-table in summer is about 45 cm below the surface. In one plot, capillary rise was made impossible by introducing an impervious layer of plastic cloth at a depth of 30 cm. The plastic layer was inserted without disturbing the soil, by drawing a wedge horizontally through the soil. The plastic cloth was on a roll inside the wedge,
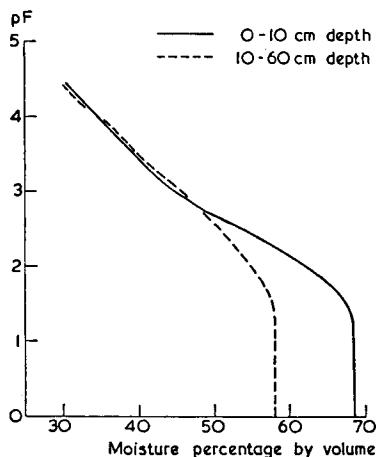

FIG. 1. THE pF CURVES OF THE SOIL ON WHICH THE EXPERIMENT WAS MADE.

which had a maximum height of 4 cm. As the wedge advanced, the plastic unrolled and remained in the soil.

The plastic cloth was 4 m long and 1.25 m broad. In addition, the sides of the soil block were provided with a plastic wall, so that the water could not enter there either.

Soil moisture content and moisture tension were measured with gypsum blocks and nylon units, according to the method of BOUYOUCOS (1940, 1948). The soil moisture units were installed at depths of 2, 5, 8, 12, 18, 22 and 28 cm. In all, 28 units were above the plastic layer.

In the untreated soil 32 moisture units were placed at the depths mentioned above, and also at depths of 32, 38, 45 and 55 cm. The resistances measured were converted into terms of 20° C with the aid of temperatures read from Philips thermistors.

The experiment started on 24th April, 1953, with introduction of the plastic layer and the moisture units. The first reading of the units took place on 28th April. From then until 14th October, 1953, the moisture units were measured 21 times, at irregular intervals.

3 EXPERIMENTAL RESULTS

The soil above the impervious plastic layer, henceforth called the treated plot, became much dryer than the untreated soil. In every dry period, the soil moisture in the treated plot showed a very rapid decrease as compared with that in the untreated soil.

Fig. 2 shows the soil moisture content in the layer 0—30 cm, in both soils.

In this diagram, the dry period in the first 20 days of May is especially interesting. During this period there were practically no losses of soil moisture in the untreated soil. In the same time the treated plot lost practically all its available moisture. The moisture content of the 30—60 cm layer remained constant, so the amount of capillary moisture supplied was nearly equal to the amount lost by evapotranspiration. In later periods there were fluctuations in the moisture content of the untreated soil, but they were not so
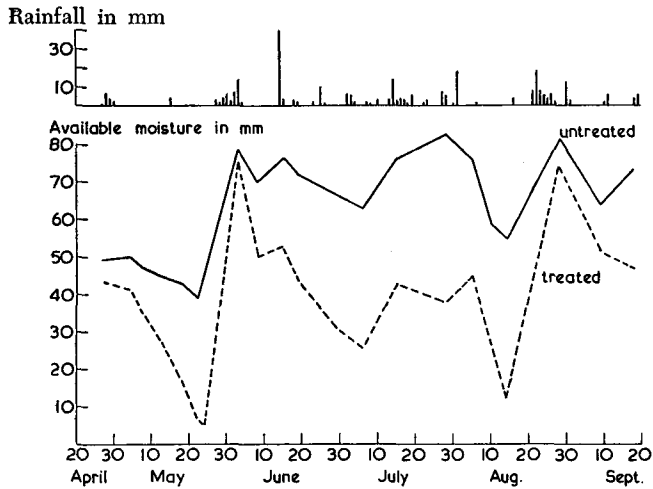
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FIG. 2. AVAILABLE MOISTURE CONTENT IN THE UPPER 30 CM OF THE TREATED PLOT AND THE UNTREATED SOIL DURING THE SUMMER OF 1953. The dotted line represents soil moisture in the treated plot, the continuous line that in the untreated soil. At the top, the rainfall.

great as those in the treated plot. Nevertheless, there was always more moisture in the untreated soil than in the treated plot, which meant that a considerable amount of moisture had been supplied by capillary rise in this soil.

