COMMISSIE VOOR HYDROLOGISCH ONDERZOEK T.N.O.

COMMITTEE FOR HYDROLOGICAL RESEARCH T.N.O.

VERSLAGEN EN MEDEDELINGEN No. 15

PROCEEDINGS AND INFORMATIONS No. 15

SOIL - WATER - PLANT

TNO

SOIL - WATER - PLANT

SOIL - WATER - PLANT (Proceedings and Information No. 15)

ERRATA Chapter V, page 90-149

where α^{z} occurs, read: αz

page 102 eq. (4) read: $(1 - e^{-\alpha z_w})$

105 line 10 read: content v_r

107 in Fig. 9: Δ W is Δ z

108 in Fig. 10: Δ W is Δ z

109 in Fig. 11: E_w is E_r; dW is dz; Δ W is Δ z

113 table line 2 : 2.282 is 0.282

line 19 : CE is CF

117 line 8 read: In case of only micro-porosity, ΔP_s is zero. The.......

120 in subscript Fig. 18 read: of fig. 16B in......

124 note read: be transformed into: $\frac{de^{-\alpha\psi}}{dz} + \alpha e^{-\alpha\psi} =$

last line read: if $f(z)e^{-\alpha z}dz$

125 table under z_s read: $\alpha = 0.01$ 160 244 311

128 table read:

1	0	$20(1 - e^{-\alpha z})$	
2			$W = (z_o - 1/\alpha)\, v_c/(z_o + z_s)\, k_o$
11	280	500W	$W = \frac{(\alpha z_o - 1)}{\alpha(z_o + z_s)} \frac{v_c}{k_o}$

130 in eq. read: $4\, L\, k_o\, \psi_a^n$; in list of symbols ψ_e is ψ_a; $k_c = \left(\frac{\psi_a}{\psi}\right)^n k_o$

131 in Fig. 22: v^n is v^l

line 8 read: $E_r = A\,(v^l - v^l_{wp})$

132 in Fig. 23 on abscissa of right hand graph: log E is log E_o

133 in eq. : E_w is E_r

in Fig. 24: E_w is E_r; W is z

134 line 11 read: depth d and......

in eq. read: $D = \frac{8kd}{L^2}$ ......; in list of symbols: W = groundwater level above zero plane

under list of symbols: $|W|$ is equal to $|z_s|$ (the groundwater depth) if the soil surface is taken as zero plane.

135 last line read: by plotting D and W or D and S for

136 in eq. read: $\sqrt[1/m]{}$

138 line 14 read: on the D- and E_r - axes

142 eq. a read: $z = \frac{G\mu^n}{(P-\mu)^m}$

144 second last eq. on the right read: $= (\alpha z + bz^2)dt$

146 line 13 from bottom read: sum Σ R would..........

COMMISSIE VOOR HYDROLOGISCH ONDERZOEK T.N.O.

COMMITTEE FOR HYDROLOGICAL RESEARCH T.N.O.

VERSLAGEN EN MEDEDELINGEN No. 15

PROCEEDINGS AND INFORMATIONS No. 15

SOIL -WATER - PLANT

VERSL. MEDED. COMM. HYDROL ONDERZ. T.N.O. 15 - 'S-GRAVENHAGE - 1969

CONTENTS

I. Hydrology, soil properties, crop growth and land drainage, J. WESSELING . . . 9
1. Introduction . . . 9
2. Water in the soil . . . 10
3. Drainage equations . . . 11
4. The effect of the watertable depth on crop yield . . . 15
5. Other factors influencing crop yields . . . 21
6. The effect of drainage on farm management . . . 24
7. Summary and conclusion . . . 25
Literature . . . 26

II. On the relation between transpiration, soil physical properties and crop production as a basis for water supply plans, P. E. RIJTEMA . . . 28
1. Introduction . . . 28
2. Evapotranspiration . . . 29
3. Transfer of crop factors in relation to evaporation . . . 32
4. Water management of soils in relation to evapotranspiration . . . 36
5. Crop production and transpiration . . . 41
6. Characterization of drought sensitivity of soils . . . 48
7. Summary . . . 57
Literature . . . 57

III. Calculation of parameters for the evaluation of the leaching of salts under field conditions, illustrated by nitrate, G. J. KOLENBRANDER . . . 59
1. Introduction . . . 59
2. Formulation of leaching . . . 59
a. Factors determining the downward movement of ions . . . 59
b. Equations of Glueckauf and Day . . . 60
c. Transformation of the equation of Day . . . 62
3. Testing the modified equation of Day under field conditions . . . 65
a. Methods . . . 65
b. Results . . . 67
c. The distribution factor *K* . . . 68
4. Discussion . . . 70
5. Conclusions . . . 71
6. Summary . . . 72
Literature . . . 72

IV. Soil water content in relation to nutrient uptake by the plant, L. K. WIERSUM . . . 74

1. Introduction 74
2. Water content in relation to amount and mode of occurrence of readily available mineral nutrients 74
3. Soil water in its function of ion transporting medium 78
4. The absorbing root system in relation to water content of the soil . 82
5. Climatological aspects 85
6. General remarks 85
Literature 87

V. Rules of transfer of water management experience, with special reference to the assessment of drainage design constants, W. C. VISSER . . 90
1. Introduction 90
2. General rules of transfer 91
3. The diagram of relevant aspects 92
4. The rules of transfer for the prediction of crop response 93
5. General aspects of plant response 94
6. A plant physiological basis of water management 97
7. Assessment of the constants 98
8. A physical basis of water management 101
9. Determination of the soil moisture parameters 103
10. The water balance derived from moisture contents 104
11. The water balance derived from groundwater depth observations . 107
12. Methods of curve fitting and assessment of parameters 110
13. The relations in the unsaturated zone 113
14. The desorption curve 116
15. Assessments of the constants 117
16. The soil moisture profile 123
17. Calculation and assessment of constants 127
18. Evaporation and soil moisture content 129
19. Adjustment of constants 131
20. Evaporation and groundwater depth 132
21. Discharge and groundwater depth 134
22. Use of the formulae 136
23. Prediction of water balance variations 137
24. Prediction of crop response 139
25. Assessment of drain depth 140
26. Assessment of drain spacing 142
27. Summary 147

AUTHORS

J. WESSELING, Institute for Land and Water Management Research, Wageningen

P. E. RIJTEMA, Institute for Land and Water Management Research, Wageningen

G. J. KOLENBRANDER, Institute for Soil Fertility, Haren-Groningen

L. K. WIERSUM, Institute for Soil Fertility, Haren-Groningen

W. C. VISSER, Institute for Land and Water Management Research, Wageningen

I. HYDROLOGY, SOIL PROPERTIES, CROP GROWTH AND LAND DRAINAGE

J. WESSELING
Institute for Land and Water Management Research, Wageningen

1. INTRODUCTION

Drainage of agricultural land is a common measure, not only in humid regions, but also in irrigated arid regions. Drainage can be defined as the removal of excess water from the soil. The purpose of it is not only to improve conditions for plant growth, but also to facilitate tillage conditions. The many problems connected with drainage can be divided into some groups, viz:

1. Hydrological aspects

a. What excess of water can be expected under given climatological conditions?
b. How does drainage interfere in the flow of water. How fast is water removed and what amount remains in the soil?
c. How does drainage change the salt content and the leaching requirement of the soil (especially in irrigated areas)?

2. Soil physical and mechanical problems

a. How does drainage change the energy status of the soil moisture and which air content will occur?
b. How does the reduced moisture content of the soil influence the bearing capacity, temperature and other physical and mechanical properties of the soil?

3. Biological problems

a. What is the reaction of the crop on an excess of water and on changes in moisture and air content of the soil?
b. What is the effect of an earlier tillage and sowing date on the crop growth and the final yield of it?

4. Technical problems

When the requirements of the crop with respect to drainage are known, the question is, how to realize the required conditions, in other words how to design a drainage system which satisfies the conditions, not only with respect to crop growth, but also with respect to the aims set by modern agriculture (larger sites for mechanization).

In this article we will not discuss technical problems, but focus our attention to research on the three first mentioned problems. The main purpose is to show how various investigations on these types of problems can be used to obtain an insight in the problem of drainage.

2. Water in the soil

In figure 1, types of flow of significance for the drainage problems are schematically given. As in most branches of hydrology a distinction is made into unsaturated zone (soil moisture) and saturated zone (ground water). Although it may be stated that conditions in the first mentioned zone are of primary importance for crop growth, most of the research in drainage is done for the last mentioned zone. For this several reasons can be given. The first one is that it

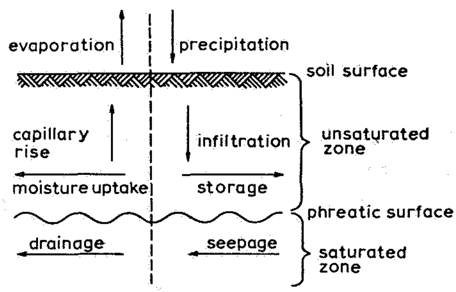


Fig. 1. Schematic diagram for the flow problems connected with drainage of agricultural soils

is much easier to measure a depth of a water table, than to determine say the energy status of the soil moisture. The second one is that flow phenomena in the saturated zone are much easier to describe than those in the non-saturated zone. A justification of the large number of investigations concerning ground water is perhaps that there is an interrelation between ground water and soil moisture.

The flow of water in the soil may be described by Darcy's law:

$$v = -K \text{ grad } \Theta \qquad (1)$$

where
v = flow velocity
K = hydraulic conductivity
Θ = potential or energy status of the water in the soil

The advantages of a mathematical description of flow as given above are:

a. the flow defined by eq. 1 is analogous with other physical processes as electricity, diffusion, flow of heat, magnetism, etc., so solutions found in other branches of physics can be applied immediately;
b. the flow can be simulated by means of models, as electric and viscous flow models;
c. solutions of problems are valid for all types of soils and transposing research results from one type of soil to another is always possible by means of the hydrological factors (hydraulic conductivity, effective porosity and thickness of the flow layers).

The difference between the unsaturated and the saturated zone is that in the latter one K may be considered as a constant. In the first case K is a function of the moisture content Θ or the suction ψ of the soil moisture. This fact complicates matters very much. Generally speaking only certain types of unsaturated flow are solved up to now. Apart from the complicating hysteresis effects, this is mainly due to the fact that there is in general no analytic expression for the relation between K and Θ (or ψ). The availability of digital computers, however, offers the possibility of obtaining numerical solutions.

In contrast with this there is a large variety of solutions available for groundwater flow problems connected with drainage, for both time independent (stationary or steady state) and time dependent (non-stationary or non-steady state) conditions.

3. Drainage equations

Especially in the Netherlands, where a great deal of the agricultural crops grows under groundwater influence, the conditions are favourable to design drainage systems on the basis of drainage equations. These equations are solutions of groundwater flow problems, linking together drain depth and spacing on one side and discharge and height of the water table on the other side.

Although drainage represents a non-steady state flow due to the fact that rainfall and evapotranspiration change from day to day, most of the drainage equations used in practice are steady state solutions of the flow problem. This, as already has been said, must be ascribed to the rather complicated nature of the non-steady state solutions. Moreover, the definition of requirements of the crop with respect to a day by day change of depth of the water table is very difficult. In other words the reaction of the crop on an each day changing water table is not yet known.

Well known steady state solutions are those of HOOGHOUDT (1940), VAN DEEMTER (1950), ERNST (1954, 1962), KIRKHAM (1958, 1961), LIST (1964) and DAGA (1964). In order to explain the nature and use of these equations let us consider Hooghoudt's solution:

$$R = \frac{8 K_2 dm + 4 K_1 m^2}{L^2} \qquad (2)$$

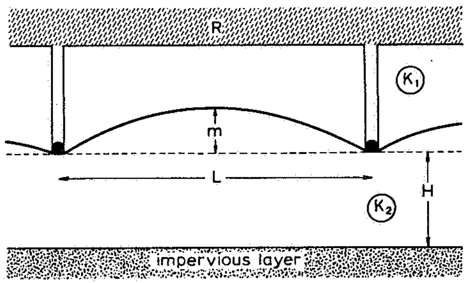


FIG. 2. Drainage by means of a system of parallel drains. The scheme shows the most important factors influencing drain discharge and height of water table

For the meaning of the symbols the reader is referred to figure 2. The value of the equivalent depth d is a function of L, H and the geometry of the drains.

The design of a drainage system is now possible when two types of data are available, viz:

a. the hydraulic properties of the soil, i.e. the hydraulic conductivity, thickness and sequence of the various layers;
b. the so-called 'drainage criterion'.

The drainage criterion is the relation between design discharge and design depth of the water table. Originally HOOGHOUDT (1940) arrived, on the basis of discharge measurements from drained fields and lysimeter studies, at a required discharge of 5 mm/day with a water table 0.5 m below surface. Later on this criterion has been changed somewhat with no other than practical reasons. Nowadays the following drainage criteria are used:

arable land:	7 mm/day	with	a	water	table	0.5 m	below	surface
	10 mm/day	„	„	„	„	0.3 m	„	„
grassland:	7 mm/day	„	„	„	„	0.4 m	„	„

With the introduction of this concept for design, the original method to base drain spacing on experience in similar areas or on non-hydrological soil properties (clay content, CaO-content, Fe-content, hygroscopicity, etc.) has been left for a more hydrological approach.

Transposition of the method to regions where other climatological conditions prevail is rather difficult, however, since for these regions other criteria must be used. The above mentioned criteria are more or less based on experience gained from certain conditions. The derivation of rather simple criteria for irrigated regions has been described by BOUMANS (1963) and BOUMANS and VAN DER MOLEN (1964).

Hydrologically the drainage criterion discussed above may be considered as a factor necessary for the use of the steady state equations. On the other hand the criterion expresses in a certain way the requirements that agricultural crops set on the depth of the water table. Increase of the discharge part or a lower required depth of the water table at the design discharge intensity will yield a narrower spacing and therefore generally a deeper water table throughout time. The criterion, however, does not say anything about possible fluctuations and their influence on final crop yield, except that fluctuations may be expected to be smaller with narrower drain spacings.

With the aid of non-steady state solutions of the drainage flow problem, it is in principle possible to compute the depth of the water table for each given drainage system and known rainfall intensities. According to solutions given by KRAYENHOFF VAN DE LEUR (1958) and MAASLAND (1959), the height h_m of the water table midway between two lines of a parallel drainage system at the end of any arbitrary m-th day may be computed from:

$$h_m = \frac{4}{\pi}\,\frac{1}{pa}\,R_m \sum_{1,3,5}^{\infty} \frac{1}{n^3}\left(1 - e^{-n^2 a}\right) + R_{m-1} \sum_{1,3,5}^{\infty} \frac{1}{n^3}\left(e^{-n^2 a} - e^{-2n^2 a}\right) + \ldots \quad (3)$$

where R_m represents the rainfall intensity on the m-th day, R_{m-1} that on the preceding day, etc. Further $a = \pi^2 Kd/pL^2$ with K, d and L defined as in eq. 2 and p the effective porosity, i.e. the part of the soil that releases or takes up water when the water table is lowered or raised.

With the aid of eq. 3 it is therefore possible to compute the height of the water table resulting from a given rainfall and the drain spacing since for a given drainage system the a-value is known.

