OPTIMAL DEPTH OF DRAINAGE [1]

J. WESSELING [2] and W. R. VAN WIJK

Laboratory of Physics and Meteorology,
Agricultural University, Wageningen (Holland)

SUMMARY

Maximum depth of drainage is calculated by considering potential and actual evapotranspiration, storage of water in the soil and capillary transport; the last-mentioned factor, however, proves to be unimportant. The criterion is, that no shortage of available water must occur during the growing season, as this would cause a decline in yield. It is found that, as regards arable crops under Dutch weather conditions, no shortage of water is likely to occur in the case of deep drainage (130 cm deep or more) in heavy clay soil.

However as regards a grass crop that is kept short by grazing or mowing, shortage of water may already occur in the case of drainage below a depth of 50 cm. The influence of a varying water table can be explained. If the water table is raised even for a short period, part of the drained soil is restored to field capacity, and this becomes important in a dry season. A definite decline in yield occurred in the case of various crops with a water supply which was less than 0.7 times potential evapotranspiration (P.E.). When the water supply exceeded 0.75 times P.E., yields were satisfactory.

INTRODUCTION

Depth of drainage is determined on the one hand by the necessity for good aeration of the soil layer penetrated by the roots, and on the other by the necessity for a sufficient supply of water during the growing season. To a certain extent the two requirements are conflicting. A low water table results in an increase of the air content of the upper soil layers, thus improving aeration of the roots; but it reduces the amount of water stored in the root zone. At present it is difficult to calculate the influence of aeration. It is, however, possible to calculate the amount of water which is evaporated during the growing season of a well-developed crop when abundantly supplied with water. In accordance with the usage of THORNTHWAITE and others we shall call this amount of water the potential evapotranspiration (P.E.) (cf. THORNTHWAITE (1948), PENMAN (1949), VAN WIJK and DE VRIES (1954) [3]).

A limit for the depth of drainage can thus be based on the demand that the water stored in the root zone which is available to the plant must equal P.E. minus the water supplied by precipitation or by other means. In that case, one can be certain that no shortage of water will occur. It seems probable that a somewhat greater depth of drainage will not harm the crops. At this moment, however, little is known about the response of crops to water deficiency. An empirical reduction factor, to calculate allowable water deficiency as compared with P.E., has been tentatively derived. In the present article, calculated P.E. and actual evaporation have been compared in relation to crop yields. Owing to variation in weather from year to year, P.E. will

[1]) Received for publication November 22, 1954.

[2]) Member of the staff of the Government Service for Land and Water Use, temporarily at Wageningen.

[3]) BLANEY and CRIDDLE (1950) use the term consumptive use of water which comes very close to P.E.

also show variations, and it is therefore necessary to decide upon a rational depth of drainage which is such that water shortage will not occur in an "average" year, or only once in 5 years, or conform to a similar principle.

We shall now calculate the depth of the water table at which sufficient water will be available for the plants to attain P.E. times an empirical factor, under average conditions in the Netherlands.

The available water in a drained soil consists of the amount stored in the root zone that can be extracted between field capacity and a suction corresponding to the wilting point (16 atmospheres, pF 4,2), and of the quantity of water that can be supplied by capillary transport from the soil below the root zone.

Available water in a clay and in a sand soil

The amount of water stored in the ground can be calculated from the moisture sorption curve if equilibrium is reached. It is assumed that this is the case at the beginning of the growing season. The water content of the soil at a height z above the phreatic surface is then the amount which corresponds to the suction of a water column of z centimetres. The moisture sorption curves of a heavy clay soil (Richards, 1931) and a sand soil containing approximately 5% of humus are represented in Fig. 1 A. The degree of saturation at which wilting occurs is 14% by vol of water in the clay soil and 10% by vol in the sand soil, corresponding to pF = 4.2 in both cases.