4   QUANTITATIVE CALCULATION OF CAPILLARY RISE OF MOISTURE

For a soil block, we can form an equation for the water-balance :

$$C + R + M_1 = M_2 + E + D. \tag{1}$$

In this equation C is the capillary rise of moisture through the bottom of the block. R is the rain, M_1 and M_2 the moisture content at the beginning and at the end of the period concerned. E is the evapotranspiration, and D is the downward water movement, called drainage.

R and M are measured. So there remain three unknown factors. If only periods with little rain are concerned, we can assume that $D = 0$. For the treated plot, $C = 0$ too. So we can calculate the evaporation of this plot, E_t. But E_t is not a good estimate of the untreated soil's evapotranspiration E_u, because the plot with the plastic layer is much dryer than the untreated soil.

Another estimate of the evapotranspiration has been provided by the lysimeter installation of the Central Institute of Agriculutural Research (MAKKINK, 1953) in Wageningen, at a distance of 30 km from the venue of the experiment. Mr. MAKKINK kindly gave us the evapotranspiration data from 5 lysimeters, in which moisture tension remains constant at a very low value, the potential evapotranspiration E_p . These data are higher than the E_t values, but they are probably higher than E_u too.

We can calculate E_u when we know the relation between evapotranspiration and pF, which relation can be determined by dividing E_t by the potential evapotranspiration E_p . In Fig. 3 this quotient, the relative evapotranspiration E_r , is shown in its relation to pF.

By means of the pF of the upper 10 cm of the untreated soil, the curve

Er relative evapotranspiration

$$E_r = -0.34 \text{ pF} + 1.85$$
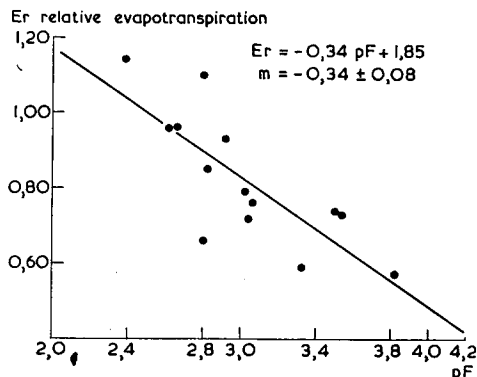$$m = -0.34 \pm 0.08$$

FIG. 3. THE RELATION BETWEEN THE RELATIVE EVAPOTRANSPIRATION, AND THE pF IN THE UPPER 10 CM OF SOIL, IN THE PLOT WITH THE PLASTIC LAYER.

$E_r = -0.34$ pF $+ 1.85$ of Fig. 3, and the potential evapotranspiration, we now can calculate the untreated soil's evapotranspiration E_u .

If we consider only periods without drainage, we can write eq. (1) in the following form:

$$C = E + M_2 - M_1 - R. \tag{2}$$

All terms in the right member of the equation are known. So we can calculate capillary rise in the periods without drainage. Altogether, 153 mm of water rose in the 14 periods, which had a total length of 98 days. There were 4 periods in which capillary rise exceeded 2.0 mm per day; in one of them the rise was 3.4 mm per day.

Table 1 gives the amounts of capillary rise, calculated according to eq. (2).

Table 1. Calculation from the experimental data of capillary rise in the 14 periods without drainage.