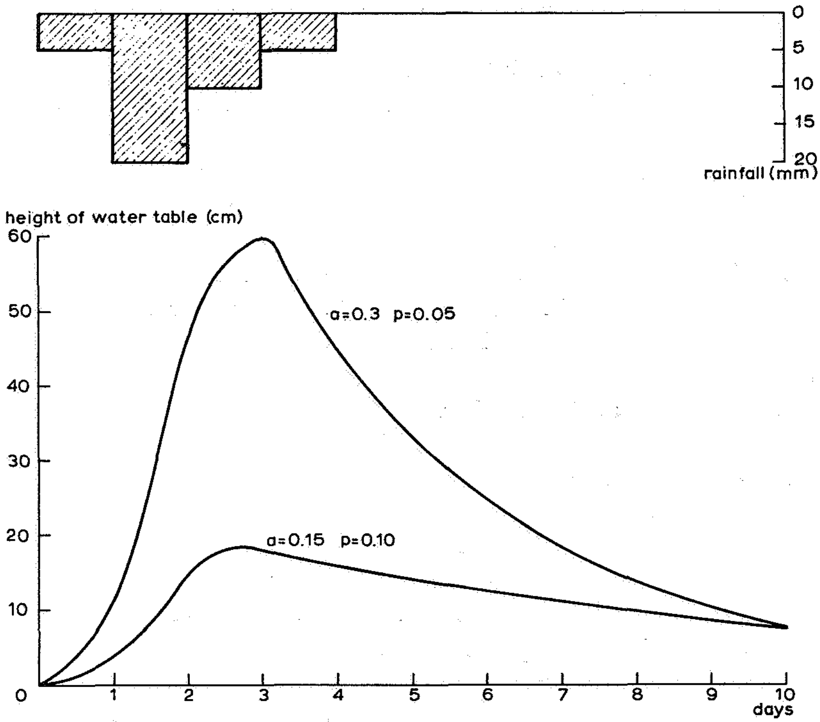


FIG. 3. Heights of the water table in two drained fields with $p = 0.05$ and 0.10 respectively. In the first case the assumed effective porosity leads to $a = 0.3$, in the second case $a = 0.15$, all other factors being the same

In figure 3 the height of the water table is given for a certain rainfall pattern. It is assumed that in both cases the same drain spacing is used. In the case $a = 0.3$ an effective porosity of 0.05 is chosen. In the case $a = 0.15$ it is assumed that the drainable pore space $p = 0.10$ and that the other factors are the same.

From the figure it is evident that in the case of a large value of p the design criterion for a steady state equation highly overestimates the required drain spacing as compared with that in case of a low p-value. It is therefore not correct to design all drainage systems with the same criterion regardless of the drainable pore space of the soil. This example is somewhat exaggerated since one may expect a certain relationship between conductivity and drainable pore space in that sense that soils with a larger K-value also will show a higher value for p.

A few remarks on the validity of non-steady state formulas should be made here. The first is that for computations carried out with non-steady state equations, certain recharge patterns of the ground water must be assumed. Generally this pattern is taken to be the same as that of the rainfall and this is not correct since there is a certain deformation of the rainfall pattern in the unsaturated zone. The mathematical description of this phenomenon is very difficult and not yet complete (RUBIN, 1966). The second remark is that non-steady state solutions are only valid for a constant value of p and this is not true either. In fact p is neither constant with time nor constant with depth, due to non-steady state flow phenomena in the non-saturated flow region. In the third place field conditions will always show a rise of the water level in the open ditches during rainfall. This causes a decrease in discharge and a higher water level in the soil for a longer time. If this phenomenon must be taken into account rather complicated equations will be obtained (WESSELING, 1958; VISSER, 1958a; ERNST, 1962). Despite all the shortcomings discussed above, DE ZEEUW (1966) proved that non-steady state solutions offer the possibility of reproduction of actual discharges, even for the more complicated problem of a watershed.

Drawing the conclusion that non-steady state flow equations offer the possibility of predicting the depth of the water table for a given rainfall at least to a good approximation, the next question is how to interprete the effect of watertable depth on the final crop yield.

4. THE EFFECT OF THE WATERTABLE DEPTH ON CROP YIELD

In the introduction of the COLN-reports, VISSER (1958b) gives the yield depression for seven soil classes with various mean depths of the water table during the growing season (fig. 4). Yield depressions at high water tables can be ascribed to lack of aeration of the soil, depressions at deeper water tables are due to shortage of water. Since both conditions may occur dependent on climatological conditions, it is evident that the curves may undergo a horizontal shift to the right in wet years and a shift to the left in dry years.

Since it is a well-known fact that under conditions prevailing in the Nether-

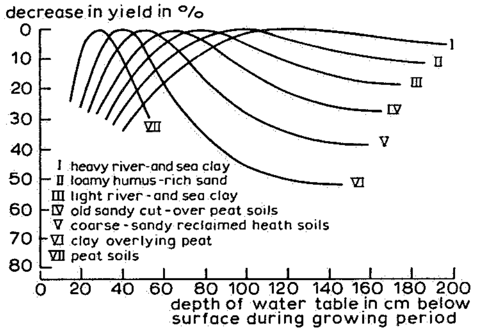


FIG. 4. The effect of the mean depth of the water table during the growing season on final crop yield for seven groups of soils

lands, heavy soils can be drained very deep without showing any depression in yield (group I, fig. 4), WESSELING and VAN WIJK (1956) tried to compute the required depth of drainage on the basis of the amount of available moisture. The principle of this method is given in figure 5. The spring water level (=

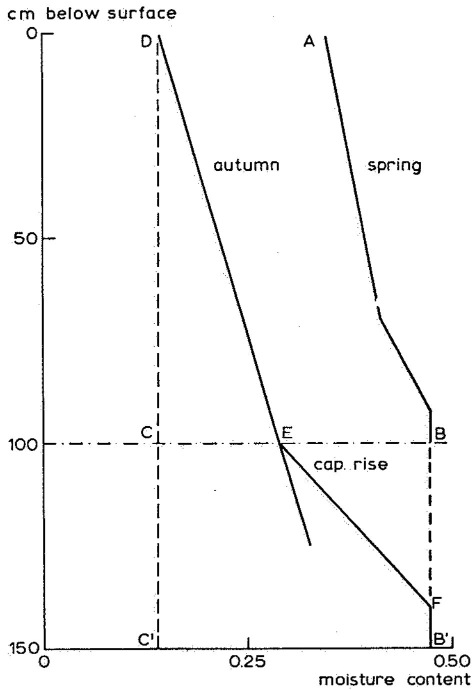


FIG. 5. Scheme for the computation of total available moisture in dependence of the depth of drainage

depth of drainage) is thought here to be at a depth of 100 cm. The equilibrium moisture content of the soil above the water table is then represented by the moisture characteristic AB. The water table in the autumn is assumed to be 150 cm below surface. The moisture content of the soil on that date is given by the line DEFB′. So the total amount of water taken up by the plant is represented by the area ABFED from which the area EBF represents the capillary rise. This area is computed on the basis of known capillary conductivity of the soil. By computing the total amount of available water in dependency of depth of root zone and spring and autumn watertable depth, figure 6 is obtained. The right part of this figure pertains to a clay soil, the left part to a sandy soil. The figures near the curves indicate the maximum depth of root penetration. It can be remarked that the normal root depth of arable crops in homogeneous soils without root-restricting layers is somewhere between 90 and 120 cm. Taking

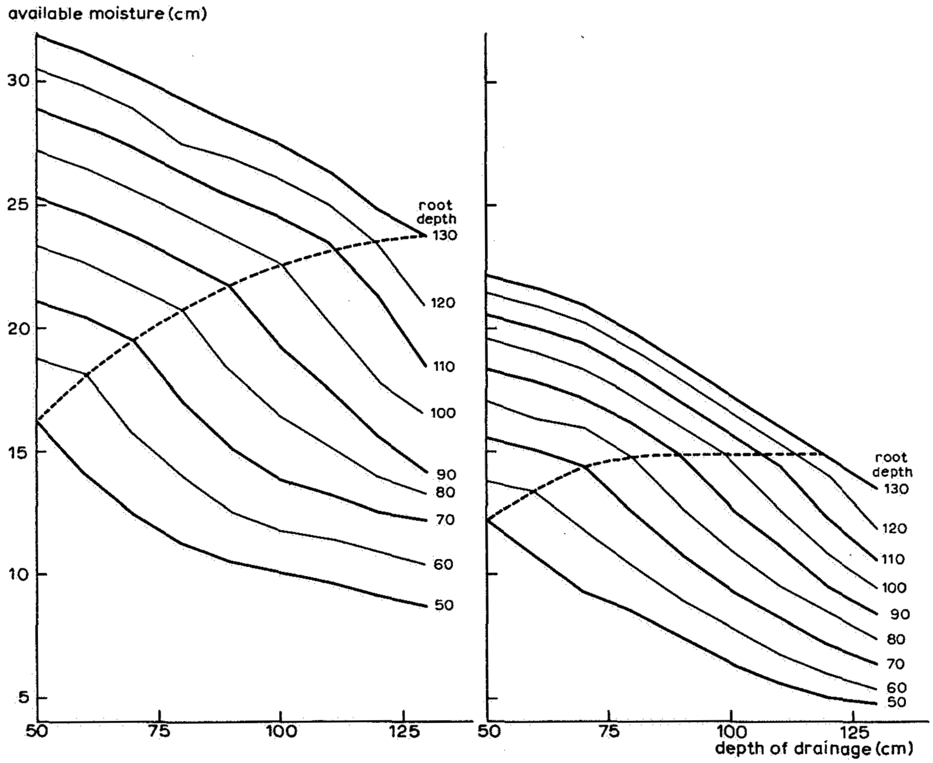


FIG. 6. Computed amount of available water as influenced by depth of drainage and root depth. Left figure pertains to a clay soil, right figure to a sandy soil. The broken line indicates data where the root depth is the same as the depth of drainage

the value of 90 cm, which is normal for say a potato crop, the clay soil delivers about 190 mm of water if the drain depth is 100 cm. The sandy soil under the same conditions, however, will provide only about 125 mm of water. In most years the soil must contain about 175 mm for a grood crop yield, hence drainage depth of the sandy soil must not exceed a value of about 80 cm, which is in good agreement with practical experience.

On the other hand, one may compute the minimum depth of drainage, using the aeration requirements of the plants. Most of the cultivated crops need an amount of oxygen of 3.5 to 4.0 mg/m²min dependent on type of crop, temperature, fertility of the soil, etc. This amount is not only required for the plant roots but also for the microbiological activity of the soil. The exchange of oxygen and carbon dioxide into and out of the soil is mainly furnished by diffusion (BUCKINGHAM, 1903, ROMELL, 1923). Using this fact WESSELING (1957a, 1957b, 1962) derived some solutions of the differential equation

$$\frac{\delta q}{\delta t} = \frac{\delta}{\delta c} (D_s \frac{\delta c}{\delta z}) + \alpha \qquad (4)$$

where

q = the amount of O_2 or CO_2 produced or delivered at the soil surface
c = concentration of the gas
D_s = diffusion coefficient of the soil
z = depth (at surface $z = 0$)
α = production (positive) or uptake (negative) of the gas per unit volume of the soil

Eq. 4 is based on Fick's law and the principle of continuity, and in fact it is of the same form as that for groundwater flow. For the solution, however, some assumptions must be made, namely:

a. the diffusion is one dimensional (vertically upward and downward);

b. at a certain depth B (root depth?) the activity equals zero and hence

$$\frac{\delta c}{\delta z} = 0 \text{ at } x = B$$

c. the activity α depending on the depth must be expressed in one or other analytical form;

d. the diffusion coefficient D_s depends on the soil moisture content and is therefore also a function of the depth.

Assuming the relations

$$D_s/D_a = 0.9\ X_a - 0.1$$

and

$$\alpha\ (z) = \alpha\ (0) \left\{ (1 - \frac{z}{B})^{\frac{1}{4}} \right\}$$

where

D_s = diffusion coefficient in the air
D_a = diffusion coefficient in the soil
X_a = air content of the soil expressed as a volume fraction
$\alpha(z)$ = activity at depth z
L = total thickness of active layer,

solutions may be obtained for various moisture and activity profiles.

An example is given in table 1. This table pertains to the rather simple case that the moisture content is thought to be independent of the depth and hence constant.

TABLE 1. CO_2-concentrations for various air contents of a sprinkler irrigated soil

Root depth (cm)	CO_2-prod. mg/m² min	CO_2-concentration % for content X_a					
		0.15		0.20		0.25	
		at 15 cm	max	at 15 cm	max	at 15 cm	max
50	3	0.91	1.49	0.41	0.69	0.30	0.44
75	4.5	1.54	2.99	0.69	1.52	0.49	0.92
100	5	2.31	5.57	1.02	2.42	0.66	1.70

As could be expected the CO_2-concentration becomes rather high for small values of X_a. These circumstances occur in dense or wet soils. Therefore the table gives a clear illustration of the air requirement of the soil in terms of CO_2. It is, however, not known what the maximum CO_2-concentration is at which crop growth is not yet hampered. Choosing a limit of 1% CO_2 at a depth of 15 cm, as was done by WESSELING (1957a), in principle a minimum depth of drainage can be obtained. For the choice of the limiting concentration a criterion remains necessary and since it is not actually known whether a too high CO_2-concentration or a too low O_2-concentration causes a retarded growth, such a criterion cannot be established yet.

Due to a lack of aeration the plants seem to form alcohol compounds. Further the nitrification and demineralization of N_2 is reduced (VAN HOORN, 1959). VISSER

(1964a) found that the air requirement of the plants in a heavy clay soil can be fulfilled with a drainage depth of about 40 cm. The further increase in yield obtained at larger depths of the water table must be ascribed to the additional supply of nitrogen by soil microbes.

From the above discussion it is clear that there are methods to determine the maximum and minimum drainage depth based on rather simple soil physical properties. A great deal of the requirements of the plants especially those concerning aeration, however, are not known.

An approach to describe the effect of high water tables on crop yields has been given by SIEBEN (1964). From a large amount of data from experimental fields in the new IJsselmeerpolders he computed the so-called SOW-30 values. This SOW-30 value is the sum of the products of days and cm height of water table above the level of 30 cm below surface during the winter period. If for instance the water table is at a depth of 20 cm below surface during 2 days, the

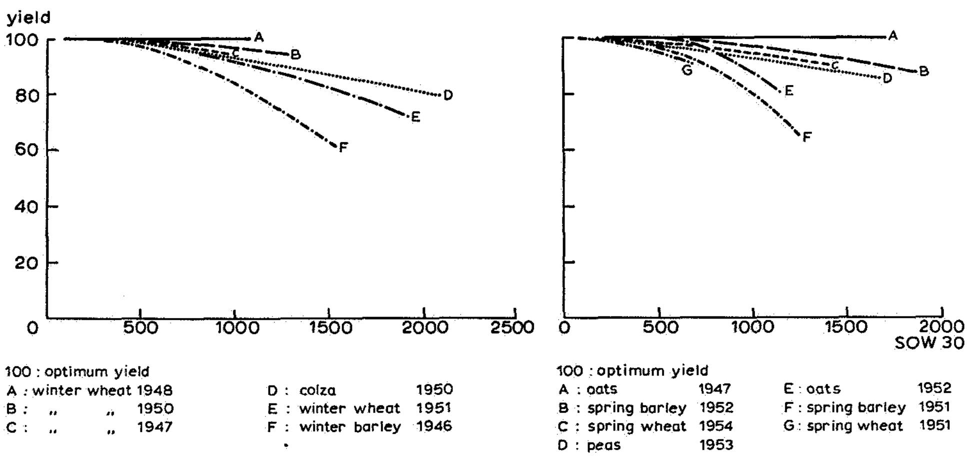


FIG. 7. The yields of various winter grain crops (left) and summer crops (right) as influenced by high water tables. The occurrence of high water tables is expressed in SOW-30 values, i.e. the sum of the products of days and cm height of water table above the level of 30 cm below surface

SOW-30 value for these two days is $2 \times 10 = 20$. The yields obtained from the fields were plotted against the SOW-30 values. The results are given in figure 7. This figure shows that continuous high water tables have a detrimental effect on both winter and summer crops. This effects starts for SOW-values somewhere between 100 and 200, hence high water tables for shorter periods apparently do no harm to the crops. Of course the chosen value of 30 cm is somewhat arbitrary and one could have chosen any other depth, but this does not change the general conclusion.