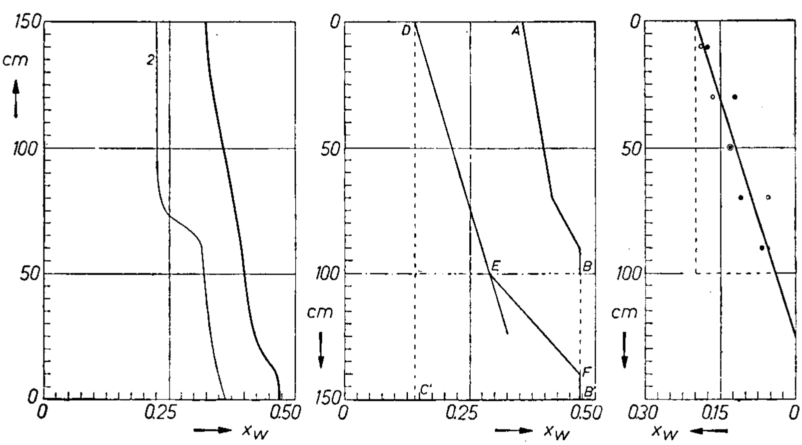

Fig. 1. a) Moisture sorption curve for a heavy clay soil (Richards (1931)) (1), and a sandy soil at Wageningen containing approximately 5% humus (2).
b) Scheme for calculating the total amount of available water in a clay soil in the case of a water table at 100 cm in spring and at 150 cm in autumn. AB is taken from the moisture sorption curve, and represents the moisture content in spring. CD represents the moisture content at wilting point (pF = 4.2). DE is taken from Fig. 1C and represents the maximum uptake of moisture by plants at various depths. The area EFB is the calculated moisture content for a capillary transport of 0.2 cm/day. The total amount of available water at a root depth of 100 cm is shown by the area DEFBA.
c) Uptake of water from May 1st for winter wheat (open signs) and rye grass (black signs), in the extremely dry year of 1947, after Verhoeven (1953). Samples were taken from the layers 0–20, 20–40, 40–60, 60–80 and 80–100 cm below surface. The continuous straight line shows the maximum amount of water that can be taken up from the soil. Note that no water is taken up at depths below 125 cm.

The available moisture stored in the clay soil when the water table is 100 cm below the surface in shown in Fig. 1 B.

The water content of the soil in relation to depth is given by its moisture sorption curve A.B. Water below 14% by vol is not available to crops, and thus the surface A.B.C.D. represents the water stored in the soil which is available in principle to a crop if its roots can penetrate to a depth of 100 cm. When the water table is lower the moisture sorption curve A.B. is shifted downwards, and, when the water table is at a shallower depth than 100 cm it is shifted upwards. The water available to plants varies accordingly, but the depth to which roots can penetrate must be estimated for each depth of the water table, in which root activity varies with depth.

In general, plants take up more water from a shallow depth than from deeper layers. Accordingly, this fact should also be taken into account in estimating the available water in the root zone.

Table 1. Uptake of water in centimetres for rye grass and winter wheat on a light clay soil in 1947 (data after VERHOEVEN, 1953).

Layer in cm	0–20	20–40	40–60	60–80	80–100
Rye grass	3.5	2.3	2.6	2.2	1.3
Winter wheat	3.6	3.3	2.6	1.1	1.0

The following method has been used for this purpose. The variation in uptake of water from different depths, as measured by VERHOEVEN (1953), is shown in Table 1. The figures pertain to winter wheat sown in the autumn and to rye grass sown in 1946 for the very dry growing season of 1947. Since a considerable water deficiency occurred in that year these figures probably represent the maximum amount of water that could be assimilated from the soil. Instead of 18% by vol of water, as in the layer 0–20 cm, only 5% by vol is taken up by the plant roots in the layer at a depth of 80–100 cm. The data from Table 1 have been plotted in Fig. 1 C, and a straight line has been drawn through the experimental points. The percentage of water, i.e. 18% by vol, which is taken up from the upper layer is approximately equal to the difference of soil moisture between field capacity and pF = 4.2. The soil in the surface layers therefore seems to have been depleted to wilting point by the plant roots. Consequently, the water available to the plants in the clay soil represented in Fig. 1 B is not shown by the area A.B.C.D., but is smaller and is, for instance, equal to the area A.B.E.D. The line D.E. in Fig. 1 B has been drawn parallel to the straight line of Fig. 1 C, through point D. In doing this, it is assumed that the amount of water represented by the area D.C.E. is not available to the plant [4]).

The quantity of water that can be supplied by capillary transport from the subsoil into the root zone has been ascertained by VERHOEVEN (1953) to be 3 cm/year in clay soils.

[4]) The curve has been drawn on the assumption of a constant mineral content of the soil per unit of volume. Actually the mineral content increases with depth, but it is doubtful wether, in view of the present degree of accuracy of the theory, it is advisable to take this refinement into consideration. The density of air dry soil is, for instance, 1.25 g/cm^3 in the layer 0–25 cm, and 1.60 g/cm^3 below a depth of 25 cm.

VERHOEVEN calculated capillary transport from salt and moisture figures determined in the course of the summer. The increment of salt content in a column of soil was divided by the concentration of the salt solution at the bottom of the column. It was assumed that this concentration had remained constant during the period of observation. The salt content in a layer 0—100, for example, amounted to 0.070 g/cm² on April 1st, and to 0.100 g/cm² on June 1st. The increase in the salt content of the column during this period was therefore 0.030 g/cm². The salt concentration at the bottom of the column during this period was 15 g/l, and thus a capillary rise from subsoil into the column 0—100 cm of $\frac{0.030}{15}$ l/cm² = 2 cm was calculated.

If the capillary conductivity K of the soil is known, capillary rise can be calculated from DARCY's law $V = K^h/l$, in which:

V = velocity of flow in cm³/cm² sec.
K = capillary conductivity coefficient in cm/day.
h = hydraulic head in cm water column.
l = length in cm.