Period	Evapotrans-piration	Increase in moisture content	Rainfall	Capillary rise
	E_u	$M_2 - M_1$	R	C
	mm per day			
May 4– 7	2.3	−1.0	0	1.3
„ 7–12	2.2	−0.4	0.1	1.7
„ 12–18	2.5	−0.4	0.6	1.5
„ 18–22	3.5	−1.0	0.1	2.2
June 3– 8	2.8	−1.7	0.3	0.8
„ 15–19	3.6	−1.3	1.3	1.0
„ 19–30	3.8	−0.6	1.3	1.9
July 30– 6	3.5	−0.4	1.9	1.2
„ 6–15	3.9	+1.5	3.0	2.4
„ 15–28	3.7	+0.5	2.7	1.5
Aug. 5–10	4.4	−3.8	0	0.6
„ 10–14	4.9	−1.2	0.3	3.4
Sept. 28– 9	3.1	−1.4	1.1	0.6
„ 9–18	2.4	+1.0	1.0	2.4

5 Discussion

If these amounts are not the result of experimental errors in calculating rainfall, evapotranspiration, etc., but are indeed true measurements of water movements caused by capillary forces, they must be in conformity with the theoretical laws for unsaturated flow.

The equation for the velocity of unsaturated flow is:

$$v = \lambda \frac{d\Theta}{dh} \qquad (3)$$

In this equation $\frac{d\Theta}{dh}$ is the potential gradient in the direction of flow, and λ is the coefficient of capillary conductivity. The potential Θ is composed of the capillary potential ψ and the potential due to gravity h, if we consider a vertical flow.

So for capillary rise the equation is

$$v = \lambda \frac{d(\psi - h)}{dh} = \lambda \left(\frac{d\psi}{dh} - 1\right) \qquad (4)$$
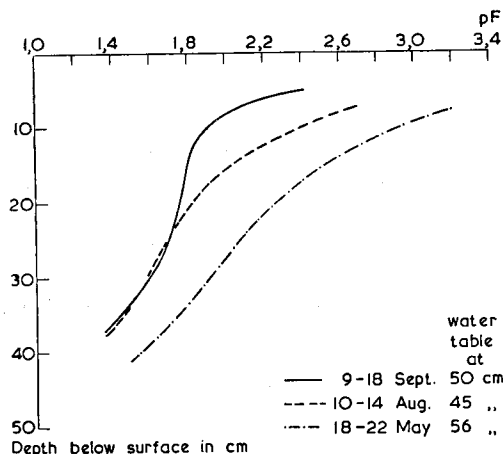

Fig. 4. The capillary potential (pF) at different depths in the untreated field, in three periods.

The tangents to the curves of Fig. 4 give us $\frac{d \log \psi}{dh}$ at any depth we wish. From these values we can calculate $\left(\frac{d\psi}{dh} - 1\right)$ in the following manner:

$$\frac{d\psi}{dh} - 1 = 2.3\,\psi \frac{d \log \psi}{dh} - 1 \qquad (5)$$

Equation (4) is now written:

$$v = \lambda \left(2.3\,\psi \frac{d \log \psi}{dh} - 1\right) \qquad (6)$$

Before we calculate λ, two points must be mentioned. Firstly, v is not the same for all depths. For v is the sum of the capillary rise from the ground water c and the moisture m extracted in unit time below the depth concerned.

So we must write:

$$c + m = \lambda\ (2.3\psi\ \frac{\mathrm{d}\ \log \psi}{\mathrm{d}h} - 1) \tag{7}$$

The second point is that moisture does not flow only through the soil, but through the grass roots too. This movement is independent of the potential gradient in the soil. If we assume that all water transport takes place via the soil, we shall find too high values for the capillary conductivity λ. Owing to the fact that the quantity of roots is greater at shallower depths, it can be expected that the values of λ at different depths will not agree with each other. In cases in which they do agree, it is likely that no active roots are present.

Table 2 gives an example of the method of calculation.

Table 2. Calculation of capillary conductivity from the data of period no. 4, between the 18th and 22nd of May, 1953.