Typical is that, although summer crops are not standing on the fields during periods of high water tables in winter, the detrimental effect on the crop yield is nearly the same as that for winter crops. The reason for this phenomenon is sought by SIEBEN in the deterioration of the soil structure, causing a poorer aeration and nitrogen mineralization during the growing season.

The SOW-30 values, used by SIEBEN, could have been computed theoretically from soil and drainage data by means of non-steady state equations. This was not done in this case but a comparison of the drain spacings occurring in the experimental fields led SIEBEN to the conclusion that SOW-30 values of 100 to 200 would agree with a steady state design criterion of 7 mm/day with a water table at 30 cm below soil surface. However, the restriction must be made that this holds only for recently reclaimed clay soils that show a large capacity in recovering of the structure. Therefore a criterion of 7 mm/day with a watertable depth of 50 cm below surface for similar but older soils with the same effective porosity, not showing the recovery of structure in such a pronounced way must be a rather good guess.

5. OTHER FACTORS INFLUENCING CROP YIELDS

In drainage projects including river regulations often flooding of the soil surface occurs. In this situation the capacity of the drainage channels plays an important role in the chance with which flooding may be expected. This is a rather serious problem since installation costs depend to a large extent on the capacity of open channels. These floodings may occur in winter as well as in summer. Since the soils along the small rivers in the Netherlands nearly always are used as grassland, BAKKER (1967) carried out a series of experiments with grass sods to find the effect of flooding. For this purpose natural grass sods as well as newly sown grasses were placed in small containers and flooded for different period lengths and heights of flooding (fig. 8). Preliminary glasshouse experiments proved that floodings which lasted a short time were only detrimental under high temperature conditions. Further experiments were carried out in the open during the summer months, with water standing over the surface in layers of 2 to 4 cm and 17 cm respectively. At the first mentioned depth only the soil was flooded completely while under the last mentioned conditions the whole crop was flooded. From both experiments yield data were collected just after the flooding and during the rest of the growing season. Figure 9 left gives

FIG. 8. Flooding experiments with natural grass sods in small containers

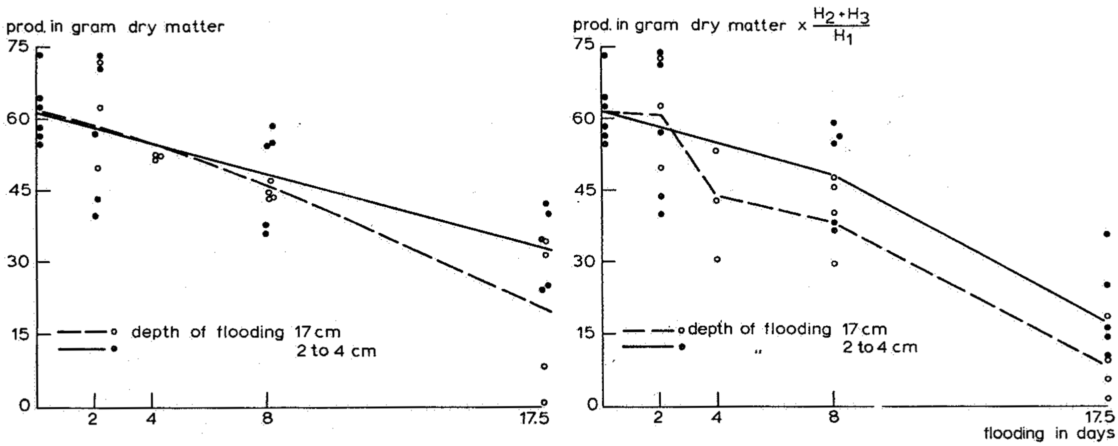


FIG. 9. Influence of flooding on yields of grass sods originating from sandy soils. Floodings started on July 23. Yields pertain to the period 6 July to 3 October. Left hand figure gives the yields, the right hand figure the yields corrected for quality

the total yields in grams of dry matter per container in dependency of the time of flooding. Flooding periods of 8 days reduce the yields with about 10 to 15 %. The scattering of the points is quite large due to the fact that the composition of the natural grass sods was changing and both the effect of the flooding and the recovery are different for the various types of grass. In order to take into account these differences the yield of the crops were multiplied with a factor expressing the quality of the grass composition. The quality of the grass sod was defined according to the percentages and quality data (1 to 10) of the occuring varieties. As a multiplication factor the factor $(H_2 + H_3)/H_1$ was used where H_1 is the quality before, H_2 that just after flooding and H_3 that at the end of the growing season. The results are given in figure 9 right. This figure shows clearly that especially the deep flooding gives relatively large damages.

In order to find the economical advantage of preventing flooding, the obtained results must be combined with a flooding frequency, preferably based on either actual floods or else on rainfall frequencies.

In older drainage literature the advantages of higher soil temperatures in good drained soils have often been advocated, without giving exact data about this advantage. The effect of soil temperature may be clearly shown by the results of a series of glasshouse experiments carried out by BIERHUIZEN (1968). Photosynthesis measurements were carried out on cotton plants grown under different conditions of soil and air temperature. The results of these experiments

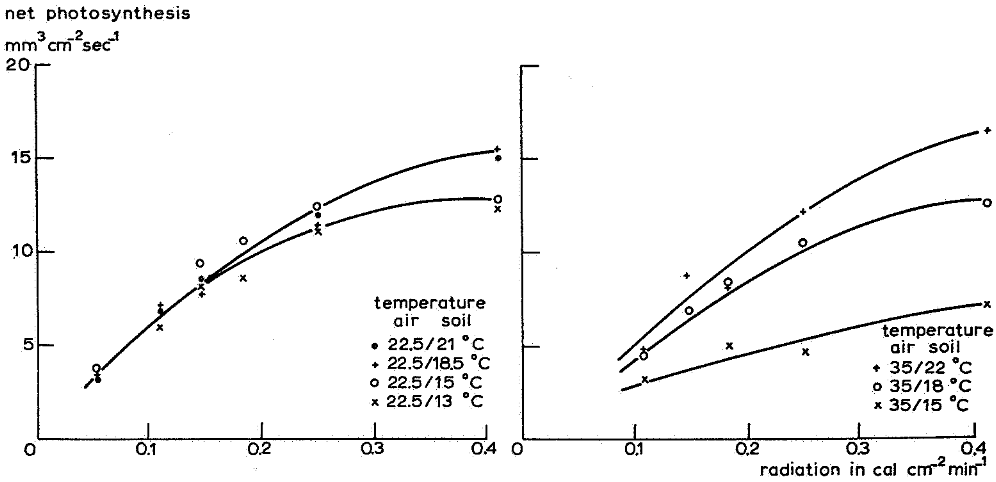


FIG. 10. The relation between radiation and photosynthesis of cotton plants as influenced by soil and air temperature

are given in figure 10. The left hand side is for air temperatures of 22.5°C, the right hand side for air temperatures of 35°. The higher the air temperature the larger the influence of the soil temperature seems to be. Similar experiments were carried out by GROBBELAAR (1963) with maize plants. He found maximum growth rates of roots and shoots at soil temperatures between 20° and 35°C, when plants were grown at an air temperature of 20°C.

Soil temperatures are of particular importance when growing crops in glass-houses. In the open, an effect of the drainage on soil temperature can only be expected to occur in early spring when soil temperatures are generally low and air temperatures are rising. The advantageous effect on final crop yields then has to be ascribed at least partly to an earlier growth of the crop, which means that interpretation of the results of experiments as those described above becomes rather complicated.

The physical phenomenon of increasing or decreasing soil temperatures, on one hand dependent on air temperatures, on the other hand on heat capacity, and conductance of the soil is well-known (VAN DUIN, 1956) and solutions for various boundary conditions are available. Here again the difficulty is the 'biological' interpretation of the results of a physical process. VISSER (1964b) states that the effect of the temperature (no distinction is made between soil- and air temperatures) is the same as that of other growth factors, for example fertilizers.

6. THE EFFECT OF DRAINAGE ON FARM MANAGEMENT

Apart from the biological effects of drainage, there is of course also an influence on farm management itself. In the first place the choice of the cropping pattern also depends on the quality of the drainage, since crops will react differently on certain moisture conditions of the soil. Apart from this still more or less biological aspect, there are other aspects. WIND (1963) mentioned some of them in reviewing the consequences of high water contents of the soil on modern farming. For arable land WIND (1960) computed a damage of some 2 Dutch guilders per ha in February to some 20 Dutch guilders per ha in May, for each day that sowing of crops has to be postponed because of soil moisture conditions. The dry period required for good tillage conditions of the soil depends largely on the depth of water table. Computations of evaporation from bare soils on the basis of known capillary conductivities, led WIND (1963) to the data given in table 2.

TABLE 2. Length of the dry period required to get good tillage conditions of the soil in dependency of the depth of water table (after Wind, 1963)

	Evaporation	Depth of water table (cm)							
	mm/day	160	140	120	100	80	60	40	20
clay	1	3	4	5	6	8	10	17	25
loam 45% $< 16\ \mu$	2	1	1	2	2	2	3	4	7
silt 18% $< 2\ \mu$	2	3	4	6	9	14	33	54	69
loam 18% $< 16\ \mu$	1	1	1	2	3	4	5	13	20

Another period of importance for farm management is the harvest, especially that of potatoes and sugar beets. In this period the bearing capacity of the soil is very important and soil mechanical problems are correlated with drainage. The same holds more or less for the trampling of grassland by grazing cattle. WIND (1963) states that a bearing capacity of 5 to 7 kg/cm^2 is necessary to prevent trampling damages, which may quite commonly be of the order of 20 % of the production of grassland.

7. SUMMARY AND CONCLUSION

In this article various aspects of drainage have been discussed. The best known part of the drainage problem comprises the hydrological aspects, i.e. the problem of the flow of ground water. Both steady and non-steady state flow solutions for the problem of drainage are available. These solutions offer the possibility of computing the to be expected depths of the groundwater table for any given drainage system, provided that soil physical data as permeability and effective porosity together with climatological data are known. The solutions are universal and can be applied anywhere in the world. Although some solutions, especially those describing the non-steady state flow, are rather complicated, application is nearly always possible in particular with the aid of modern computation techniques.

A serious drawback of the applications is that the effects of a given watertable depth on soil properties and final crop yields are not known with sufficient accuracy. The water table to be maintained in a soil depends highly on climatological circumstances. In humid climates it seems to be sufficient to keep the water table down to about 20 to 30 cm below surface. In arid irrigated regions deeper water tables must be maintained because of the danger of salinization.

Several aspects of the watertable depth with respect to crop yield have been more deeply investigated. The best known part is the problem of the maximum depth of drainage whether it is a matter of water shortage or not. The minimum depth of water table is closely related with the aeration of the soil. Although for this problem several solutions of diffusion equations, valid for a wide range of boundary conditions are available, practical application is difficult since the crop requirements are not yet known. The same holds more or less for soil temperature effects as influenced by the drainage system.

Summarizing one could say that the present state of knowledge is such that for most problems physical-mathematical solutions are available, but that the biological interpretation of them still is in progress. Full solutions are now only possible for the hydrological problem. For use in practice one then has to aim at a certain optimum depth of the water table, which must be based on experience.

LITERATURE

BAKKER, J. W. 1967. Schade door inundaties van grasland tijdens de vegetatie-periode. Nota I.C.W. 391: 27 pp.

BIERHUIZEN, J. F. 1968. The effect of soil and air temperature on the growth of cotton plants. In press.

BOUMANS, J. H. 1963. Some principles governing the drainage and irrigation of saline soils. Recl. of salt affected soils in Iraq. Publ. 11. Int. Inst. for Land Reclamation and Improvement, Wageningen.

BOUMANS, J. H. EN W. H. VAN DER MOLEN 1964. Drainagebehoefte van bevloeide gronden in samenhang met de zoutbalans. *Landbouwk. Tijdschr. 76,* 20: 880-887.

BUCKINGHAM, G. 1904. Contribution to our knowledge of the aeration of soils. U.S. D.A. Bureau of soils, Washington, Bull. 25: 67 pp.

DAGAN, G. 1964. Spacing of drains by an approximate method. *J. Irr. and Drainage Division. Proc. A.S.A.E.* paper 3824: 41-46.

DEEMTER, J. J. VAN 1950. Bijdrage tot de kennis van enige natuurkundige grootheden van de grond nr. 11. *Versl. Landbouwk. Onderz. 56.7:* 67 pp.

DUIN, R. H. A. VAN 1956. Over de invloed van grondbewerking op het transport van warmte, lucht en water in de grond. *Versl. Landb. Onderz. 62.7:* 87 pp.

ERICKSON, A. E. 1966. Proc. Conf. Drainage for efficient crop production. St. Joseph, *Am. Sci. Agr. Eng. 11-12,* 23.

ERNST, L. F. 1954. Het berekenen van stationaire grondwaterstromingen welke in een vertikaal vlak afgebeeld kunnen worden. Rapp. Landb. Proefstat. en Bodemk. Inst. T.N.O. Groningen: 55 pp.

ERNST, L. F. 1962, Grondwaterstromingen in de verzadigde zone en hun berekening bij aanwezigheid van horizontale evenwijdige leidingen. *Versl. Landbouwk. Onderz. 67.15:* 189 pp.

GROBBELAAR, W. P. 1963. Response of young maize plants to root temperatures. *Med. Landbouw Hogeschool Wageningen 63:* 1-71.

HOOGHOUDT, S. B. 1940. Bijdragen tot de kennis van enige natuurkundige grootheden van de grond nr. 7. *Versl. Landbouwk. Onderz. 46:* 515-707.

KIRKHAM, DON. 1958. Seepage of steady rainfall through soils into drains. *Trans. Amer. Geophys. Union. 39:* 829-908.

KIRKHAM, DON. 1961. The upper limit for the height of the water table in drainage design formulas. *Int. Soc. Soil Sci. Proc. Madison, 1:* 486-492.

KRAYENHOFF VAN DE LEUR, D. A. 1958. A study of non-steady groundwater flow with special reference to a reservoir coefficient. *De Ingenieur 70* B: 87-94.

LIST, E. J. 1964. The steady flow of precipitation to an infinite series of tile drains above an impervious layer. *J. Geophys. Res. 69:* 3371-3381.

MAASLAND, M. 1959. Water table fluctuations induced by intermittent recharge. *J. Geophys. Res. 64:* 549-559.

ROMELL. 1922. Luftväxlingen i marken som ekologsk faktor. *Med. från Statens Skoy försöksamtalt 19:* 125-361.

SIEBEN, W. H. 1964. Het verband tussen ontwatering en opbrengst bij de jonge zavelgrond in de Noordoostpolder. *Van Zee tot Land 40.* Zwolle: 117 pp.

VISSER, W. C. 1958a. De Landbouwwaterhuishouding van Nederland. Rapp. 1 Comm. Onderz. Landbouwwaterhuish. Nederland T.N.O.: 159 pp.

VISSER, W. C. 1958b. De afstroming bij geremde slootafvoer. Nota ICW: 16 pp.

VISSER, W. C. 1964a. De stikstofvorming in de grond en de ontwatering. *Stikstof 43:* 231-237. Verspr. Overdr. ICW 18.

VISSER, W. C. 1964b. Formulae for the ecological reaction of crop yields. The Water Relations of Plants, Blackwell, Oxford 1963. Verspr. Overdr. ICW 12.

WESSELING, J. 1957. Enige aspecten van de waterbeheersing in landbouwgronden. *Versl. Landb. Onderz. 63.5:* 90 pp.

WESSELING, J. 1958. Vergelijkingen van de niet-stationaire afvoer. Nota ICW: 21 pp.

WESSELING, J. 1962. Some solutions of the steady state diffusion of carbon dioxide through soils. *Neth. J. Agr. Sci. 10:* 109-117. Techn. Bull. ICW. 26.