It is assumed that the capillary transport is 0.2 cm/day and that the conductivity coefficient is constant throughout every range of 10 cm. Fig. 2 represents the capillary conductivity coefficient at different tensions as determined by RICHARDS (1931) [5]) in respect of the clay of Fig. 1A. In the layer 0—10 cm above the water table the conductivity coefficient is 2 cm/day. The pressure gradient which causes a transport of 0.2 cm/day is $\frac{0.2}{2} = 0.1$ cm water/cm. The suction at 10 cm above water table must then be $10 + 1 = 11$ cm. With a suction of 11 cm, a conductivity coefficient of 0.7 cm/day is read from Fig. 2. The required pressure gradient for transport of 0.2 cm water/day throughout the soil layer 10—20 cm above water table is $\frac{0.2}{0.7} = 0.3$, and the suction at 20 cm above water table must be $11 + 10 + 3 = 24$ cm. The required pressure gradient can be calculated for other layers in a similar way. Table 2 represents the suction required at different distances above water table. In the case of a suction of about 150 cm, capillary transport is zero, according to RICHARDS. The corresponding moisture contents can be found from the moisture sorption curve. It appears from Table 2 that transport of 0.2 cm/day is possible up to a distance of 50 cm above water table. This means that, if the water table is 50 cm beneath the root zone, the moisture content in the different layers will be represented by EFB[1] in Fig. 1 B. The quantity of

---

[5]) According to RICHARDS's investigations K is measured in seconds according to the formula Q = K.F., in which Q is velocity of flow in cm³/cm²sec and F is the water-moving force in dynes/gram. The unit of measurement of K is therefore cm³/cm²sec × sec²/cm = sec. MUSKAT (1946) defines K as $\frac{\text{volume/area}}{\text{time (pressure gradient)}}$. Conversion into conventional permeability units, and expression of the water-moving force in dynes/gram, give a pressure gradient (dynes/cm²)/cm, and the unit of measurement of K becomes $\frac{\text{cm}^3}{\text{cm}^2\text{sec(dynes/cm}^2\text{)/cm}}$. In order to express K in cm/day RICHARDS's values must be multiplied by $9.7399 \times 10^2 \times 86{,}400$ (cf. MUSKAT: Conversion Table for Permeability Units, p. 75).

Table 2. Suction and moisture content at different distances above the water table for a capillary transport of 0.2 cm/day in a clay soil.

Distance above water table (cm)	Suction cm water column	Moisture content % by vol
10	11	47
20	24	42
30	42	40
40	94	35
50	187	29

water supplied by capillary rise is then represented by the area EFB. For the clay soil under discussion the total quantity is 3.5 cm [6]).

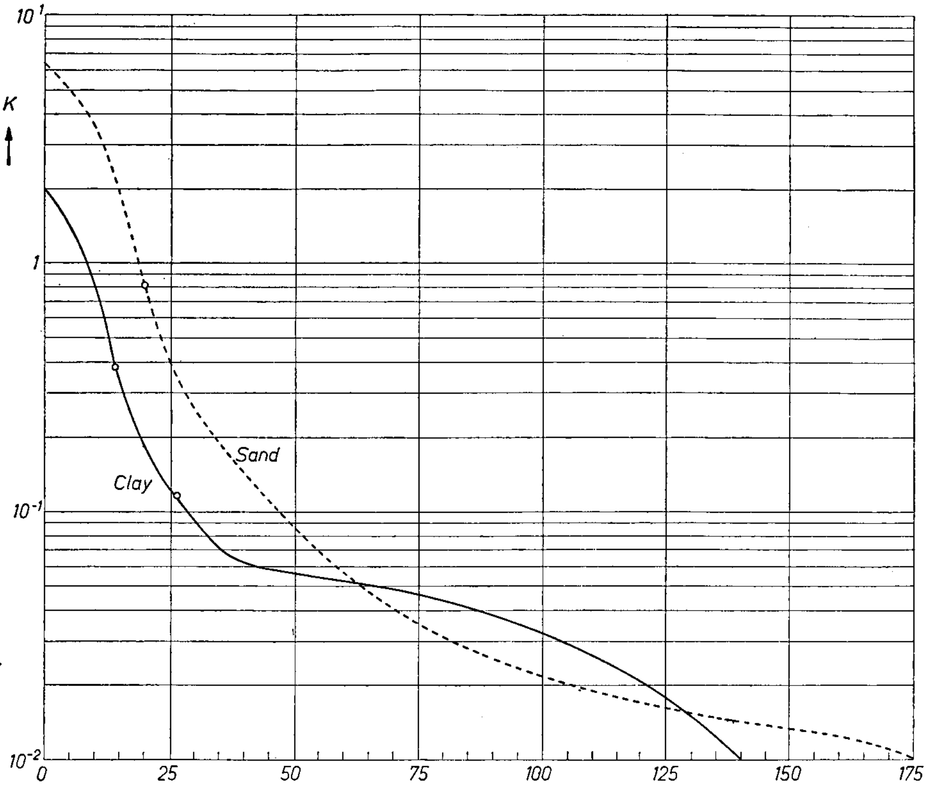

FIG. 2. RELATION BETWEEN CAPILLARY CONDUCTIVITY COEFFICIENT K AND TENSION IN CM WATER COLUMN, IN THE CASE OF A HEAVY CLAY SOIL (CONTINUOUS LINE) AND BENNET SAND (DOTTED LINE), AFTER RICHARDS (1931). K IS DEFINED AS CM/DAY, AT A PRESSURE GRADIENT OF 1 CM H_2O/CM.

---

[6]) In a later article RICHARDS and MOORE (1952) give more detailed conductivity data for the clay soil under discussion, which data differ slightly from those of Fig. 2. Exact calculation of the capillary rise from these data showed, that 0.2 cm/day can be transported at 62 cm above the water table, assuming that transport of water in the liquid phase is possible to approximately wilting percentage.

