SOME RESULTS OF FIELD DETERMINATIONS OF THE MOISTURE CONTENT OF SOIL FROM THERMAL CONDUCTIVITY MEASUREMENTS ¹)

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ABSTRACT

In continuation of previous work further results of field determinations of the thermal conductivity at depths of 4, 8 and 16 cm in a clay soil cropped with grass are presented. Moisture contents are deduced from the thermal conductivity values with the aid of a calibration curve (fig. 1).

The soil moisture content in the layer between 4 and 16 cm is compared with precipitation (P) and potential evapotranspiration (E_T) for periods of 1 month (table 1). During the first month (May 1951) the moisture contents show rather strong fluctuations under the influence of frequent rainfalls (fig. 2). From the end of May onward E_T exceeds P and a general drying of the soil occurs. During the dry months June and July the rainfall only affects the measurements at 4 cm depth, while the moisture contents at 8 and 16 cm become constant after initial drying. During August P is in excess of E_T and a general rise of the moisture content is observed.

Figs. 3 and 4 contain examples of a diurnal variation of the moisture content; variations of this quantity with about 10 volume percents at one depth are observed within 24 h.

In discussing the accuracy of the moisture content values it is concluded that for accurate determinations of the soil moisture content from thermal conductivity measurements sandy soils will be more suitable than clay soils, since only with the former soils the moisture range between field capacity and wilting point will coincide with the steep section of the calibration curve.

LIST OF SYMBOLS AND UNITS

Symbol		Unit
C(*)	– heat capacity per unit of volume	cal/cm³ °C
E_T	– potential evapotranspiration	cm H_2O
P	– precipitation	cm or mm H_2O
Q,S	– gain of heat	cal/cm²
t	– time	sec
x(*)	– volume fraction	–
z	– vertical coördinate	cm
ϑ	– temperature	°C
λ	– thermal conductivity	millical/cm sec °C
τ	– time	sec

(*) With these quantities the index *a*, *s* or *w* refers to air, solid material or water respectively.

1 INTRODUCTION

In previous papers (DE VRIES, 1952 a and b) a method for the determination of the thermal conductivity of soil in situ was described and some experimental results were reported. From these measurements the moisture content can be deduced if the relation between the latter quantity and the thermal conductivity is known. To obtain this relation a calibration in the laboratory will usually be necessary.

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The author (DE VRIES, 1952 a) also described a method for a theoretical computation of the thermal conductivity of a soil, starting from the volume fractions and the thermal conductivities of its constituents (including water and air). The shape of the soil grains, which enters into these calculations, must be approximated by that of an ellipsoid in order to facilitate a mathematical treatment. These calculations can be used to support the experimentally obtained calibration values and to reduce the required number of experimental points on the calibration curve.

In the present paper results of field measurements of the thermal conductivity at three depths in a clay soil, cropped with short grass, during a part of the growing season of 1951 are reported. A calibration curve giving the relation between the thermal conductivity and the moisture content is presented and moisture contents are obtained with the aid of this curve. The behaviour of the moisture content versus time curves is discussed.

2 THE CALIBRATION CURVES

The thermal conductivity measurements were carried out in a clay soil at depths of 4, 8, 16 and 32 cm. The top layer of this soil had been dug up to a depth of about 35 cm in the early spring of 1950, after which grass was sown. Therefore the soil showed little variation in composition and packing in the upper 35 centimeters. The measurements at 32 cm depth proved to be unreliable however, probably owing to the presence of air in the neighbourhood of the measuring element. These measurements were therefore discarded hereafter.

Duplicate soil samples were taken at each of the four depths mentioned above with the aid of steel rings of about 5 cm diameter and 5 cm length. These samples were oven-dried at a temperature of 105° C. The average weight of dry material obtained in this way was 1.56 ± 0.04 g/cm^3. The weight of plant roots was determined separately by treating one of the samples for each depth with a solution of sodium nitrate. The density of this solution was adjusted in such a manner that the roots became floating on its surface. This weight was in all cases less than 0.005 g/cm^3. This small amount of roots was neglected in the subsequent calculations of the thermal conductivity.