WESSELING, J. AND W. R. VAN WIJK 1957. Soil physical conditions in relation to drain depth. Drainage of Agr. Lands Am. Soc. of Agron. Chapter V-1.

WIND, G. P. 1960. Opbrengstderving door te laat zaaien. *Landbouwk. Tijdschr. 72:* 111-118.

WIND, G. P. 1963. Gevolgen van wateroverlast in de moderne landbouw. *Versl. Med. Comm. Hydrol. Onderz. T.N.O. 9:* 18 pp.

ZEEUW, J. W. DE 1966. Analyse van het afvoerverloop van gebieden met hoofdzakelijk grondwaterafvoer. *Med. Landbouw Hogeschool Wageningen 66-5:* 139 pp.

II. ON THE RELATION BETWEEN TRANSPIRATION, SOIL PHYSICAL PROPERTIES AND CROP PRODUCTION AS A BASIS FOR WATER SUPPLY PLANS

P. E. RIJTEMA
Institute for Land and Water Management Research, Wageningen

1. INTRODUCTION

It is the main aim of farming to obtain high yields of good quality of those parts of the plants, which are of economical interest. These yields depend on the total amount of dry matter present at harvest and on the distribution of dry matter over the various parts of the plants. One of the factors which can highly affect the dry matter production is the amount of water available for transpiration.

It has been shown (RIJTEMA, 1965), that actual transpiration not only depends on meteorological factors, but also on factors related to the crop itself and on the soil physical conditions. For this reason it cannot be expected that transpiration has a direct relation to the evaporation from a free water surface. However, it appears from literature that under conditions of an optimum water supply, a more or less linear relationship between both variables exists. The relations differ under different climatological conditions. The transfer of these relationships to widely different climates is of particular value for the calculation of potential transpiration from various crops, when designing irrigation projects under any given climatological condition. The development of a generally applicable method, as proposed in previous papers (RIJTEMA, 1965; 1966a) can be useful for this purpose.

As transpiration also depends on the soil physical conditions, attention must be given to the effect of soil properties and of the depth of the groundwater table on the amount of water available for transpiration.

The relation between crop production and transpiration will indicate whether supplemental irrigation will be justified or not. It seems possible to give a reasonable prediction of this relation when the vapour pressure deficit of the air is taken into account.

A new characteristic for the classification of the drought sensitivity of soils will be given, based on the soil physical properties in relation to the depth of the groundwater table. The relation between this soil characteristic, precipitation and crop production will be discussed. This characterization of soils in relation to depth of the water table can be of use in water management studies.

It will be clear that the success of application of this type of data strongly depends on the knowledge of the effect of meteorological, plant physiological and soil physical data on transpiration and dry matter production. A discussion of the interaction of these factors is given in the following sections.

2. Evapotranspiration

It has been shown in previous papers (Rijtema, 1965; 1966b) that actual evapotranspiration can be calculated for practical purposes with a combined aerodynamic and energy balance approach, taking into account the properties of the crop and the soil. The general equation is:

$$E_{re} = E_T^{re} + E_I = \frac{\triangle H_{nt}/L + \gamma\{E_a' + f(z_o, d)\ uR_cE_i\}}{\triangle + \gamma\{1 + f(z_o, d)\ uR_c\}} \tag{1}$$

where: E_{re} is the real evapotranspiration, E_T^{re} the real transpiration from the crop, E_I the evaporation of the precipitation intercepted by the crop, $\triangle$ the slope of the temperature saturated vapour pressure curve, H_{nt} the net radiation, L the latent heat of vaporization, γ the psychrometer constant, $E_a' = f(z_o, d)\ u(\varepsilon_a - e_a)$, ε_a the saturated vapour pressure at air temperature, e_a the real vapour pressure, $f(z_o, d)$ a function depending on the roughness length (z_o) and the zero plane displacement (d) of the evaporating surface, u the wind velocity at 2 m height and R_c the diffusion resistance of the crop.

The value of $f(z_o, d)$ depends on crop height and on wind velocity. The combined effect has been expressed (Rijtema, 1965) as:

$$f(z_o, d) = g(l) \cdot h(u) \tag{2}$$

where: $g(l)$ is a function of crop height with the same dimensions as $f(z_o, d)$ and $h(u)$ is a dimensionless factor, which depends on wind velocity. Values of $g(l)$ and $h(u)$ are given in table 1 in relation to respectively crop height and wind velocity.

Table 1. Values of $g(l)$ in relation to crop height and values of $h(u)$ in relation to wind velocity at 2 m height

Crop height (cm)	0	2	5	10	20	30	40	50	70	90
$g(l)$	0.18	0.23	0.47	0.74	1.00	1.12	1.22	1.32	1.42	1.50
Wind velocity ($m.sec^{-1}$)	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0
$h(u)$	1.32	1.17	1.05	0.96	0.90	0.86	0.79	0.75	0.72	0.69

VAN WIJK and DE VRIES (1954) introduced the factor E_{wet}, which represents the evaporation from a wet surface of similar shape and dimensions as the crop considered. E_{wet} can be calculated with equation (1), taking R_c equal to zero. It appeared (VAN BAVEL et.al, 1963; RIJTEMA, 1965) that under conditions of a complete soil cover, of high light intensity and of optimum water supply the value of R_c equals zero for some crops, so E_{re} equals E_{wet} under these conditions.

Substitution of E_{wet} in equation (1) (see also RIJTEMA, 1966b) gives the following relationship between E_{re} and E_{wet}:

$$E_{re} = E_T^{re} + E_I = \frac{\Delta + \gamma}{\Delta + \gamma\{1 + f(z_o, d)\ uR_c\}}(E_{wet} - E_I) + E_I \qquad (3)$$

The diffusion resistance R_c takes into account the geometry of the evaporating surface as well as the effect of both stomatal opening and transport resistances in the liquid flow path. The value of the diffusion resistance depends on the following factors:

a. soil cover and leaf area;
b. light intensity in relation to stomatal opening;
c. availability of soil moisture and transport resistance for liquid flow in soil and plant.

Although the factors are independent of each other, it is difficult to analyse their combined effect on the reduction of transpiration. For this reason it has been assumed (RIJTEMA, 1966b) that the combined effect can be given with the expression:

$$R_c = R_c^c + R_c^l + R_c^{\psi} \qquad (4)$$

where: R_c^c is the diffusion resistance term depending on soil cover, R_c^l the factor depending on light intensity and R_c^{ψ} the factor giving the effect of soil moisture conditions on the value of R_c.

Only few data are available concerning the effect of partial soil cover on transpiration. Data of R_c^c in relation to soil cover for spring wheat are given in table 2.

TABLE 2. Values of the diffusion resistance R_c^c and the soil cover for spring wheat

Soil cover %	10	20	30	40	50	60	70	80	90	100
R_c^c mm Hg.day.mm^{-1}	2.33	1.72	1.27	0.90	0.60	0.35	0.18	0.08	0	0

Further experimental confirmation of the data given in table 2 is still necessary.

The effect of light intensity on stomatal resistance is well-known from plant physiological literature. RIJTEMA (1965) introduced the mean radiation intensity during the balance period as a measure for the light dependent factor, controlling stomatal opening under conditions of optimum water supply. The relation between R_c^l and mean radiation intensity during the day-time hours is given in table 3.

TABLE 3. General values of the diffusion resistance R_c^l and mean radiation intensity during the day-time hours valid for various crops

Radiation intensity cal.cm^{-2} min^{-1}	0.10	0.15	0.20	0.25	0.30	0.38	>0.38
R_c^l mm Hg.day. mm^{-1}	3.77	2.76	1.94	1.21	0.66	0.0	0.0

Transpiration of water by crops may be regarded as a continuous flow of water by potential gradients from the groundwater level through the soil and roots of the plants to the leaves, where it is transformed by solar energy into water vapour. When transpiration reduces the water content of an initially wet soil, there is a progressive increase in the soil moisture suction and hence in the general level of the suction in the plant. Furthermore, while transpiration occurs in the sub-stomatal cavities, the suction must be the greatest in the leaves, since they constitute the final stage of the liquid pathway.

Even when soil water appears to be freely available, the transpiration demand can be so high during day-time, that temporary suctions develop which are sufficient to cause a closing of the stomata. The presence of a water supply to the leaves too small to ensure potential transpiration from the crop results in an increase of the diffusion resistance R_c^ψ. The relation between R_c^ψ and the suction in the leaf tissue can be given by the general equation (RIJTEMA, 1965):

$$R_c^\psi = \mathrm{f}(\psi_l^{re}) = \mathrm{f}\left\{E_T^{re}(R_{pl} + b/k) + \psi\right\} \tag{5}$$

where: ψ_l^{re} is the mean suction in the leaf tissue, E_T^{re} the real transpiration, ψ the mean suction in the effective root zone, k the capillary conductivity of the soil at suction ψ, R_{pl} the transport resistance for liquid flow in the crop and b a geometry factor of the root system related to rooting depth, root density and root activity.

Mean values of R_{pl} and b, determined for a grass crop, are respectively 1042 cm.day.mm^{-1} and 0.47 cm. Mean values of R_{pl} and b for spring wheat, as given by RIJTEMA and RYHINER (1968) are respectively 3000 cm.day.mm-1 and 0.22 cm.

However, the value of E_T^{re} is often unknown in many hydrological investigations, so it appears to be useful to relate for practical purposes R_c^{ψ} to another parameter, also depending on both climatological and soil physical factors. For this reason the concept of the potential suction in the leaf tissue was introduced (RIJTEMA, 1965); it is defined as the theoretical suction necessary in the leaf tissue to ensure potential transpiration at the soil physical conditions prevailing in the root zone of the crop. This theoretical suction value can be calculated with the following expression:

$$\psi_l^{pot} = E_T^{pot} \, (R_{pl} + b/k) + \psi \tag{6}$$

where E_T^{pot} is the potential transpiration, while the other factors have the same meaning as in equation (5). The potential transpiration can be calculated with the expression:

$$E_T^{pot} = \frac{\Delta + \gamma}{\Delta + \gamma\{1 + f(z_o, d)\, u(R_c^c + R_c^l)\}} (E_{wet} - E_l) \tag{7}$$

The relation between R_c^{ψ} and ψ_l^{pot} varies from crop to crop. Values of R_c^{ψ} and ψ_l^{pot} for grass and spring wheat are given in table 4.

TABLE 4. Values of $R_c\psi$ (mm Hg.day. mm-1) for various values or ψ_{pot}^l (atmospheres), valid for gross and spring wheat

ψ_l^{pot}	0	2	4	6	8
0	0	0	0	0	0
10	0.03	0.10	0.21	0.34	0.48
20	0.61	0.77	0.91	1.07	1.23
30	1.41	1.58	1.75	1.93	2.13
40	2.33	2.53	2.74	2.96	3.18
50	3.41	3.65	3.88	4.12	4.37
60	4.62	4.87	5.12	4.39	4.67
70	5.95	6.23	6.52	6.80	7.08
80	7.50	7.83	8.15	8.49	8.83

3. TRANSFER OF CROP FACTORS IN RELATION TO EVAPORATION

It appears from literature (STANHILL, 1961; TALSMA, 1963) that a reasonable empirical relationship is present between potential evapotranspiration and evaporation from a free water surface, when this relation is determined for mean monthly values.

For the determination of the irrigation requirements of a certain crop it will in general be sufficiently accurate, when the data of the evaporation from a free water surface are multiplied by an empirically determined crop coefficient. Difficulties arise, however, when these crop coefficients are used under other climatological conditions. It has been shown (RIJTEMA, 1965, 1966a) that the relation between E_{wet} and E_o, the latter either calculated, or measured with sunken pans, can be given for any climatological condition, proceeding from the following arguments:

a. the difference in reflection between a crop ($r = 0.23$) and a free water surface ($r = 0.05$) is taken into account;

b. the difference in the wind function holding for a crop $\left[f(z_o, d)\ u\right]$ and for a free watersurface ($0.182\ u$) is taken into account;

c. the difference in net longwave radiation from a crop and from a free water surface can be neglected.

The relation between E_{wet} and E_o can be given under these conditions as:

$$E_{wet} = E_o - 0.18 \frac{\Delta}{\Delta + \gamma} H_{sh}/L + \frac{\gamma}{\Delta + \gamma}\{f(z_o, d) - 0.182\}\ u(\varepsilon_a - e_a) \tag{8}$$

The equation demonstrates, that the relation between E_{wet} and E_o depends on the empirical relations between E_o and respectively $0.18\ \Delta(H_{sh}/L)\ .\ (\Delta + \gamma)^{-1}$ and $\gamma u(\varepsilon_a - e_a)\ .\ (\Delta + \gamma)^{-1}$. The correlation between E_o and the first meteorological term appears to be very high under various climatological conditions. This must be explained by the fact that the second meteorological term has only a small influence on the value of E_o. The empirical relation between E_o and the radiation term can be given by a linear equation as:

$$0.18 \frac{\Delta}{\Delta + \gamma} \frac{H_{sh}}{L} = aE_o + b \tag{9}$$

The correlation between E_o and the second meteorological term is less, due to the fact the value of E_o is not very sensitive to changes in the value of the vapour pressure deficit term. However, in general the relation can also be approached by a linear expression as:

$$\frac{\gamma}{\Delta + \gamma}\ u(\varepsilon_a - e_a) = cE_o + d \tag{10}$$

Values of the constants *a, b, c* and *d* for some climates are given in table 5.

TABLE 5. Values of the constants *a, b, c* and *d* at various locations

Place	Type of climate	*a*	*b*	*c*	*d*
Wageningen the Netherlands	temperate zone humid	0.20	0.09	0.48	1.08
Bejaoua Tunisia	arid	0.193	0.15	0.80	1.15
Kut-el-Hai Iraq	arid	0.185	0.15	1.93	— 0.40
Hulah Valley Israel	arid	0.185	0.12	0.84	0.53
Karuzi Burundi	tropical dry and wet season	0.192	0.17	4.45	—16.47

It appears that the constants *a* and *b* vary only very slightly with climate, so it seems to be justified to give for practical purposes *a* and *b* mean values of respectively 0.19 and 0.15.

The constants *c* and *d* change to a great extent in dependence of the climate. The extreme values of these constants for the arid conditions in Iraq are partly due to the fact that the relative humidity was determined from day-time observations instead of from 24-hour means.

The large values of *c* and *d* for the Karuzi area are characteristic of the tropical climate, with only a slightly varying value of E_o over the whole year, while the climate has a dry and a wet season.

Substituting the linear equations (9) and (10) in equation (8) gives as general expression of the relation between E_{wet} and E_o:

$$E_{wet} = \left[1 - a + c\{f(z_o, d) - 0.182\}\right] E_o + d\{f(z_o, d) - 0.182\} - b \qquad (11)$$

It is clear from this expression that the relationship between E_{wet} and E_o depends on the value of $f(z_o, d)$. The mean values of $f(z_o, d)$ for crops like grass and alfalfa, are for monthly periods more or less constant due to the frequency of mowing. In that case a linear relationship exists between E_{wet} and E_o.