No capillary conductivity coefficients are available in respect of the sandy soil. It is assumed that the capillary behaviour of this soil is the same as that of Bennet sand (Fig. 2). In this way the capillary rise has been ascertained to be 2 cm/year.

The total amount of available water in the case of various water tables and root depths is represented in Figs. 3 A and 3 B, for the clay and the sand soil respectively.

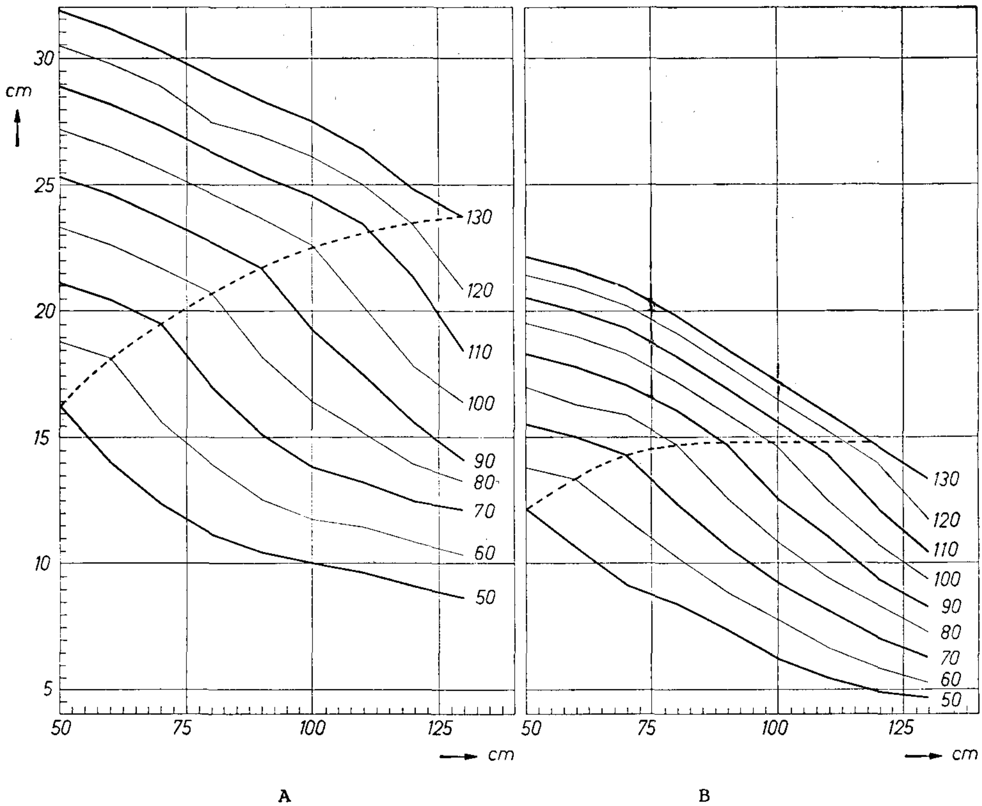

FIG. 3. TOTAL AMOUNT OF AVAILABLE WATER (ORDINATE) AT VARIOUS DEPTHS OF WATER TABLE IN SPRING (ABCISSA). The left-hand set of curves pertains to the heavy clay soil, the right-hand set pertains to the sandy soil. The figures near each curve indicate maximum penetration of roots at the end of the growing season. In the case of the points lying on the dotted curve, penetration of roots equals depth of water table, in spring.

WATER REQUIREMENT OF CROPS

Having calculated the content of available water in a soil in respect of various depths of water table, the next step is to estimate the requirements of water for a crop. If the latter is known, the maximum depth of drainage can be determined. This is the depth at which the available water in the soil equals the difference between water requirement and rainfall. One may equate the quantity of water taken up by a plant with the quantity which is evaporated by it, as only a negligible fraction (1% or less) is stored in the tissues or consumed in the synthesis of organic matter. Thus, the evaporation of a crop must now be calculated. A method of doing this has been described by PENMAN (1949), for the case of a crop which covers the soil completely, owing to growing under favourable conditions, and which is abundantly supplied with water. The method consists in calculating the amount of heat which is available for evaporation under the prevailing weather conditions and applying an empirical reduction factor. This reduction factor was determined for a short grass cover of considerable extent in England, but can probably also be applied approximately to other vegetation covers of great horizontal extent, provided the surface is flat and the soil is completely covered. The amount of water thus calculated will be called the potential evapotranspiration (P.E.), according to THORNTHWAITE (1949) and others, in order to distinguish it from actual evaporation from the crop. The latter can never exceed P.E. but it may fall considerably below P.E., owing to shortage of water in the soil or to other causes [7]).