Depth in cm below surface	pF log ψ	ψ cm	$\frac{\mathrm{d}\ \log \psi}{\mathrm{d}h}$	$(\frac{\mathrm{d}\ \psi}{\mathrm{d}h} - 1)$	$c + m$ mm/day	λ mm/day
10	2.89	780	0.088	157.0	2.6	0.017
15	2.51	320	0.061	43.0	2.2	0.051
20	2.27	186	0.035	13.7	2.2	0.16
25	2.10	126	0.036	9.1	2.2	0.24
30	1.91	81	0.037	5.8	2.2	0.38

The results of similar calculations for the 14 periods without drainage, and at the 5 depths mentioned in Table 2, are given in Fig. 5. It appears, in accordance with the results of RICHARDS (1952) and others, that capillary conductivity is not a single value. The data are dependent on the soil moisture tension; so we show them in their relation to pF.
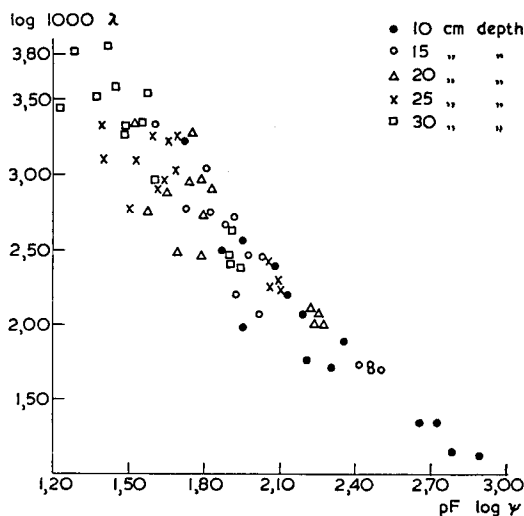

FIG. 5. THE CALCULATED CONDUCTIVITY DATA PLOTTED AGAINST pF.

In this figure we see that a very close degree of agreement exists between

the data of the 5 depths. We must therefore conclude that at these depths practically all movement of water is via the soil, and that only very little water is transported by the roots. At depths of less than 10 cm the calculated values of λ deviated strongly from the other values. It is most likely that at these depths the flow of water through the roots becomes important. Obviously there are no water-absorbing roots at depths below 10 cm.

Fig. 5 provides proof that the quantities of water calculated as resulting from capillary rise are indeed due to capillary water movements. They were not the result of errors in the experimental data. For in that case such a close relation between capillary conductivity and capillary potential would not be found to exist.

As will be seen from Fig. 6, the capillary conductivity of this soil is very low.
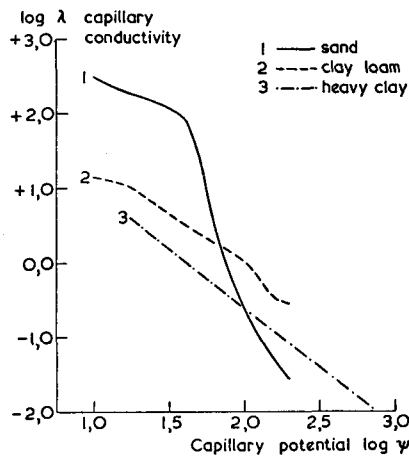

FIG. 6. COMPARISON OF CONDUCTIVITY DATA FROM RICHARDS AND MOORE (SAND AND CLAY LOAM) WITH THE RESULTS OF OUR EXPERIMENT (HEAVY CLAY).

Our data for heavy clay are compared here with two curves plotted by RICHARDS and MOORE (1952) for clay loam and sand. In wet condition, the conductivity of sand is about 100 times as high as that of the heavy clay. Above pF 2.0 the conductivity of heavy clay is greater. The clay loam curve is nearly parallel with ours, but it lies 3 times as high. Nevertheless, in spite of this low conductivity, an appreciable amount of water can rise capillarily.