The density of the dry material was measured with a pycnometer; this determination yielded a value of 2.63 g/cm^3. Thus the average volume fraction of solid material in the soil, x_s, equals 0.59.

The samples which had not been treated with sodium nitrate were wetted again and the thermal conductivity was measured at different moisture contents. The value of x_s during these determinations was slightly different from the original one, viz. 0.57 in stead of 0.59. The experiments were carried out at room temperature (about 20° C). The experimental points are represented by open circles in fig. 1.

These experiments provided a starting point for a theoretical calculation of the calibration curve. For a detailed description of calculations of this kind we refer to a previous paper (DE VRIES, 1952 a). Some additional information pertaining to the case under consideration is presented below in small type. The resulting theoretical calibration curve is shown in fig. 1 (lower curve).

In accordance with previous work the depolarizing factor in the direction of the short axis of the oblate spheroids representing the soil particles was taken equal to 0.75, which corresponds to a ratio of 5 : 1 between the long axis and the short axis.

The value of the thermal conductivity of the soil particles which gave a best fit to the experimental points was 9.5 millical/cm sec °C.

It was assumed that the contribution of the destillation of water to the heat transfer ($\lambda^{(v)}_l$ in the notation of de Vries (1952 a)) decreases from its value in saturated soil to zero in the moisture range $0.10 < x_w < 0.15$.

The calibration curve for $x_s = 0.59$ was obtained from theory, using the same values for the parameters as in the calculations referred to above. This curve is also represented in fig. 1 (upper curve). Both curves in fig. 1 hold for a temperature of 20° C. A second curve was computed for a temperature of 10° C. The latter curve can be found approximately from the curve at 20° C by multiplying the ordinates with a factor 0.96.

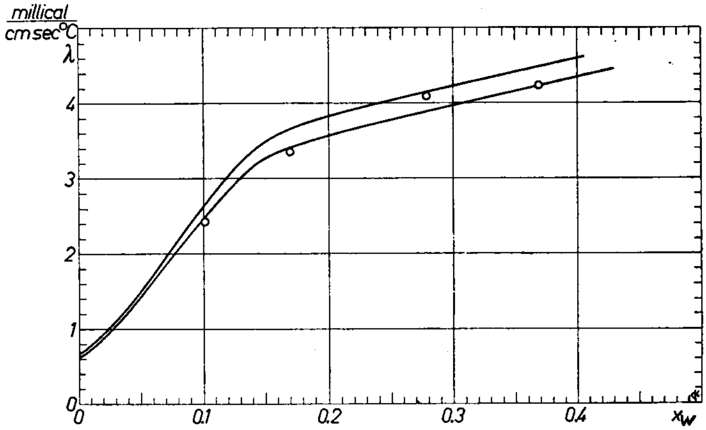

Fig. 1. Relation between the thermal conductivity, λ, and the volume fraction of water, x_w, for a field soil. Lower curve : $x_s = 0.57$, upper curve $x_s = 0.59$. Laboratory determinations for $x_s = 0.57$ are denoted by open circles.

3 Results of field measurements

The experimental results obtained in the field during a part of the growing season of 1951 are represented in the figs. 2, 3 and 4.

The time between consecutive measurements in fig. 2 varies from one or two days in the beginning of the period to several days toward its end. No measurements were carried out between September 3rd and September 24th. The lines connecting the points are introduced as a visual aid, they do not mean to represent the actual variations. In most cases the measurements were performed between 8 h and 9 h local mean time. In fig. 2 determinations of the thermal conductivity at 4 cm depth in bare sand are included as well.

Figures 3 and 4 show two cases of a diurnal variation of λ and x_w together with the variation of soil temperature at the corresponding depths. The thermal conductivities belonging to the values of x_w in figure 3 were published previously (de Vries, 1952, a, b).

4 Discussion

A general idea of the variation of the soil moisture content with time can be obtained by comparing the precipitation P, during a certain period, e.g. one month, with the potential evapotranspiration values (E_l) for the same period. Some numerical results for the case under consideration are presented in table 1.