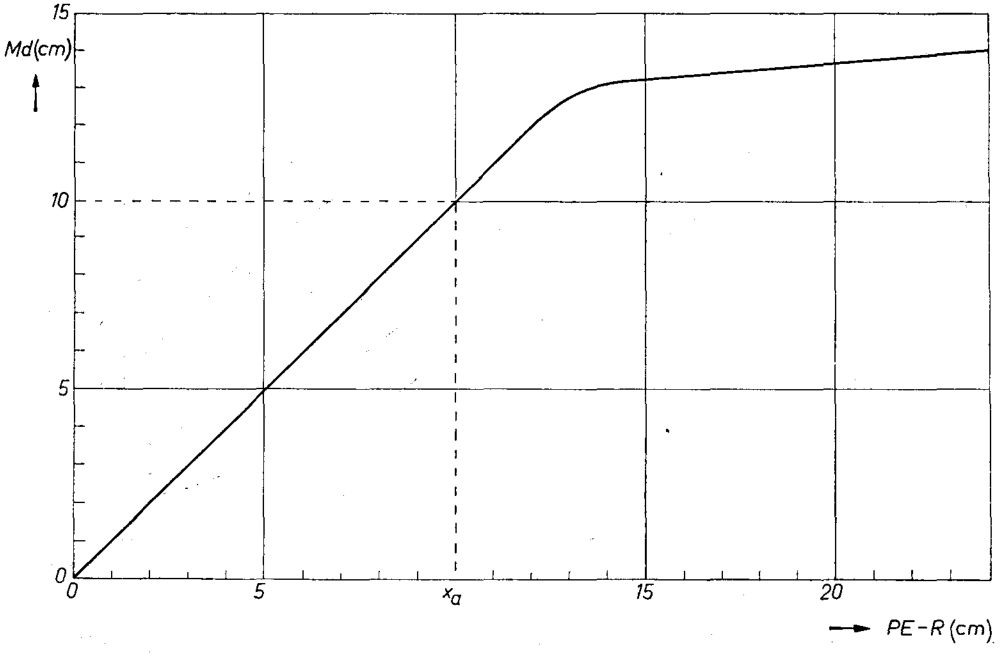

FIG. 4. RELATION BETWEEN POTENTIAL EVAPOTRANSPIRATION MINUS RAINFALL (P.E.—R) AND MOISTURE DEFICIT IN THE SOIL (Md), AFTER PENMAN (1949). The moisture deficit is defined as the water content of the soil minus water content at field capacity. The distance OX_a represents the quantity of available water in the root zone. If this amount of water has been transpired by the plants, transpiration does not drop immediately, owing to supply of water from the soil below the root zone throughout the entire growing season.
After consumption of this extra quantity of water actual transpiration will rapidly decrease. The slope of the curve for a moisture deficit of approximately 12.5 cm is the same as for a bare soil.

BLANEY and CRIDDLE (1950) express water need of crops in terms of "consumptive use of water". This covers both evaporation and transpiration for a

[7]) Actual evaporation from a vegetation cover consisting of plants of different heights can exceed the P.E. relevant to a horizontal, flat, vegetation cover (cf. VAN WIJK and DE VRIES (1954)).

crop which is sufficiently supplied with water during the entire growing season. It is slightly different from potential evapotranspiration since the evaporation from bare soil during the period that the soil is not completely covered by the crop is also taken into account. Actual evapotranspiration remains below "consumptive use", if shortage of water occurs during the growing season [8]). In principle, the quantity "consumptive use of water" could be used instead of P.E. in the following calculations.

A considerable shortage of water definitely has a detrimental effect on crop yield. On the other hand, very high yields have been obtained in the case of an actual evaporation which was less than P.E. (VAN DUIN, 1953; BAUMANN, 1949, 1951; UHLIG, 1951). It is at present not possible to calculate beforehand the minimum amount of water which plants must have if the yield is not to decline. In the following cases, therefore, P.E. has been calculated, and it is compared with experimental data on actual evapotranspiration.

For the Netherlands P.E. has been calculated by VAN DUIN (1954) in respect of the period 1947 until 1951, inclusive. The results are given in Table 3.

Table 3. Potential evapotranspiration minus precipitation, in cm, in the Netherlands (after VAN DUIN (1954)).

Years	March	April	May	June	July	Aug.	Sept.	Oct.	Total [9])
1911—1950	—1.2	+0.6	+4.6	+6.1	+3.1	+1.0	—2.3	—5.1	+15.4
1947	—6.1	+2.0	+6.3	+7.7	+6.5	+8.3	+1.2	+0.8	+32.8
1948	+0.8	+1.7	+5.4	+3.5	+2.2	+0.4	+0.6	—1.6	+14.6
1949	—0.4	+1.3	+3.2	+8.8	+7.9	+3.4	—0.8	—4.9	+24.6
1950	+0.9	—1.3	+2.5	+8.2	+0.4	—0.1	—7.5	—1.5	+12.0
1951	—4.6	—1.3	+3.5	+6.0	+5.0	—2.5	—1.8	+0.1	+14.6

Actual evaporation for some crops has been determined by BAIER (1952), ATANASIU (1948), FRECKMANN and BAUMANN (1937), MOREL and RICHER (1953) and UHLIG (1951), by frequent sampling of the soil in order to measure its moisture content.

By way of example, the data of FRECKMANN and BAUMANN are given in Table 4. Experiments were carried out near Berlin, in Germany.

Table 4. Water uptake (cm) in 1935 from soil layer 0–80 cm (after FRECKMANN and BAUMANN).