6 PRACTICAL APPLICATION

It is possible now, on the basis of this new knowledge of capillary moisture rise, to answer the question about the best summer depth of the water-table for this soil. The stipulation we make is that the pF at the bottom of the root zone is not allowed to exceed a certain value. That means that in dry periods capillary rise must be able to compensate for water lost by evapotranspiration.

We shall now calculate the relation of the pF at 10 cm depth to the depth of the water-table.

If we adjust the points of Fig. 5 we get the following formula:

$$\log 1000 \, \lambda = -1.57 \log \psi + 5.54.$$

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The mean errors are 0.10 and 0.34 respectively.

We can write this equation as:

$$\lambda = b\psi^{-a} \tag{8}$$

$$a = 1.57 \pm 0.10 \qquad\qquad \log b = 2.54 \pm 0.34$$

For the sake of simplicity we make $a = 1.50$ (the mean error of a allows that), but b then has to be altered too; otherwise the line would no longer pass through the points.

Thus, $\log b = 2.40 \longrightarrow b = 250$.

From equations (4) and (8) we form

$$v = b\,\psi^{-a}\,(\frac{d\psi}{dh} - 1) \tag{9}$$

We may change v into c because when capillary rise equals evapotranspiration, no water is extracted from the soil.

$$\frac{d\psi}{dh} = \frac{c}{b}\psi^a + 1$$

$$h = \int \frac{d\psi}{\frac{c}{b}\psi^a + 1} \tag{10}$$

If a were 1 or 2, this form could be elementarily integrated. We now introduce: $y^2 = \psi$; then $d\psi = 2y\,dy$. Instead of equation (10) we now write:

$$h = \int \frac{2y\,dy}{\frac{c}{b}y^3 + 1} \tag{11}$$

The solution of equation (11) is:

$$h = \frac{2}{3}\,(\frac{b}{c})^{\frac{2}{3}}\left\{\tfrac{1}{2}\ln\,(x^2 - x + 1) + \sqrt{3}\,\text{arc}\,\tan\frac{2x - 1}{\sqrt{3}} - \ln\,(x + 1) + K\right\} \tag{12}$$

In this $x = (\frac{c}{b})^{\frac{1}{3}}\quad y = (\frac{c}{b})^{\frac{1}{3}}\psi^{\frac{1}{2}}$

In the case of the water-table $h = 0$ and $\psi = 0$

$$0 = \frac{2}{3}\,(\frac{b}{c})^{\frac{2}{3}}\,(0 + \sqrt{3}\,\text{arc}\,\tan\frac{-1}{\sqrt{3}} - 0 + K)$$

$$\text{So}\qquad K = 0.91 \tag{13}$$

In Fig. 7 a graph is given for equation 13 when $c = 0, 1, 2, 3$ and 4 mm per day.

In integrating equation (11) from 0 we are making a mistake by assuming that equation (8) is valid from $\psi = 0$. In that case λ would be ∞. It would be better to assume that equation (8) is valid when $\log\,\psi > 1.20$ (see Figs. 5 and 6), and to suppose that λ is constant between this value and $\psi = 0$. But for the sake of simplicity we integrate from $\psi = 0$, because the error involved is very small.
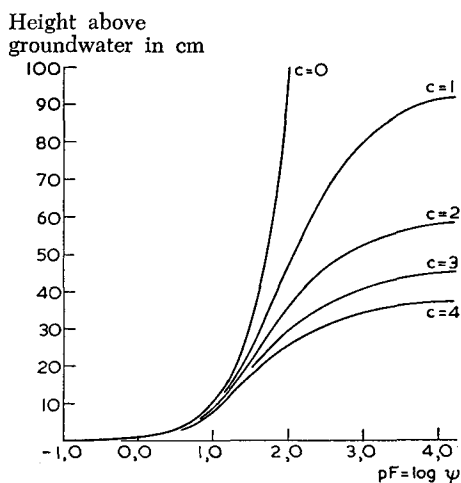
Height above groundwater in cm

Owing to this the curves in Fig. 7 are about 1.5 cm too high.