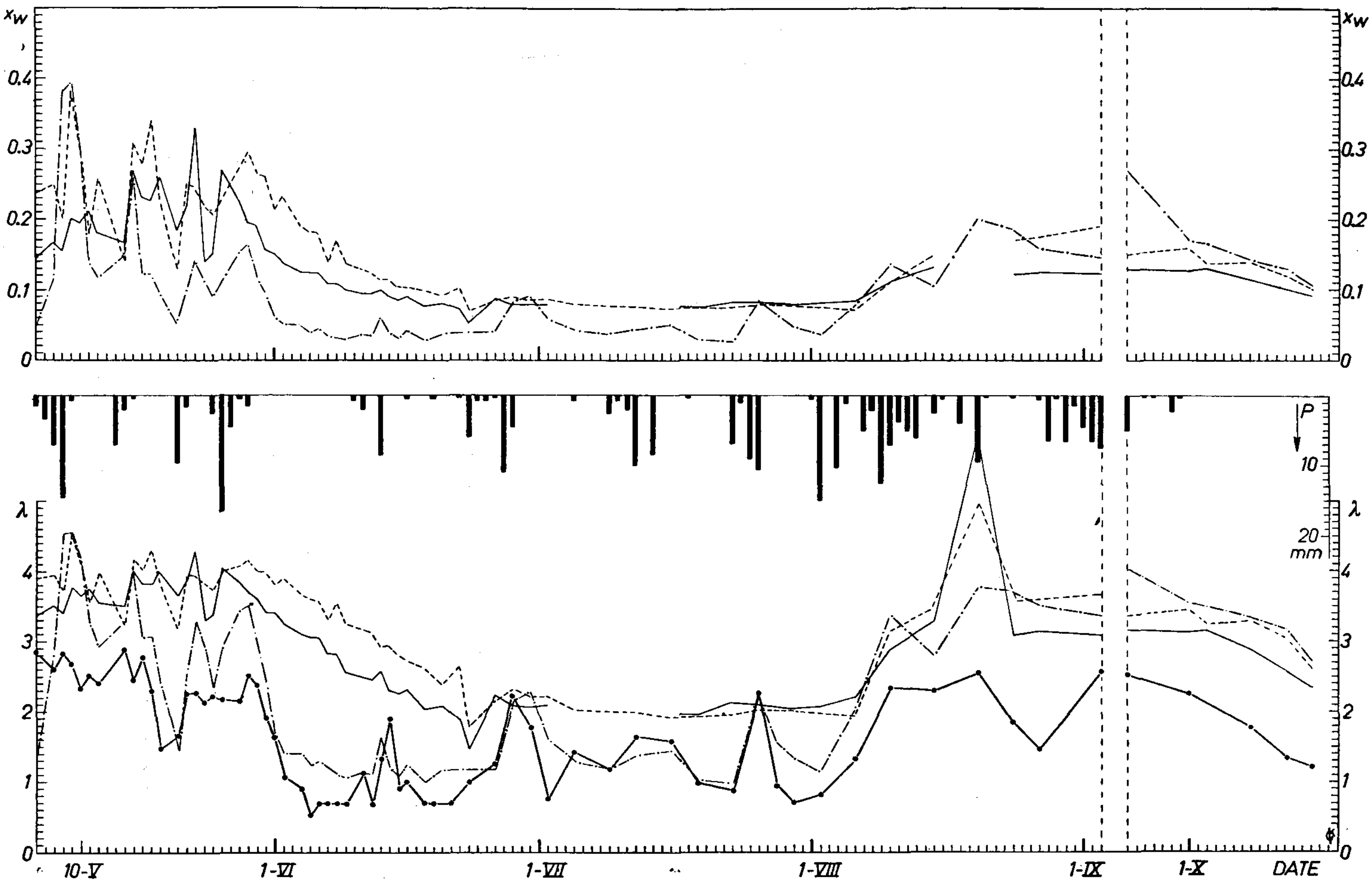

FIG. 2. LOWER PART : THERMAL CONDUCTIVITY, λ (IN MILLICAL/CM SEC °C) AT 3 DEPTHS IN A CLAY SOIL CROPPED WITH GRASS (– · — · 4 CM, ——— 8 CM, - - - - 16 CM DEPTH) AND AT 4 CM DEPTH IN BARE SAND (.——.). P = RAINFALL DURING 24 H MEASURED AT 8 H LOCAL MEAN TIME.