	Available moisture	Uptake by		
		Wheat	Sugar beets	Rye grass
Clay	14.5	11.7	12.2	14.8
Loam	11.3	10.5	12.7	11.9
Sandy loam	10.3	11.5	12.4	13.0
Loamy sand	12.1	9.8	10.4	11.9
Sand	7.4	4.0	4.5	5.4

8) Consumptive use of water is estimated by irrigation engineers from mean monthly temperatures and monthly average of day length. Since the relation between temperature and the energy which is available for evaporation varies in course of a year and is also different for different regions, similar limitations are expected to hold in this case as with P.E. (cf. VAN WIJK and DE VRIES (1954)).

9) Totals refer to the sum of the positive figures only.

A maximum value of the actual uptake of water was determined for grass and oats in 1950 by BAIER (1952). The results were 15 cm and 11 cm respectively, for the period May until July, inclusive.

Similar experiments were carried out by VERHOEVEN (1953) in Zealand. In this case the crops were grown on soil which had recently been flooded with sea water, and it was therefore possible to determine the capillary rise of soil water from the displacement of salt in the soil (cf. page 109). Some representative data from VERHOEVEN's investigations have been collected in Table 5.

Table 5. Actual transpiration and water uptake from soil (cm), after VERHOEVEN (1953). g = good, m = moderate, p = poor.

Year	Crop	Yield	Period	Actual transpiration	Precipitation	P.E.	Uptake from soil Total	Root zone	Cap. rise	Actual Evp/P.E.
1947	Wheat	m	1/5– 1/8	23.9	11.9	35.5	12.0	9.1	2.9	0.69
	Grass	m	23/5–28/8	22.0	10.7	39.3	11.3	–	–	0.56
	Barley + alfalfa	m p	10/5– 1/9	23.7	11.6	44.6	12.1	9.1	3.0	0.53
	sugar beets (roots)	p	28/4– 2/9	25.4	13.3	48.5	12.1	–	–	0.53
	”	m	28/4– 2/9	30.4	13.2	48.5	17.2	14.2	3.0	0.63
	Grass	m	28/4– 2/9	32.8	13.6	48.5	19.2	–	–	0.68
	”	p	28/4– 2/9	23.6	13.6	48.5	10.0	–	–	0.49
	”	g	28/4– 2/9	34.3	14.3	47.8	20.0	–	–	0.72
1948	Various crops	g	9/3–30/8	47.0	32.6	49.2	14.4	–	–	0.95
	”	g	9/3–30/8	38.3	32.6	49.2	5.7	–	–	0.78
	”	g	9/3–13/9	43.0	33.4	53.4	9.6	–	–	0.80
1949	”	g	11/3– 2/9	49.0	32.6	51.4	16.4	–	–	0.95
	”	g	15/3–30/9	41.8	30.3	56.0	11.5	–	–	0.75

The seventh column contains the P.E., calculated according to PENMAN, and using his experimental factor 0.6–0.8 for the ratio of evaporation from a grass cover to evaporation from a wet horizontal surface. Satisfactory yields have been obtained from the crops for which the ratio of actual evaporation to P.E. exceeded 0.7. As the crop did not cover the soil 100 per cent throughout the entire period for which actual evaporation was determined, the latter figures include evaporation from the bare soil in August and September (precipitation exceeded evaporation in March, 1947).

In 1947, VERHOEVEN's investigations commenced in May. During April, however, P.E. exceeded precipitation by a certain amount. The observed actual transpiration in all periods is therefore too low. Taking this difference into account, it may be stated that the ratio of actual evaporation to P.E. must exceed 0.75 if a satisfactory yield is to be obtained.

A third method of calculating actual evaporation, which was originally used by PENMAN (1949), could be applied to data obtained by HUDIG and WELT (1911) in a trial field for drainage on a heavy clay soil. Depth of drainage ranged from 110 to 130 cm. The available quantity of water in the root zone was estimated at 10 cm. The relation between actual evaporation and P.E. is assumed to be represented by the curve of Fig. 4.