For most arable crops the value of $f(z_o, d)$ varies over the year and the relation between E_{wet} and E_o does not need to be linear. It appears, however, (RIJTEMA and RYHINER, 1968) when a certain correlation is present between $f(z_o, d)$ and E_o the apparent relation between E_{wet} and E_o can be a linear one again. This could also be shown for alfalfa growing under the Tunisian climatological conditions. The mean height of the crop was 25 cm during the summer half year, whereas it was 15 cm over the winter half year. The mean values of $f(z_o, d)$, based on experiments in the Netherlands, were respectively 0.92 and 0.76. The mean values of E_o in the summer and winter period were respectively 5.63 and 2.04 mm.day^{-1}. With equation (11) the calculated mean values of E_{wet} are respectively 8.57 and 3.10 mm.day^{-1}. These calculated means are connected by a straight line given by the following equation:

$$E_{wet} = 1.52\ E_o + 0.02 \qquad (12)$$

In particular when large values of c have to be substituted in equation (11), which means a steep slope of the line given by equation (10), the deviation between calculated and observed values of the term $\gamma u(\varepsilon_a - e_a) \cdot (\Delta + \gamma)^{-1}$ may lead to considerable errors. Under these conditions it might be better to substitute only equation (9) in expression (8) and to use the directly measured data of wind velocity, temperature and relative humidity. Equation (8) then becomes:

$$E_{wet} = 0.81\ E_o + \frac{\gamma}{\Delta + \gamma}\{f(z_o,\ d) - 0{,}182\}\ u(\varepsilon_a - e_a) - 0.15 \qquad (13)$$

The required calculation of E_{wet} can be made with data of E_o, measured with sunken pans with a standard exposure (RIJTEMA, 1965) or with data of E_o calculated from climatalogical observations. Reliable results, using equation (13), were also obtained for weekly periods.

A comparison of the calculated data of E_{wet} with the observed data given by VAN 'T LEVEN and HADDAD (1964) of E_o, E_{pot}, determined with the waterbalance of lysimeters, and E_{re}, determined with the waterbalance of irrigated fields, under the Tunisian climatological conditions is given in table 6.

TABLE 6. Observed data of E_o, E_{pot} and E_{re} from alfalfa and the data calculated with the equations (12) and (13) under the climatological conditions in Tunisia in 1963. All data in mm.day^{-1}

Month	E_o	E_{pot} water balance	E_{re} water balance	E_{wet} eq. (12)	E_{wet} eq. (13)
January	1.1	1.7	1.6	1.7	1.4
February	1.6	1.1	1.2	2.5	2.7
March	2.9	3.6	—	4.4	3.8
April	3.7	4.1	4.2	5.6	5.2
May	4.6	6.9	3.8	7.0	6.9
June	5.9	7.7	7.4	9.0	8.1
July	6.9	9.9	7.5	10.5	9.6
August	6.4	10.0	9.1	9.7	9.4
September	4.3	6.5	3.6	6.6	6.0
October	2.5	4.1	2.5	3.8	4.0
November	2.8	5.4	3.2	4.3	4.4
December	1.2	2.2	0.9	1.8	2.5

The agreement between the calculated data of E_{wet} with the observed data of E_{pot} is very good, taking into account the very rough estimates of crop height used in the determination of $f(z_o, d)$ during the winter and the summer half year. The deviating data of E_{re} are not surprising. Directly after irrigation a potential transpiration rate will be present, but the transpiration declines after some days, due to the loss of moisture from the soil.

4. WATER MANAGEMENT OF SOILS IN RELATION TO EVAPOTRANSPIRATION

The soil moisture content is changing during the course of the year under influence of precipitation, evapotranspiration and drainage. The amount of precipitation during the growing season is generally not sufficient to cover the water requirements of crops under the climatological conditions in the Netherlands. For this reason the water supply of crops depends for a major part on the availability of soil moisture.

Though the effect of soil moisture on the reduction of transpiration has been described in section 2 by the moisture conditions and soil physical properties of the effective root zone, this does not mean that both the physical properties of the subsoil and the depth of the groundwater table do not affect the availability of soil moisture. Due to the uptake of water from the root zone by the crop a potential gradient is established below the root zone causing a rise of water from the subsoil and from the groundwater table to the root zone, which results in an additional supply of water. The amount of water, which comes available from the subsoil and from the groundwater table, determines to a great extent the moisture conditions in the root zone, when natural precipitation fails to rewet this zone during growth. The depth of the groundwater table as well as its fall during the growing season are determined to a great extent by the hydrological conditions of the area in which the soil is situated. It will be clear that due to periodical rewetting of the soil by precipitation, to variations in the transpiration rate and to the hydrological conditions no steady-state conditions in the water supply by the soil will be present. Nevertheless, a fair approach of the water supply from the layers below the root zone can be obtained, using the steady-state solutions for capillary rise, in which the suction at the lower boundary of the effective root zone effects the moisture transport.

A full discussion on the relations between capillary conductivity and suction used in literature has been given in a previous study (RIJTEMA, 1965). It appeared that the relationship between both factors in the low suction range can be given by the expression:

$$k = k_o e^{-\alpha(\psi - \psi_a)} \qquad \psi > \psi_a \tag{14}$$

Where: k is the capillary conductivity, k_o conductivity at zero suction, ψ the suction, ψ_a the suction at the air-entry point and α is a constant depending upon the soil.

The conductivity k_o at saturation, obtained by extrapolation from the relationship given in equation (14) is not in all soils equal to the hydraulic conductivity k_s determined under saturated conditions. The extent to which k_s exceeds the value of k_o depends on the existence of an apparent non-capillary pore space, such as root holes and cracks losing water immediately when a very small suction is present. Under these conditions the value of ψ_a equals zero. The deviation present at very low suctions has very little influence on the considerations concerning capillary rise, so the extrapolated values can be used.

Equation (14) holds only in the low suction range. The maximum value of the suction to which this equation is valid varies from soil to soil. The relation between capillary conductivity and suction can in the high suction range be expressed by the type of equation, proposed by WIND (1955) and WESSELING (1957), as:

$$k = a\psi^{-n} \tag{15}$$

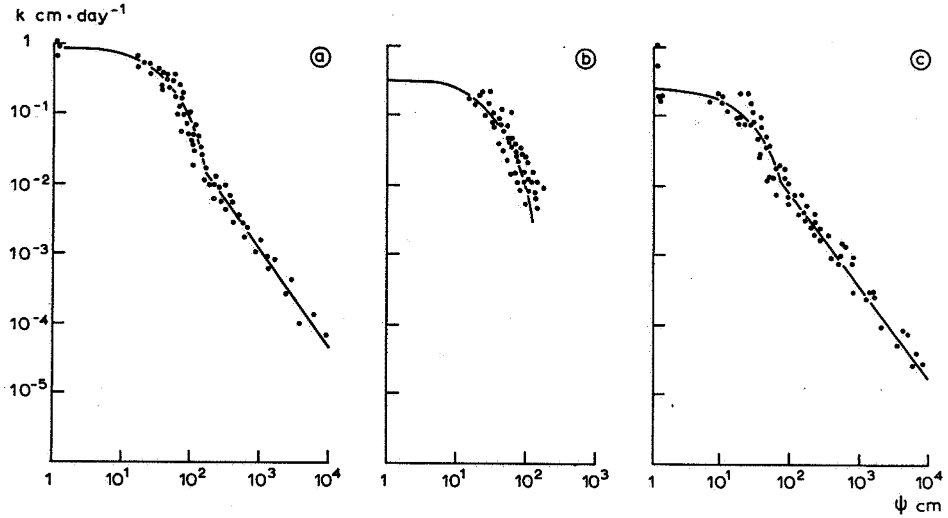
It has been shown (RIJTEMA, 1965) that the value of n for different soils is close to 1.4. The value of the constant a varies from soil to soil. An example of the relation between capillary conductivity and suction is presented in figure 1.

The relation between suction and height above the groundwater table can be calculated for various flow rates v, using for steady-state conditions and upward vertical flow Darcy's law

$$v = k(\frac{\delta\psi}{\delta z} - 1) \tag{16}$$

and the given relations between capillary conductivity and suction.

The relation between flow velocity and suction at the lower boundary of the effective root zone for various values of the depth of the groundwater table can also be given. These relationships are presented in figure 2 for the three soils given in figure 1. The flow rate increases already strongly, particularly when shallow groundwater tables are present, at low suctions at the lower boundary of the effective root zone, so the capillary supply from the groundwater table can be considerable even at low suctions in the root zone. The capillary rise from the groundwater table depends under these conditions to a great extent



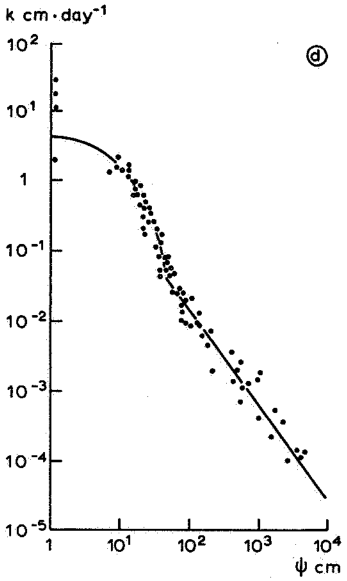


FIG. 1.

Relation between capillary conductivity and suction
a. humous loamy sand (topsoil);
b. loamy sand (subsoil);
c. sticky clay;
d. peat

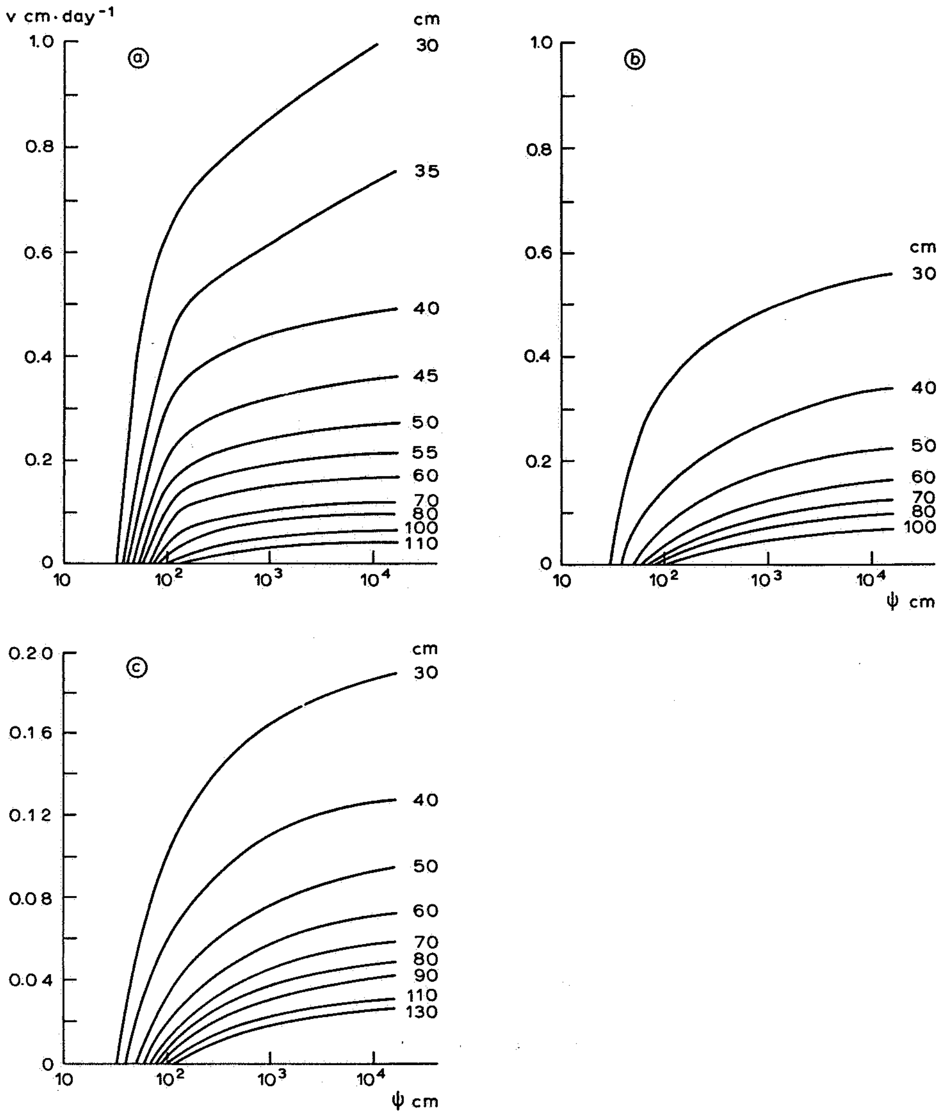


FIG. 2. The relation between capillary rise and suction at the lower boundary of the effective root zone for various depths of the water table in cm below the effective root zone a. loamy sand; b. peat; c. sticky clay

on transpiration, since the value of capillary rise cannot exceed the transpiration rate for a long time. The capillary rise is small in soils with a poor capillary conductivity, or in soils with the groundwater table at greater depth. The trans-

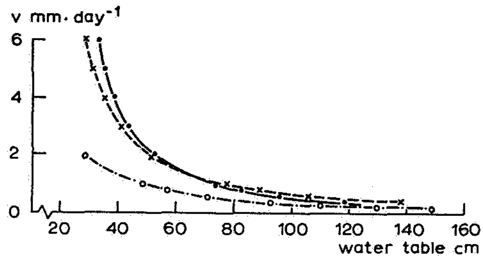


FIG. 3. Relation between the maximum capillary rise for a suction of 16000 cm at the lower boundary of the effective root zone and the depth of the water table below this zone
. ——— . loamy sand;
o — . — o sticky clay;
x - - - - x peat

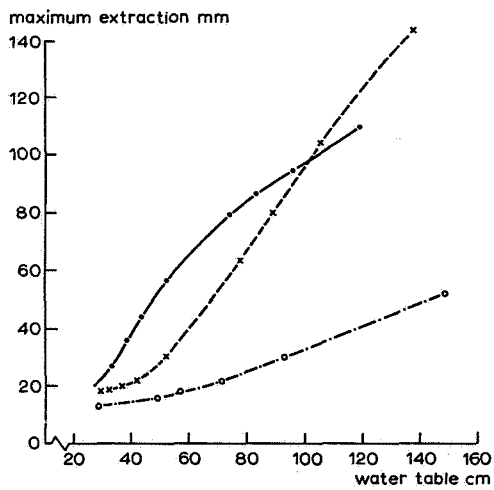


FIG. 4. Relation between the maximum amount of moisture available below the effective root zone and the depth of the water table below this zone
. ——— . loamy sand;
o — . . — o sticky clay;
x - - - - x peat

piration rate exceeds the capillary flow velocity considerably and there is a gradual increase in suction in the root zone of the crop, which in its turn affects the capillary flow velocity.

It is necessary, however, in investigations concerning the influence of the groundwater table on transpiration, to determine also the amount of water which can be extracted from the layers between the lower boundary of the effective root zone and the groundwater table. The calculations of the amount of moisture available from these layers are also based on the steady-state solution of the capillary flow equation (16), assuming a maximum suction of 16.10^3 cm at the lower boundary of the effective root zone. The relation between the maximum values of capillary rise and the depth of the groundwater table in cm below the effective root zone is presented in figure 3 for the three soils. The maximum amounts of moisture which can be extracted from the subsoil are shown in figure 4 in relation to the depth of the groundwater table.

It will be clear from the preceding discussion, that both the hydrological conditions, which determine the depth of the groundwater table, and the physical properties of the subsoil, which determine the capillary flow rate as well as the maximum amount of moisture which can be extracted from this layer, highly affect the moisture conditions in the root zone of the crop.

5. Crop production and transpiration

The dry matter production of crops is mainly the result of net photosynthesis, as the production of compounds other than carbohydrates can be ignored quantitatively during the growth of a field crop. Net photosynthesis is, under conditions of high light intensity, mainly determined by the diffusion process (de Wit, 1958; Bierhuizen and Slatyer, 1965). Light intensity can affect this diffusion rate only indirectly through an influence on the stomatal resistance (Gaastra, 1959). Both de Wit (1958) and Gaastra (1959) state that under conditions of low light intensity production is not limited by the diffusion process, but by the light sensitive photochemical process. However, a study of Bierhuizen and Slatyer (1964) shows that the resistance for CO_2 transport in the leaf mesophyll is also affected by light intensity. The results of this study indicate that net photosynthesis under conditions of low light intensity might also be governed by the diffusion process.