What, it may be asked, is the purpose of the curves in Fig. 7 ? They are the same as the curves, examples of which were given in Fig. 4. Those curves were differentiated by drawing the tangents to them. The differential ratios, together with the relevant rates of capillary rise, were adjusted. The mean line from this adjustment was then integrated. And this integration yielded a formula in which three independent factors were found, namely, those that occur in Fig. 4: the height above the water-table, the pF and the rate of capillary rise of moisture. Fig. 7 gives the relation between those 3 factors.

When there is no capillary movement, the capillary potential (in cm) equals the height above the water-table (in cm). So for $c = 0$ we get:

$$pF = \log \psi = \log h.$$

When there is a certain capillary rise, there must be a certain potential gradient. The higher the rate of capillary rise the further to the right must the curve go. The soil must therefore be drier. At a height of 40 cm above the water-table the pF is 1.85 if capillary rise is 1 mm per day. When the rise is 3 mm per day the pF is 2.85. At this height, capillary rise cannot be as much as 4 mm per day, for then the pF would have to be higher than 7. But at 30 cm a capillary rise of 4 mm per day is possible. At 50 cm even 3 mm has ceased to be possible. So the rate of capillary rise is limited by the height above the water-table. That means that Fig. 7 can give us the most desirable depth for the water-table in summer.

In dry periods capillary rise must equal evapotranspiration. If the latter is greater than the former the soil will become drier, the result of which will be firstly, that capillary rise will become greater, and secondly, that evapotranspiration will decrease (see Fig. 3).

If we wish to calculate the most suitable depth for the water-table for this soil we must make two stipulations. We must demand, for instance, that the pF of the lower limit (10 cm) of the active root zone shall not exceed 3.0. That means that the upper 10 cm of soil will be rather dry.

The second stipulation is that the rate of capillary rise must be 3 mm.

That amount is not very high, for in dry periods evapotranspiration is about 4 mm per day.

We now look at the diagram to see the depth at which the curve for 3 mm crosses the line pF = 3.0. That is at 41 cm. So the lower limit of the active root zone must be 41 cm above the water-table. Since the root zone is 10 cm thick, the water-table in summer must lie at a depth of 50 cm or less.

When we allow the pF to reach higher values, there is only a slight difference in the most suitable depth for the water-table if we remain on the curve c = 3. But, as appears from Fig. 3, evapotranspiration decreases if moisture tension increases. So it will not be necessary to maintain a capillary rise of 3 mm per day. If the pF is 4.0, capillary rise must be $\frac{49}{83} \times 3.0$ mm per day, according to Fig. 3, i.e., 1.8 mm. In that case a water-table at a depth of 70 cm will be sufficient to maintain equilibrium.

LITERATURE

BOUYOUCOS, G. J. & A. H. MICK: An electrical resistance method for the continuous measurement of soil moisture under field conditions. *Mich. Agr. Exp. Sta. Tech. Bull.* 172 (1940).

− −, − −: A fabric absorption unit for continuous measurement of soil moisture in the field. *Soil Sci.* 66 (1948) 217−232.

EDELMAN, C. H.: Soils of the Netherlands. Amsterdam, 1950.

MAKKINK, G. F.: Een nieuw lysimeterstation. *Water* no. 13 (1953) 159−163.

MINDERHOUD, J. W.: Personal communication.

PONS, L. J.: Rapport waterhuishouding van komkleigronden. Internal report 1949.

RICHARDS, L. A. & D. C. MOORE: Influence of capillary conductivity and depth of wetting on moisture retention in soil. *Trans. Am. Geophys. Un.* 33 (1952) 531−540.

VISSER, W. C.: De vochthuishouding van komkleigebieden. Internal report 1949.