UPPER PART : VOLUME FRACTION OF WATER, x_w DEDUCED FROM λ .

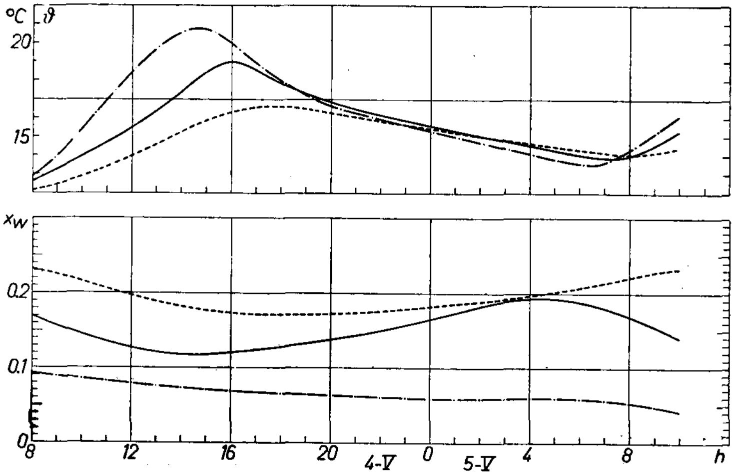

FIG. 3. VARIATION OF x_w AND OF TEMPERATURE, ϑ, ON MAY 4TH—MAY 5TH, 1951.
— · — · 4 CM, ——— 8 CM, - - - - 16 CM DEPTH.

The potential evapotranspiration was calculated according to PENMAN'S (1948) theory, using meteorological data from the experimental site of the Laboratory for Physics and Meteorology, where the thermal conductivity determinations were carried out as well. The figures in the last column represent the integrated soil moisture contents in the soil layer between 4 and 16 cm depth (in cm^3 of water/cm^2 of soil surface) at the beginning and at the end of each period. To obtain these figures the values of x_w were plotted against depth for each date in question, a smooth curve was drawn through these plots, after which the

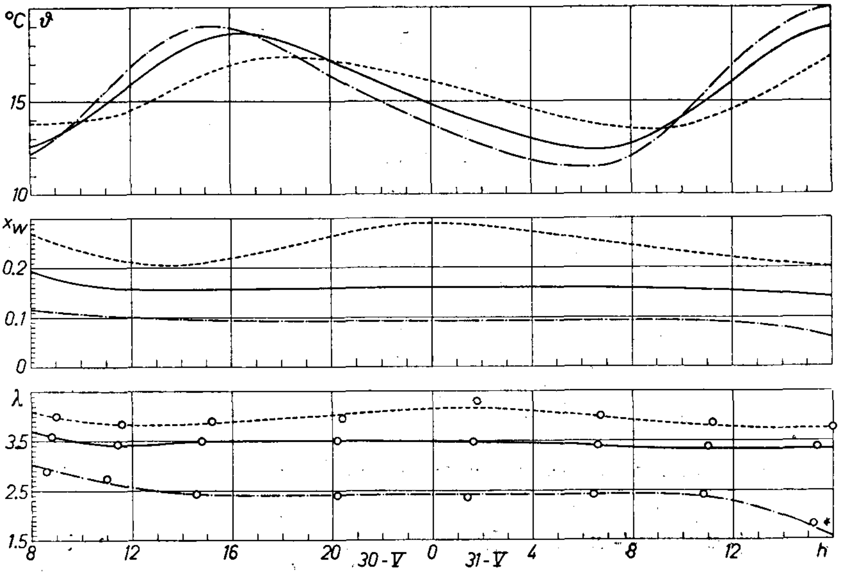

FIG. 4. VARIATION OF λ, x_w AND ϑ ON MAY 30TH—MAY 31ST, 1951.
— · — · 4 CM, ——— 8 CM, - - - - 16 CM DEPTH.