Bierhuizen and Slatyer (1965) and Rijtema (1966a) did show that the relation between net photosynthesis and transpiration under steady-state conditions can be given by the relation:

$$P = A \frac{R_a + R_c}{R'_a + R'_c + R'_m} \cdot \frac{[CO_2]_a - [CO_2]_i}{\varepsilon_i - e_a} \cdot E_T \qquad (17)$$

The factor A is a conversion factor to keep consistent units, when the rate of dry matter production (P) is expressed in kg.day^{-1}, the transpiration rate (E_T) in mm.day^{-1}, the various resistances R and R' in sec.cm^{-1}, the internal saturated vapour pressure (ε_i) in the leaves and the actual vapour pressure (e_a) in the bulk air in mm Hg and the internal carbondioxyde concentration $[CO_2]_i$ in the leaves and the concentration $[CO_2]_a$ in the bulk air in cm^3 CO_2 per cm^3 of air.

R_a and R'_a are comparable resistances for mass flow in the turbulent moving air, so $R'_a \simeq R_a = \{f(z_o, d)u\}^{-1}$.

The values of the diffusion resistance of the crop for water vapour transport (R_c) and for CO_2 transport (R'_c), as well as the resistance in the leaf mesophyll for CO_2 transport (R'_m), depend on crop density and light intensity. Under condition of a limited water supply both R_c and R'_c increase due to stomatal closure. At present it is not known, whether the value of R'_m is also affected by a lack of water, or not.

For practical purposes the total production of dry matter is of much more interest than the daily production rate. Since factors as crop height, crop density, leaf arrangement and lack of water vary in a complex way over the growing season, the total dry matter production can hardly be calculated in a theoretical way. For this reason the relation between dry matter production and total transpiration has to be determined experimentally. This might be done by using mean values for the various resistances over the growing season, introducing the mean vapour pressure deficit at 2 m height and a mean CO_2 gradient, instead of the actual ones.

Substituting for E_T in equation (17) the total transpiration during the period of growth, gives the total dry matter production in kg.ha^{-1} as a linearly dependent variable. Differences in the various climatic conditions are taken into account by the variation in the mean value of the vapour pressure deficit.

The ratio $E.P^{-1}$ of various crops in relation to the vapour pressure deficit in the air is presented in figure 5, based on data from literature as collected by BIERHUIZEN and SLATYER (1965). The scatter of the data is rather large, due to the fact that the authors calculated the vapour pressure deficit from the W.M.O. tables, which give only long range mean values of relative humidity for a restricted number of places. The actual mean vapour pressure deficit during the years of the experiments, and at the locations where the experiments were per-

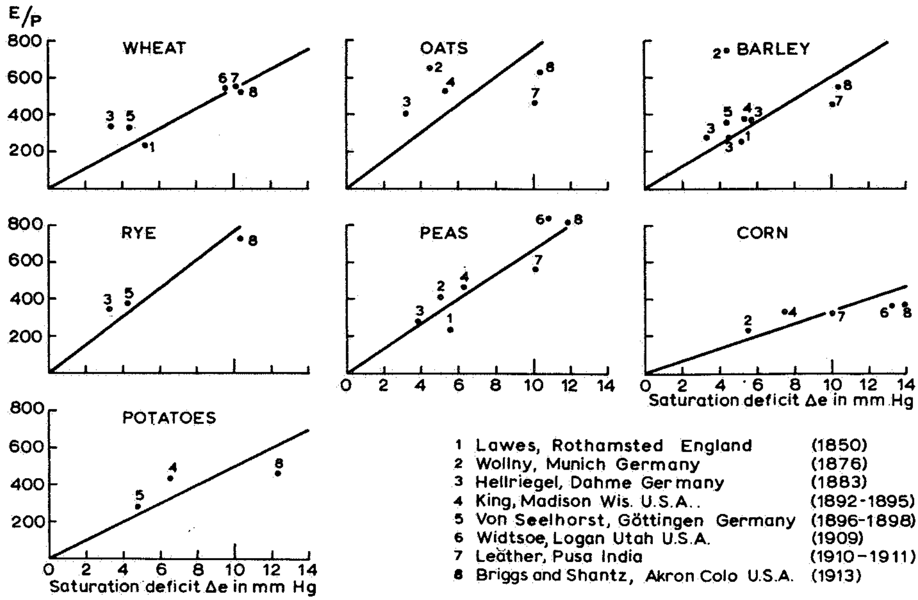


FIG. 5. The ratio $E.P^{-1}$ of various crops at different locations versus the mean saturation deficit after data collected by Bierhuizen and Slatyer (1965)

formed, may differ considerably from the mean values used. However, the results clearly demonstrate that the vapour pressure deficit allows the transfer of the ratio $E_T P^{-1}$ of a crop to different climates.

The net photosynthetic rate of crops per unit of leaf surface decreases at low mineral nutrient levels (WATSON, 1952; VAN DER PAAUW, 1956). It is also known from literature (RIPLEY, 1966) that water is used more efficiently, when an adequate supply of fertilizers was given, than when a low state of fertility was present. This means that under conditions of low fertility transpiration is not affected by it to a great extent, whereas the dry matter production strongly reacts. Data concerning the yield of alfalfa hay obtained in irrigation experiments in the U.S.A. were collected by DE WIT (1958). This author uses the estimates of daily mean evaporation from a free water surface (E_o) instead of the vapour pressure deficit in the air. The relation between the yield of alfalfa and the ratio $E.E_o^{-1}$ is presented in figure 6.

This figure clearly demonstrates, that under conditions of low soil fertility a large reduction in transpiration may exist before the production of alfalfa hay decreases considerably. Under these conditions it is not useful to apply such an amount of irrigation water that potential transpiration is ensured; it is economic-

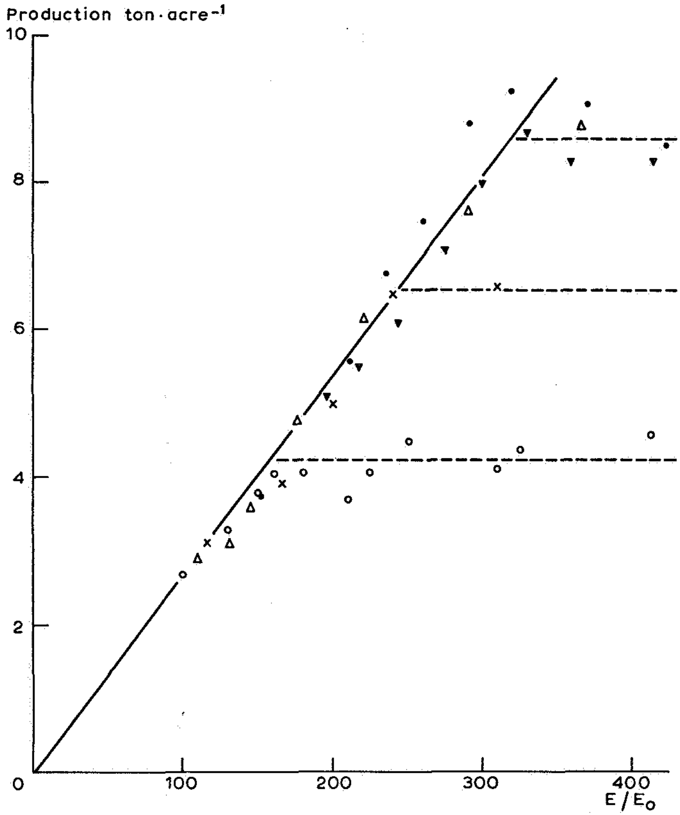


Fig. 6. The relation between the yield of alfalfa hay in tons per acre and the ratio $E.E_0^{-1}$ after data collected by De Wit (1958)

o	Logan (Utah)	$E_0 = 4.5$ mm.day^{-1}
x	Gooding (Idaho)	$E_0 = 4.0$ mm.day^{-1}
•	Davis (Cal.)	$E_0 = 5.5$ mm.day^{-1}
▼	Delhi (Cal.)	$E_0 = 5.5$ mm.day^{-1}
△	Highley (Ariz.)	$E_0 = 6.0$ mm.day^{-1}

ally better to give this amount of water over a larger area in order to raise dry matter production per unit of applied water.

Periods of drought do generally not affect the relation between dry matter production and transpiration to a great extent, provided that the dry matter of the wilted parts of the crop is also harvested. The relation between dry matter production and transpiration, as given in equation (17) is linear and passes through the origin. However, generally the above ground parts of the crop are only harvested. The relation between production and transpiration depends in that case on the quantity of dry matter present in the roots. When the sprout-root ratio is large and when the main quantity of roots is formed during the early stages of growth, small fluctuations in the amount of dry matter present in the roots do not affect the linear relationship very much. With a small value of the sprout-root ratio, continuous root production and several yields during the growing season, the relationship between matter production and transpiration might be affected to a great extent.

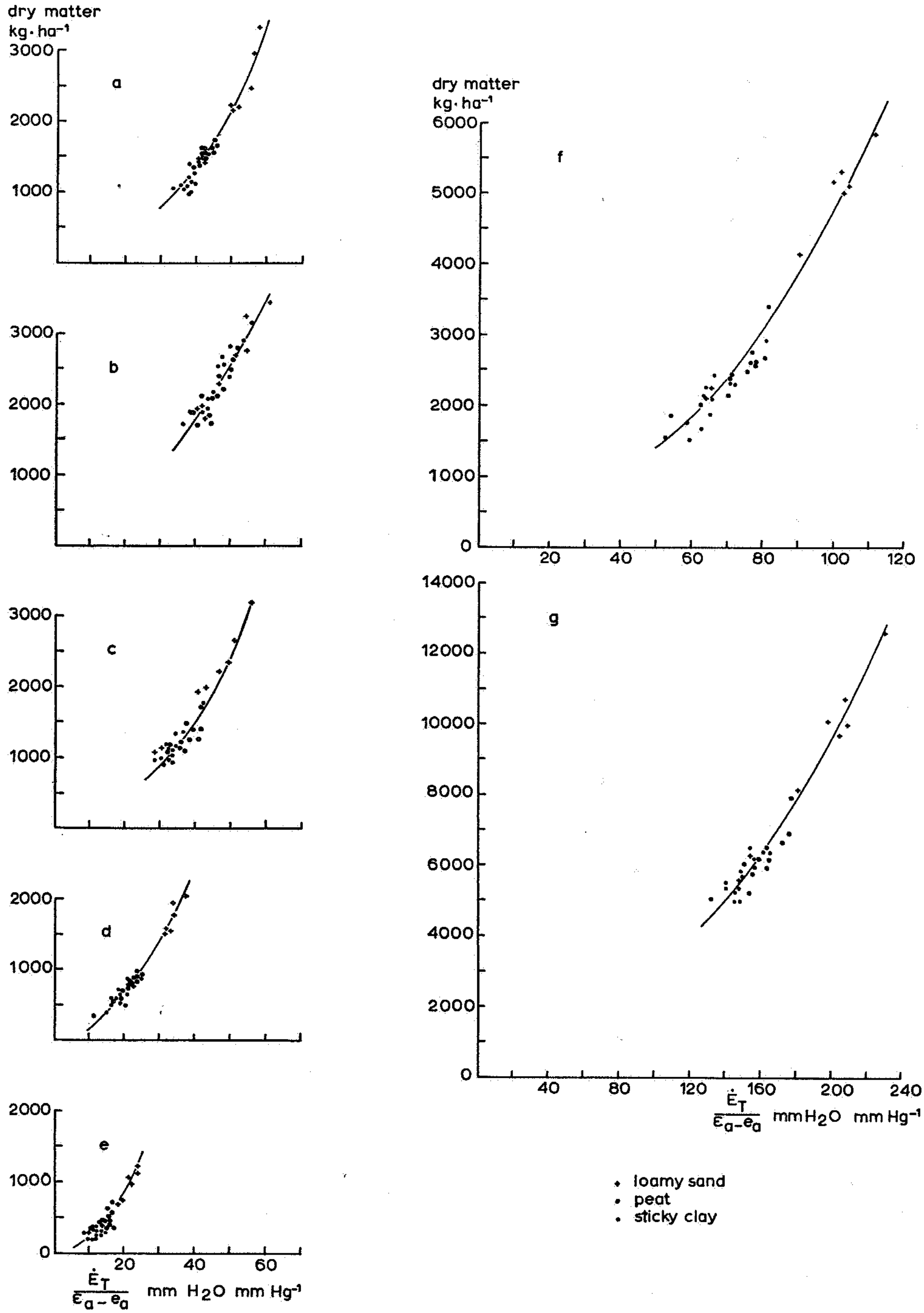
The evaporation of intercepted precipitation may also affect the relation between dry matter production and transpiration, as the evaporation (E_I) of the intercepted precipitation reduces the transpiration rate. An approach to eliminate this effect can be derived from equation (3) resulting in the following equation:

$$\dot{E}_T^{re} = \frac{E_{re} - E_I}{E_{wet} - E_I} E_{wet} \qquad (18)$$

where $\dot{E}_T^{re}$ is the transpiration from the crop when E_I equals zero.

The relation between dry matter production of various cuttings of grass and $\dot{E}_T^{re} . (\varepsilon_a - e_a)^{-1}$ is presented in figure 7. The deviation from linearity might partly be caused by the variation in root production. However, DE WIT (1965), approaching dry matter production of grass in relation to radiation, showed that the rate of photosynthesis depends on the leaf distribution of the crop, which changes with its age. It appears from data (MAKKINK, 1962) of the highest grass yields per mm water used by the crop against the effective radiation, that at the same value of the effective radiation the mean daily production during the period of growth varies by a factor exceeding 2. It can be shown (RIJTEMA, 1968) that the relation between dry matter production and $\dot{E}_T^{re} . (\varepsilon_a - e_a)^{-1}$ varies in relation to crop height. In particular the regrowth of grass after cutting is strongly affected by the soil moisture conditions. The relation between production and $\dot{E}_T^{re} . (\varepsilon_a - e_a)^{-1}$ differs under wet and dry soil moisture conditions, due to the effect of the difference in mean crop height during the short period of growth between two successive cuttings.

No attention has been given yet to the effect of the distribution of available water during growth on the distribution of dry matter over the various parts of the crop. Some data of sprinkler irrigation experiments, performed in the Netherlands (DE VOS en TOUSSAINT, 1966), with oats, in which the main purpose was to investigate the effect of time of irrrigation on the yield and the production



dry matter
kg·ha⁻¹
3000
2000
1000
a
b
c
d
e
0
20
40
60
Ė_T / (ε_a − e_a) mm H2O mm Hg⁻¹
6000
5000
4000
f
0
20
40
60
80
100
120
14000
12000
10000
8000
6000
4000
2000
g
40
80
120
160
200
240
loamy sand
peat
sticky clay

FIG. 7. The relation between dry matter production of grass in kg.ha^{-1} and the ratio $\dot{E}_T\,(\Sigma_a - e_a)^{-1}$ in 1959

a	6/5 — 2/6	E_I =	2.6 mm
b	2/6 — 6/7	E_I =	18.2 mm
c	6/7 — 13/8	E_I =	13.4 mm
d	13/8 — 7/9	E_I =	2.8 mm
e	7/9 — 4/10	E_I =	0.0 mm
f	13/8 — 4/10	E_I =	16.2 mm
g	6/5 — 4/10	E_I =	37.0 mm

of grains are give in table 7. The experiments were performed in 1959 on a coarse sandy soil, with an available amount of soil moisture of 100 mm.