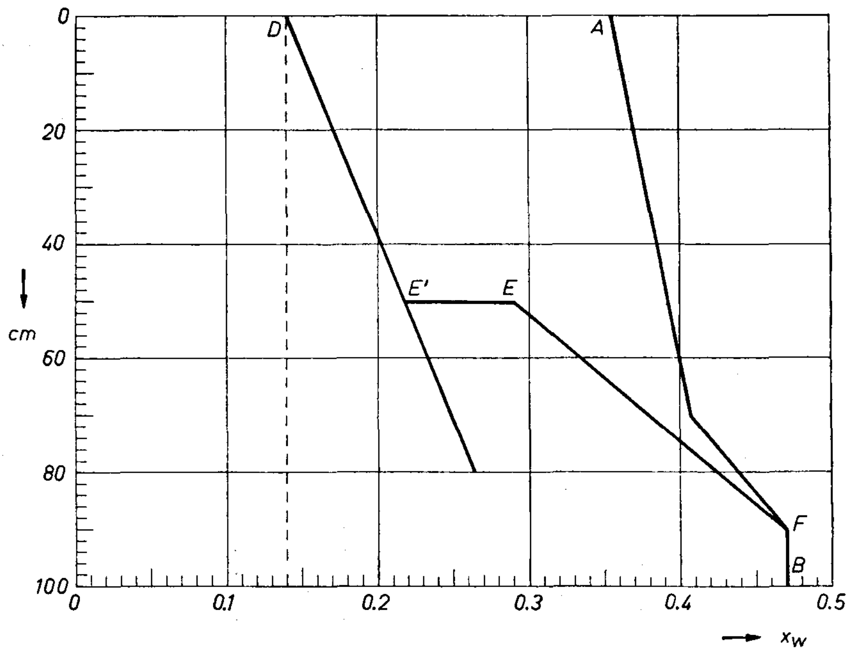

FIG. 5. SCHEME FOR CALCULATING THE TOTAL AMOUNT OF AVAILABLE WATER IN THE SOIL FOR A ROOT DEPTH OF 50 CM AND A WATER TABLE 100 CM BELOW THE SURFACE IN SPRING. THE TOTAL AMOUNT OF AVAILABLE WATER IS REPRESENTED BY THE AREA DE'EFA.

If the soil is assumed to be at field capacity when the drains stop running in spring and when they start running in autumn, it is possible to calculate the latter moment from P.E. and precipitation data with the aid of Fig. 5. Summing P.E.–R for each month, the moisture deficit of the soil can be read from the figure. If P.E.–R is negative, the drains will run. The distance OX^A represents the quantity of water in the root zone. This amount is variable. To determine OX_A the calculation is made for the year 1904, and OX_A estimated so that the actual instant at which the drains started to run coincided with the calculated one. In this case, $OX_A = 10$ cm. Using this amount, the instant at which the drains started to run in the years 1903 and 1905 till 1908 inclusive could be predicted to within 2 to 5 days.

The amount of water in the root zone (10 cm) is considerably greater than the amount represented by PENMAN's formula $C = 5.0–0.6 \Sigma R$, in which ΣR is the sum of the precipitation in April and May. Firstly the drainage depth is twice as great as in PENMAN's case. Secondly, all crops were deep-rooting; and thirdly, the moisture-holding capacity if the soil was probably better.

Table 6. Uptake of moisture from soil (cm) by various crops, calculated with the aid of Fig. 4 from data of HUDIG & WELT's drainage trial field.

Year	P.E. crop	Uptake	Highest deficit in soil in
1903	Caraway + vetch	5.2	June
1904	Barley	14.0	Aug.
1905	Oats	13.9	,,
1906	Flax + Clover	11.0	July
1907	Clover	11.7	Sept.
1908	Clover	3.0	Aug.

Depth of drainage

On the strength of the data discussed above, it would appear that a reasonable criterion for depth of drainage is that the soil in the root zone must contain 15 cm of available water at field capacity. This applies to conditions in the Netherlands and, judging from the passable yields of crops of wheat, barley and sugar beets in the abnormally dry year 1947, it seems a sufficiently safe criterion for agricultural engineering practice. In Table 7 the sum of 0.75 times P.E. minus precipitation is given for the years 1941 until 1951 inclusive (except 1945). From this table it appears that only in the very dry growing season of 1947 did water deficiency occur in respect of the above criterion.

Table 7. 0.75 times potential evapotranspiration minus precipitation (cm) for Netherlands climatic conditions. P.E. has been calculated after Penman (1949).

Year	March	April	May	June	July	Aug.	Sept.	Total [10])
1941	—64	+16	—27	+62	+44	—90	+12	122
1942	— 7	+24	+16	+47	—80	+11	—23	87
1943	+ 6	+11	+43	—12	+84	—29	—12	132
1944	— 9	+20	+35	+ 7	— 4	+54	—57	112
1946	—22	+28	+21	— 2	+22	—24	—56	69
1947	—67	+ 3	+38	+44	+34	+52	— 3	171
1948	+ 4	+ 1	+29	+ 6	— 3	—18	— 6	40
1949	—11	— 5	+10	+60	+50	+19	—12	139
1950	+ 0	—28	+ 3	+50	—15	—26	—87	53
1951	—54	—28	+11	+33	+25	—47	—30	69

Under other climatic conditions the present method of calculation would indicate that a different amount of available water would have to be stored in the root zone, equal to the difference between 0.75 P.E. and precipitation. It would be very interesting to check the value of the proposed criterion with reference to other climatic conditions.

The effective root zone may be estimated from Fig. 1 C, for cereal crops, to which the curve applies. Water has been taken up from the soil to a depth of 125 cm. In the case of a potato crop no active roots seem to penetrate below a depth of 100 cm (Goedewaagen, 1942), and in the case of grass which is kept short by mowing or grazing an effective root depth of 50 cm seems a reasonable estimate. The curve of Fig. 1 C is then applied to these different root depths by a reduction of the vertical scale as shown in Fig. 5. This is, of course, a crude approximation, but it will have to be made as long as experimental data pertaining to potatoes and grass are lacking.

The following maximum depths for drainage have been calculated by using the method described :

	a Clay soil	b Sand soil
cereal crops	> 130	110
potatoes	> 130	90
grass	50	< 50

[10]) Totals refer to the sum of the positive figures only.