Table 1. A comparison of precipitation, P, potential evapotranspiration, E_T, and soil moisture content between 4 and 16 cm depth.

Period	P (cm)	E_T (cm)	Soil moisture (cm)	
			beg.	end
May 5 – May 31 ..	7.13	7.1	1.9	1.9
June 1 – June 30 ..	3.66	9.6	1.9	1.0
July 1 – July 31 ..	5.35	9.4	1.0	0.9
Aug. 1 – Aug. 31 ..	10.11	7.0	0.9	1.6
Sept. 1 – Sept. 30 ..	5.21	4.1	1.6	1.7

moisture content was found from a determination of the appropriate area with a planimeter.

Starting from May 29th E_T is in excess of P and a decrease of moisture in the deeper layers occurs. The thermal conductivities at 4 cm depth generally show a marked response to rainfall, both in the sand and in the clay soil. The moisture contents in the latter are apparently small for this rather heavy soil (the wilting point is estimated to correspond to $x_w \simeq 0.15$). The fact that the measurements at 4 cm depth show no response to a rainfall of 15 mm on August 2nd indicates on the other hand that the top layers of the soil were extremely dry by that time.

During August the rainfall exceeds E_T and a refilling of the soil moisture storage occurs. The abnormally high values of λ at August 20th are probably caused by additional heat transfer owing to percolating rain water. No moisture contents were assigned to these values. In the period August 28th–September 3rd the observed response of soil moisture to rainfall is below expectation.

A consideration of figures 3 and 4 shows that a diurnal variation of x_w with an amplitude of 0.05 may occur, probably as a consequence of the influence of temperature on surface tension and on vapour pressure.

An attempt was made to compare the net gain of heat, Q, into the soil layer between 8 and 16 cm depth during a certain period, τ, with the heat stored in this layer, S, as calculated from the observed temperature rise.

If we consider a vertical soil cylinder with a cross section of 1 cm², Q and S are represented by the following formulae:

$$Q = \int_{t}^{t+\tau} \left\{ \left(\lambda \frac{\delta \vartheta}{\delta z}\right)_{z=16} - \left(\lambda \frac{\delta \vartheta}{\delta z}\right)_{z=8} \right\} dt$$

$$S = \int_{t}^{t+\tau} \int_{8}^{16} C \frac{\delta \vartheta}{\delta t}\, dt\, dz$$

Here t = time, z = the vertical coördinate, increasing in a downward direction and C = the heat capacity per unit volume of soil. C can be calculated from: $C = x_s C_s + x_w C_w + x_a C_a$, where the index a refers to air. The term $x_a C_a$ is negligible, $C_w = 1$ and $C_s \approx 2.63 \times 0.19$ cal/cm³ °C (cf. KERSTEN (1949)).

For the period of 13 h till 15 h on May 4th the calculated values of Q and S

are for instance 4.6 cal/cm^2 and 5.4 cal/cm^2 respectively. The agreement between these figures is reasonable, if one considers that there exists an uncertainty of about 20% in the values of $\delta\vartheta/\delta z$, which had to be determined from temperature measurements at 4 depths only. To obtain accurate values of this quantity a much more detailed temperature profile would be required. As a consequence of this large uncertainty in the determination of the temperature gradient, a comparison of Q and S does not provide a check on the determinations of λ and x_w.

The experimental accuracy of the λ-values is about 5 % in most cases. The uncertainty in the values of the moisture content is therefore rather large, especially if $x_w > 0.15$ (cf. fig. 1) where the error in x_w may amount to 0.06. In the latter region of x_w-values this quantity will also be largely affected by uncertainties in the volume weight of the soil.

Accurate determinations of the moisture content from thermal conductivity data will only be possible if the moisture range between field capacity and wilting point coincides with the steep section of the calibration curve. This will generally be the case with sandy soils. Moreover these soils show no marked shrinkage on drying, so that the danger of a deterioration of the thermal contact between the measuring elements and the soil is small. Thermal conductivity measurements in a sandy soil are now in preparation.

LITERATURE

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