TABLE 7. Amount of irrigation water and natural precipitation in mm water during the growth of oats, as well as the yield of grain and straw. Dry matter content 83%

Plot no	20/4-10/5	May		June			July		Total water	Yield kg.ha^{-1}		
		II	III	I	II	III	I	II		grain	straw	total
1	—	25	25	—	—	—	—	—	139	2070	3260	5330
2	—	—	25	25	—	—	—	—	139	2470	2950	5420
3	—	—	—	25	25	—	—	—	139	2100	3400	5500
4	—	—	—	—	25	25	—	—	139	1890	3940	5830
5	—	—	—	—	—	25	25	—	139	1480	3510	4990
6	—	—	—	—	—	—	25	25	139	1290	2210	3500
7	—	—	—	—	—	—	—	—	89	1280	2300	3580
8	—	—	—	—	—	—	—	—	89	1360	2600	3960
9	—	—	50	—	50	—	—	—	189	3150	4100	7250
10	—	—	—	—	45	35	—	—	169	2240	3560	5800
11	—	—	—	30	45	35	—	—	199	2940	5060	8000
12	—	20	30	55	35	60	—	—	289	4330	6320	10.650
13	—	—	50	65	35	40	40	—	319	4510	6430	10.940
Precipitation	21	13	1	4	—	19	31	—	89			

The heading of the crop started during the first 10-day period in June and flowering was during June II/III. No large differences in dry matter production were present on the plots with an irrigation gift of 50 mm, except when the water was given in July. The grain-straw ratio, however, varied markedly from 0.42 to 0.84 depending on the time of irrigation. The maximum value was reached with irrigation just before and during heading. The same holds for the plots 9, 10 and 11. The maximum yields were obtained on the frequently sprinkled plots.

A similar result was obtained with winter wheat and with spring wheat in 1966 (TOUSSAINT, 1967) when before and during heading a 3.5 weeks period of severe drought was present, which was detrimental for the non-sprinkled plots. The sprinkled plots of winter wheat and spring wheat had an increase in yield of respectively 1000 and 1700 kg grain.ha^{-1}. The abundant amounts of precipitation fallen after this period could not restore the drought damage during heading.

The large variation in the increase in yield from 0 to 19 kg grain.ha.$^{-1}$ per mm water as presented in the literature on sprinkling irrigation of cereals, must be explained by the possible occurrence of a severe moisture stress just before and during heading.

The probability, that a period of severe drought is present just before and during heading, gives a second criterion to decide whether sprinkling of cereals is economically attractive or not.

6. CHARACTERIZATION OF DROUGHT SENSITIVITY OF SOILS

The relation between yield and mean depth of the groundwater table is very frequently used as a characteristic of drought sensitivity. The main disadvantages of this characteristic are:

a. the relationship between yield and the depth of the groundwater table varies from soil to soil;

b. the relationship changes, within one type of soil, dependent on the climatic conditions during growth.

The figures 2, 3 and 4 offer a possibility to given another characteristic of drought sensitivity of soils in relation to the depth of the groundwater table. The maximum amount of water which can be extracted by the crop within a certain number of days is calculated from these figures, to which the amount of moisture available in the root zone is added. The calculations are starting from equilibrium conditions at the beginning of the period of growth, while the following propositions have been made:

a. the extraction rate of moisture present in the effective root zone of the crop is not restricted between field capacity and wilting point;

b. the mean extraction rate of the moisture from the layer between the lower boundary of the effective root zone and the groundwater table, to a maximum amount of extraction as given in figure 4, is two times the maximum flow rate presented in figure 3;

c. the flow rate for capillary supply from the groundwater table is derived from figure 2, assuming a mean suction of 1000 cm at the lower boundary of the effective root zone.

The maximum amounts of moisture which can be extracted by a grass crop, with an effective root zone of 25 cm, in relation to the depth of the groundwater table are calculated for periods of 30, 60, 90 and 120 days. The results of these calculations are given in table 8.

TABLE 8. Maximum amounts of moisture (mm) available for transpiration by grass in relation to the depth of the groundwater table for periods of 30, 60, 90 and 120 days

Soil	Period length (days)	Depth of the groundwater table (cm —surface)						
		50	55	60	75	100	125	150
Sticky clay	30	144	—	128	120	107	102	95
	60	201	—	167	150	124	120	111
	90	258	—	206	176	136	127	125
	120	315	—	245	203	151	137	132
Peat	30	—	241	204	152	135	121	110
	60	—	388	315	212	170	161	152
	90	—	535	417	260	197	190	183
	120	—	682	528	314	219	210	205
Loamy sand	30	—	355	290	192	148	111	85
	60	—	510	448	261	195	150	110
	90	—	765	600	330	221	173	135
	120	—	1020	752	399	250	201	160

It appears from this table that the sticky clay has the smallest amount of available water in comparison with the two other soils. This is due to both the small values of capillary rise from the groundwater table and the small amount of moisture which can be extracted from the layers between the lower boundary of the effective root zone and the groundwater table. Moreover, it appears that a fall in the groundwater table from 125 to 150 cm below surface does not affect the available moisture in the sticky clay and in the peat soil to a great extent, whereas it does in the loamy sand.

Although the large amounts of available moisture calculated for shallow water tables are not withdrawn by transpiration under the climatological conditions in the Netherlands, this does not imply, that these figures are meaningless, as they are a measure of the conditions for growth of the crop. The crop grows under conditions of a high suction in the effective root zone during the main part of the season, when only a small amount of water is available in the soil.

Very large amounts of available water mean low suctions in the effective root zone of the crop even when long continued periods without precipitation are present.

The amount of water available for transpiration increases during growth due to precipitation and also when water is added by irrigation. For this reason the total maximum amount of available water is introduced, being the sum of the maximum available soil water, precipitation and irrigation water during the growing season.

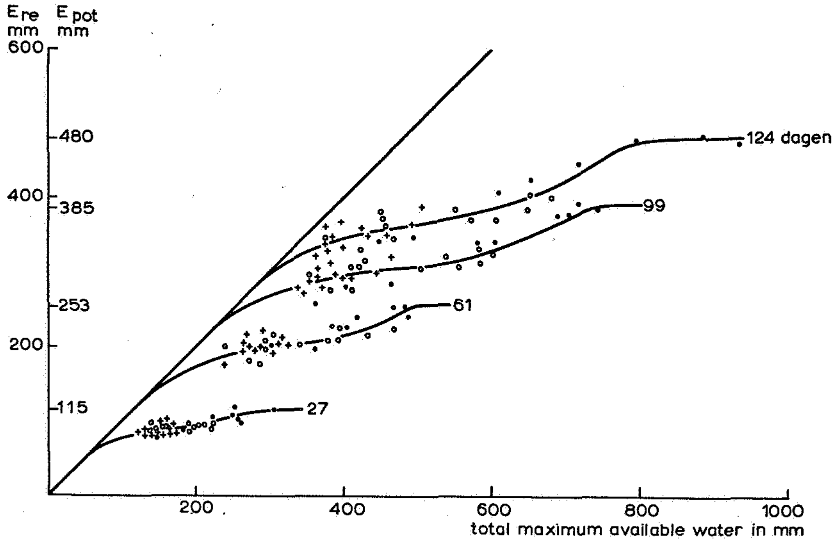


FIG. 8. The relation between evapotranspiration and total maximum available water for various period lengths
- • loamy sand;
- x peat;
- o sticky clay

The relation between real evapotranspiration from grass and the total maximum available water in 1959 is presented in figure 8 for various periods, starting in the beginning of May. The straight line drawn in this figure gives the situation in which E_{re} equals the total amount of available water. Figure 8 shows, as a very rough estimate, that potential transpiration is ensured throughout the growing season if E_{pot} is smaller than 60 % of the total available water. This 60 % is of course a very crude figure, as it will strongly depend on the distribution of precipitation and irrigation water over the summer season. This per-

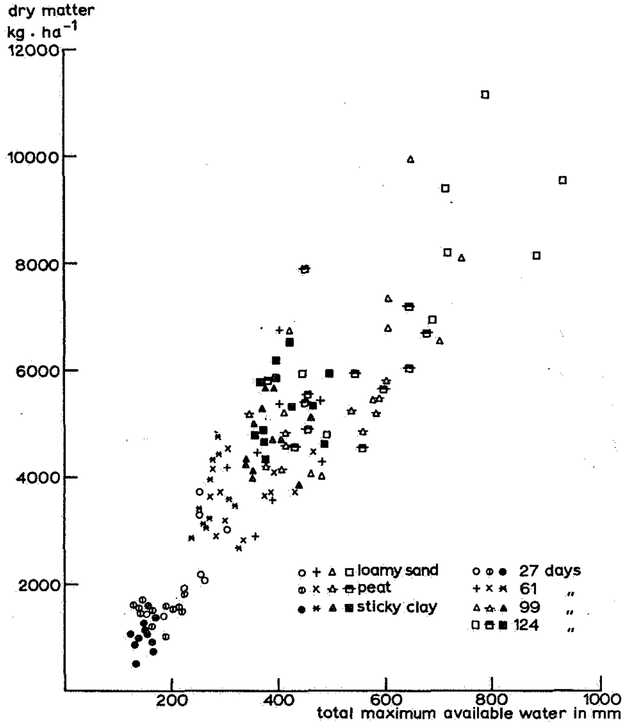


FIG. 9. The relation between dry matter production of grass in 1959 and total maximum available water

centage will increase when a favourable distribution of precipitation is present, whereas it decreases with an unfavourable distribution. The calculated data for the three soils show a similar reaction in the reduction of transpiration.

The relation between dry matter production of grass and the total maximum amount of available water in 1959 is presented in figure 9. The weather conditions in 1959 can be characterized as warm and dry. Figure 9 shows that no maximum production rate can be proved, so it is concluded that under the climatological conditions in 1959 the available water was the limiting factor for crop production. The data of the various soils and various periods are mixed reasonably well. The scatter in the observations is still rather large.

The corresponding relation in 1960 is presented in figure 10. The climatological conditions in 1960 can be characterized as cool weather, without much precipitation during May and the first half of June, whereas in July and in August extremely large amounts of precipitation were present. An examination

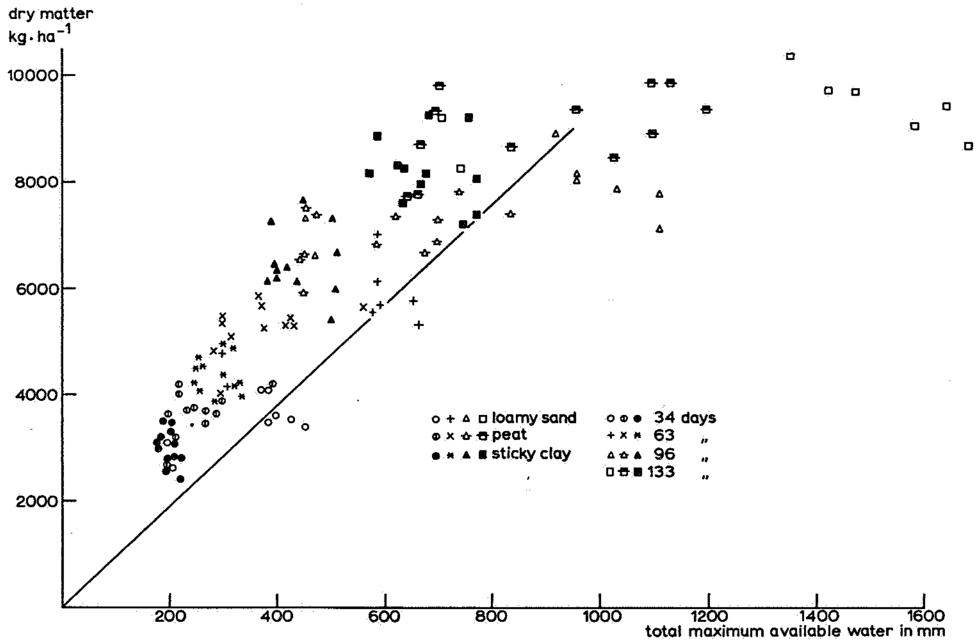


FIG. 10. The relation between dry matter production of grass in 1960 and total maximum available water

of the data shows, that in each period the maximum production could be reached, so it must be concluded that water was not always the limiting factor for crop production. The data of the 133-day period show even a weak optimum, indicating that due to the extremely wet conditions in the second half of the period, in soils with large amounts of maximum available soil moisture aeration might become the limiting factor.

The data of 1960, left of the straight line drawn in figure 10 and the 1959-data are presented again in figure 11. The observations are divided in groups of maximum available soil moisture. It appears that the data of soils with a small amount of maximum available soil moisture are situated at the left side in the figure, whereas soils with large amounts of available soil moisture are at the right hand side. The scatter of the observations in the various groups can be partly explained by the fact that the production in 1960 was close to its maximum, which affects the relation between dry matter production and total maximum available water for a number of the observations.

A large difference in dry matter production appears to exist at a same amount of total maximum available water between soils with a small and a large amount

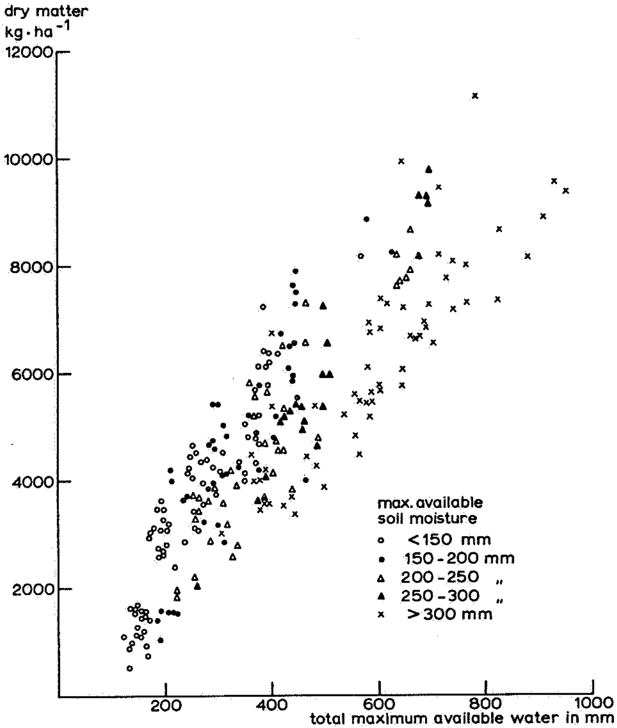


FIG. 11. The relation between dry matter production of grass and total maximum available water for various classes of maximum available soil moisture

of maximum available soil moisture. This variation can be explained by the extra amount of precipitation and irrigation water required to come to the same amount of total maximum available water in soils with a small amount of available soil moisture. This extra amount of water, generally, rewets only the effective root zone of the crop, due to the distribution over the growing season. In soils with a large amount of maximum available soil moisture, the main part of the soil water comes from the subsoil and from capillary rise from the groundwater table. In the latter case the mean suction in the effective root zone, will be higher than in the first one. This situation appears to have a great effect on the dry matter production.

A further examination of the data of dry matter production of grass, total maximum available water and maximum available soil moisture resulted in the curves presented in figure 12. The relationships given in this figure, combined with an analysis of the frequency of occurrence of a certain amount of precipi-

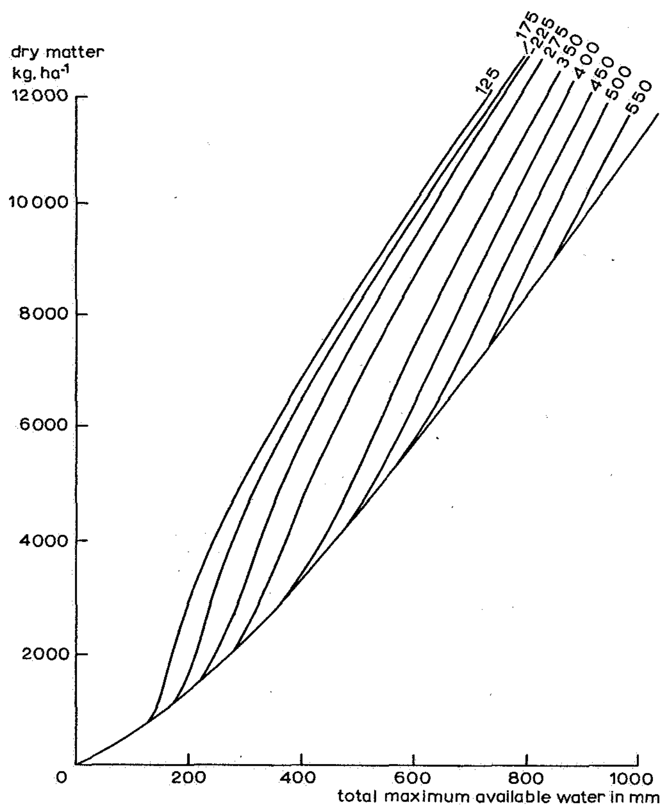


FIG. 12. The relation between dry matter production of grass and total maximum available water for various classes of maximum available soil moisture

tation during a certain period, gives the opportunity to calculate the dry matter production of grass, which must be expected under various conditions of precipitation in a given hydrological situation, which is already present or which will be realized in future.