From this it can be concluded that, whatever the depth of the water table may be, arable crops in clay will not suffer from shortage of water. Aeration is probably the most important factor in this case, since the shallow layers at 20 to 50 cm contain 12% by vol of air if the ground water lies 130 cm deep.

These conclusions are supported by the results of experiments (HOOGHOUDT, 1951). The sandy soil of Fig. 1 is rather abnormal, since it contains 5% of humus even at a depth of 130 cm. The above data are, therefore, not representative for a sand soil.

A very shallow depth of drainage is required to meet the water requirements of a grass crop. This opinion is supported by experience. Maximum yield was obtained with a water table at 50 to 60 cm on a sandy soil containing approximately 8% of humus in the upper layer (v. D. WOERDT, 1953) and on a clay soil the yield was increased by keeping the water table at a depth of 40 cm in the summer. The extent to which aeration becomes restrictive in the case of water tables at such shallow depths would appear to be worth investigating.

VARIATIONS IN WATER TABLE

So far calculations have been based on the assumption that the depth of the water table remains constant after it has reached a certain depth during the growing season.

It is, however, also possible to calculate the available water if the depth of the ground water level varies. The effect of such a variation on yield will differ according to P.E. and precipitation.

If precipitation exceeds P.E., as is the case, for instance, in winter and autumn, no advantage can be expected from a rise in the ground water level. On the contrary, damage may be done to the roots by bad aeration.

In a period when P.E. exceeds precipitation, raising the ground water level, even for a short time, restores part of the soil to field capacity, and this may be important if shortage of water is likely to occur at a later date.

This explains the empirical relationships reported by BLOEMEN (cf. VISSER, 1953), who found that an oscillating water table had an adverse effect on yield at a high average water level, but had an advantageous effect if the average level was low, e.g. at a depth of approximately 125 cm.

BIBLIOGRAPHY

ATANASIU, W.: Ein Beitrag zum Studium des Wasserverbrauches unserer Kulturpflanzen. *Zeitschr. Pflanzenernährung, Düngung und Bodenkunde* 42 (87) (1948) 103–123.

BAIER, W.: Ergebnisse von Bodenfeuchteuntersuchungen in Stuttgart-Hohenheim. *Ber. des Deutschen Wetterdienstes in der U.S. Zone* 6 (1952) 37–53.

BAUMANN, H.: Wasserversorgung und Ertragsbildung. *Zeitschr. Acker- und Pflanzenbau* 93 (1951) 497–513.

BLANEY, H. F. and W. D. CRIDDLE: Determining water requirements in irrigated areas from climatological and irrigation data. *U.S.D.A. Soil Cons. Service* S C S 96, 1950.

DUIN, R. H. A. VAN: Waterbehoefte der gewassen. *Landbouwk. Tijdschr.* 66 (1954) 240–243.

FRECKMANN, W. and H. BAUMANN: Zu den Grundfragen des Wasserhaushaltes im Boden und seiner Erforschung. *Bodenk. und Pflanzenernährung* 2 (47) (1937) 127–166.

GOEDEWAAGEN, M. A. J.: Het wortelstelsel der landbouwgewassen, 1942.

Hooghoudt, S. B. : De resultaten van het grondwaterstandsproefveld te Nieuw-Beerta. *Versl. Techn. Bijeenk. T.N.O.* 1–6 (1952) 56–63.

Hudig, J. and H. Welt : Het drainageproefveld te Uithuizermeden in de jaren 1901–1910. *Versl. Landb. Ond.* 10 (1911) 123–244.

Morel, R. and A. Richer : Etude de profiles hydriques sous différentes cultures dans un sol de limon. *Ann. Agron. Série A.* 4 (1953) 687–715.

Muskat, M. : The flow of homogeneous fluids through porous media. 1946. J. W. Edwards Inc. Ann Arbor, Michigan, U.S.A.

Penman, H. L. : The dependence of transpiration on weather and soil conditions. *J. of Soil Sci.* 1 (1949) 74–89.

Richards, L. A. : Capillary conduction of liquids through porous media. *Physics* 1 (1931) 318–333.

– – and D. C. Moore : Influence of capillary conductivity and depth of wetting on moisture retention in soils. *Trans. Am. Geoph. Union.* 33 (1952) 531–539.

Thornthwaite, C. W. : An approach toward a rational classification of climate. *The Geogr. Rev.* 38 (1948) 55.

Uhlig, S. : Die Untersuchung und Darstellung der Bodenfeuchte. *Ber. des Deutschen Wetterdienstes in der U.S. Zone,* 4 (1951), No. 30.

– –: Gedanken zur Auswertung der Bodenfeuchtebestimmungen. *Zeitschr. Acker- und Pflanzenbau* 93 (1951) 513–522.

Verhoeven, B. : Over de zout- en vochthuishouding in geïnundeerde gronden. Thesis, Wageningen, 1953.

Visser, W. C. : De grondslagen van de drainageberekening. *Landbouwk. Tijdschr.* 65 (1953) 66–81.

Wijk, W. R. van and D. A. de Vries : Evapotranspiration. *Neth. J. of Agric. Sci.* 2 (1954) 105–120.

Woerdt, D. van der : Nadelen van het overschrijden van de optimale watervoorziening bij blijvend grasland. *Landbouwvoorlichting* 10 (1953) 137–143.