An example of the calculated expectation values of the dry matter production of grass, precipitation, frequency of occurrence and maximum available soil moisture is given in table 9. The data of precipitation and frequency of occurrence were derived from an analysis given by SNIJDERS (1966) of the observations at Winterswijk. Each period begins at May 1st. An amount of precipitation of 21 mm over 30 days, with a frequency of once in 10 years, means that once in 10 years over a 30-day period the amount of precipitation is 21 mm or less.

TABLE 9. Expected dry matter production of grass (kg.ha^{-1}) in relation to maximum available soil moisture and precipitation

Period length (days)	Precipitation (mm)	Frequency of occurrence (n × per 100 years)	Maximum available soil moisture (mm)								
			125	175	225	275	350	400	500	600	700
30	10	1	900	1350	1770	2200	2930	3470			
	21	10	1150	1600	1970	2400	3000	3500			
	50	50	2200	2450	2650	3000	3450	3500			
60	39	1	1800	2100	2380	2750	3270	3800	5000	6280	
	69	10	2730	3030	3200	3450	3770	4260	5380	6670	
	117	50	3910	4300	4450	4550	4620	4900	6000	7000	
90	75	1	2880	3180	3300	3550	3870	4280	5460	6750	8090
	125	10	4100	4480	4660	4730	4770	5120	6100	7400	8770
	185	50	5320	5750	6000	6100	6150	6220	6880	8220	9600
120	120	1	4000	4360	4530	4600	4670	5030	6030	7350	8700
	182	10	5270	5700	5970	6030	6100	6170	6850	8170	9550
	255	50	6550	7050	7330	7480	7610	7720	8020	9190	10550

The total maximum amount of water required for a certain dry matter production of grass is very large in comparison with the data for oats given in table 7. A dry matter production of oats of 9100 kg.ha^{-1} (0.83 × 10940) requires a total amount of available water of 419 mm (319 + 100), whereas a same dry matter production of grass on a soil with 125 mm maximum available soil moisture requires 545 mm. The large difference in required amounts of water can be explained by the difference in root production. ALBERDA (1962) states that the leaf production of grass is about 60 % of the total dry matter production. As a consequence a dry matter production of grass of 7000 kg.ha^{-1} is equivalent to a total dry matter production of 11,690 kg.ha^{-1}.

HIDDING and WIND (1963) give as dry matter weight of roots and stubble of oats 2000 kg.ha^{-1}. Conditions of drought do not affect this amount to a great extent, as the main part of the root system will be produced during the early stage of growth. A dry matter production of grains and straw of oats of 9100 kg.ha^{-1} is in that case equivalent to a total dry matter production of 11,100 kg.ha^{-1}. The preceding discussion gives the opportunity to express the dry matter production of grass in an equivalent dry matter production of oats.

The full drawn line in figure 13 represents the calculated equivalent production of oats, calculated from the corresponding grass curve taking into account the difference in dry matter present in the roots and stubble, in relation to the total maximum available water. The points represent the dry matter production of oats on a basis of 100 % dry matter, as derived from table 7. The agreement

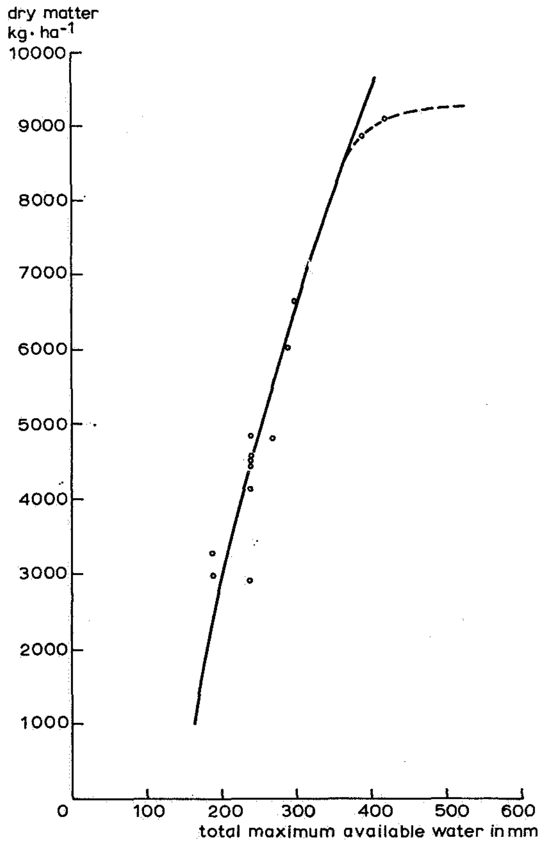


FIG. 13. The relation between dry matter production of oats and total maximum available water on a coarse sandy soil with a maximum amount of available soil moisture of 100 mm. The points are derived from table 7 on a 100% dry matter basis. The full drawn line is the calculated equivalent production of oats. The dashed line indicates the maximum production level on this soil

between the calculated equivalent curve and the observations is very good, indicating that a similar family of curves, as given for grass, holds for cereals. The dashed line in the figure indicates the maximum production level of oats on this coarse sandy soil.

The results shown in the preceding discussion, illustrate clearly, that the proposed method of a drought sensitivity classification of soils might be useful in hydrological studies, to characterize the effect of available soil moisture in relation to production.

7. Summary

A discussion is given on the effect of climate and soil physical conditions on transpiration and dry matter production.

The transfer of crop coefficients to various climates has been treated. A general expression has been given of the relation of evaporation from a wet crop surface, with the evaporation from a free water surface, the vapour pressure deficit and the wind velocity, holding for completely different climates.

The effect of soil physical factors on the reduction in transpiration, on capillary rise from the groundwater table and on extraction of water from the subsoil is dealt with.

The relation between transpiration and dry matter production depends on both climate and soil fertility. It is possible, however, to give a reasonable prediction of the ratio E_T/P for any climatological condition when the vapour pressure deficit of the air is taken into account.

In particular for crops of which the grain production is of primary importance, a severe moisture deficit during heading and during early flowering affects grain production highly.

A hydrological soil classification system has been proposed, depending on the physical properties of the soil and based on a standard calculation of the maximum amount of available soil moisture. Such data are given for three different soils, as well as the relation between these data and both transpiration and dry matter production. It appeared that a same amount of maximum available soil moisture calculated for the various soils gives identical results in relation to the reduction in transpiration, as well as in relation to dry matter production.

An example has been given of the calculation of the expected dry matter production of grass in relation to the frequency distribution of precipitation totals during the growing season.

LITERATURE

Alberda, Th. 1962. Actual and potential production of agricultural crops. *Neth. J. Agric. Sci. 10:* 325-333.

Bavel, C. H. M. van, L. J. Fritschen and W. E. Reeves 1963. Transpiration by Sudangrass as an externally controlled process. *Science 141:* 269-270.

Bierhuizen, J. F. and R. O. Slatyer 1964. Photosynthesis of cotton leaves under a range of environmental conditions in relation to internal and external diffusive resistance. *Australian J. Biol. Sci. 17:* 348-359.

Bierhuizen, J. F. and R. O. Slatyer 1965. Effect of atmospheric concentration of water vapour and CO_2 in determining transpiration-photosynthesis relationships of cotton leaves. *Agric. Met. 2:* 259-270.

GAASTRA, P. 1959. Photosynthesis of crop plants as influenced by light, carbon dioxide, temperature and stomatal diffusion resistance. *Med. Landbouwhogeschool Wageningen 59,* 13.

HIDDING, A. P. AND G. P. WIND 1963. Practical results of the improvement of clay cover soils. Inst. for Land and Water Man. Res., Techn. Bull. No. 30.

LEVEN, J. A. VAN 'T ET M. H. HADDAD 1964. Compte rendu des recherches de la station expérimentale de Bejaoua. Années 1962 et 1963. Office de la Mise en Valeur de la Vallée de la Medjerda. Rep. Tunisienne.

MAKKINK, G. F. 1962. Vijf jaren lysimeteronderzoek. *Versl. Landbouwk. Onderz. 68.1:* 1-241.

PAAUW, F. VAN DER 1956. De plaats van de fotosynthese in het productieproces. *Landbouwk. Tijdschr. 68:* 635-646.

RIJTEMA, P. E. 1965. An analysis of actual evapotranspiration. *Agric. Res. Rep. 659:* 1-107.

RIJTEMA, P. E. 1966a. Transpiration and production of crops in relation to climate and irrigation. Inst. for Land and Water Man. Res., Techn. Bull. No. 44.

1966b. Derived meteorological data; transpiration. Proceedings Symposium on Methods in Agroclimatology. Reading 1966. Unesco Paris: 55-72.

RIJTEMA, P. E. 1968. Weather, water and dry matter production of grass. In preparation.

RIJTEMA, P. E. EN A. H. RYHINER 1968. Lysimeteronderzoek in Nederland. *Versl. Meded. Hydrol. Comm. T.N.O. 14:* 86-149.

RIPLEY, P. Q. 1966. The use of water by crops. Spec. Session Rep. I.C.I.D. No. 2: S9-S21.

SNIJDERS, J. H. 1966. Neerslag-frequentie in de Achterhoek. Inst. voor Cultuurtechn. en Waterhuish. Nota 376.

STANHILL, G. 1961. A comparison of methods calculating potential evapotranspiration from climatic data. *Isr. J. Agric. Res. 11:* 159-171.

TALSMA, T. 1963. The control of saline groundwater. *Med. Landbouwhogeschool Wageningen 63.10.*

TOUSSAINT, C. G. 1967. Private communication.

VOS, N. M. DE EN C. G. TOUSSAINT 1966. De vochtvoorziening van zomergranen op een droogtegevoelige zandgrond. *Versl. Landbouwk. Onderz. 67.9:* 1-29.

WATSON, D. J. 1952. The physiological basis of variation in yield. *Adv. in Agron. 4:* 101-145.

WESSELING, J. 1957. Enige aspecten van de waterbeheersing in landbouwgronden. *Versl. Landbouwk. Onderz. 63.5.*

WIJK, W. R. VAN AND D. A. DE VRIES 1954. Evapotranspiration. *Neth. J. Agric. Sci. 2:* 105-119.

WIND, G. P. 1955. A field experiment concerning capillary rise of moisture in a heavy clay soil. *Neth. J. Agric. Sci. 3:* 60-69.

WIT, C. T. DE 1958. Transpiration and crop yields. *Versl. Landbouwk. Onderz. 64.6.*

WIT, C. T. DE 1965. Photosynthesis of leaf canopies. *Agric. Res. Rep. 663:* 1-57.

III. CALCULATION OF PARAMETERS FOR THE EVALUATION OF THE LEACHING OF SALTS UNDER FIELD CONDITIONS, ILLUSTRATED BY NITRATE

G. J. KOLENBRANDER
Institute for Soil Fertility, Haren-Groningen

1. INTRODUCTION

In agricultural practice the downward movement of salts in profiles is mostly hidden from our observations. Only repeated sampling of the profile with short intervals, will supply enough details. It is clear that in practice such an intensive sampling is not feasible. Still it is all-important to the farmer to know where the applied plant nutrients will be found in the profile after a wet period. Might this be partly beyond the range of the root system then this part of the nutrients must be given up for lost, and only a new application can avoid a yield decrease.

The movement of water-soluble salts has been intensively studied in the past 20 years in columns filled with adsorption media or with soil. Hereby various mathematical formulations have been developed, describing the process of the downward movement of salts in such columns. The problem is now whether it will be possible to use these expressions for the assessment of the leaching of salts in soil profiles under field conditions and to determine the parameters for the different soils.

2. FORMULATION OF LEACHING

a. *Factors determining the downward movement of ions*

The rate of vertical displacement of ions in a soil profile at field capacity is determined by:

1. the pore-space volume and distribution,
2. the concentration of the ions in the soil moisture,
3. the quantity of drain water.

The mean pore size and pore-size distribution are important factors as they determine the quantity and the mean velocity of the flow of soil moisture at field capacity. The smaller the mean pore diameter of the soil is, the more water that soil will contain at field capacity, but the mean velocity of this water flow will decrease proportionately. Due to differences in pore size this velocity in the profile will not be uniform. Ions passing through great pores will reach a greater depth than those travelling through smaller pores in the same time. This results in a great difference in time of the ions staying in the profile, which is called "dispersion". This holds also for diffusion, but its velocity is much smaller.

The concentration of ions in the soil moisture is a function of the water content of the soil at field capacity, the rate of the water flow in the interstices, and the equilibrium concentration of the ions. The latter depends on the type of ion and the type and size of the adsorption complex. This entire process is so complex that the mathematical formulation is limited to a linear adsorption isotherm. Many investigators also exclude this possibility and use only anions which are not absorbed under normal conditions as chloride or nitrate ions.

After an application of $Ca(NO_3)_2$ on a fallow soil a narrow band of high nitrate ion concentration turns up in the top of the profile. Since the nitrate ions are not adsorbed, a surplus of water will cause a migration of nitrate ions to the subsoil. But the pore-size distribution not being uniform the speed of their migration will vary considerably. Consequently, the narrow band will be extended over a great part of the profile after a while taking the shape of a concentration-wave.

Maintaining the precipitation on a constant level the top of this wave migrates downward with a constant speed (in agreement with the average water flow) but the shape of the wave changes, becoming gradually flatter and longer. This phenomenon is the result of the action of dispersion brought about by the pore-size distribution and increasing with time.

b. *Equations of Glueckauf and Day*

GARDNER (1965) has given a mathematical description of the various processes that are playing an important role in the migration of nitrogen in soil, while FRISSEL and POELSTRA (1967a) composed an excellent, critical survey about the various theoretical evaluations of chromatographic transport during the last 25 years.

The experiments of FRISSEL and POELSTRA (1967d) proved that the best description of the experiments was given by the equation of Glueckauf. NIELSON and BIGGAR (1967) arrived at the same conclusion.

GLUECKAUF (1949) has given the following equation for the condition that mixing of the ions is caused by convection and diffusion:

$$\frac{\delta C}{\delta t} = K.v \frac{\delta^2 C}{\delta x^2} - v \frac{\delta C}{\delta x}$$

C = salt concentration in g/ml,
t = time in days,
x = depth of the column in cm,
v = mean water flow velocity in cm/day,
K = distribution factor in cm.

VAN DER MOLEN (1958) designating the water moved downward through the soil in mm, has given the solution of this equation for the boundary conditions $D = 0$; $x > 0$; $C = C_0$ and $D > 0$; $x = 0$; $C = 0$. This solution is also used in this paper. Using the equation of Glueckauf we obtain as losses of the original amount of the ions in the profile (as percentage):

$$\text{Loss in } \% = 100 \left\{ \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{1}{2}z^2} dz + e^{2\frac{x}{K}} \left(1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-\frac{1}{2}u^2} du\right) \right\}$$

$$z = \frac{\frac{D}{v} - 1}{\sqrt{\frac{D}{v}}} \sqrt{\frac{x}{K}}; \qquad u = \frac{\frac{D}{v} + 1}{\sqrt{\frac{D}{v}}} \sqrt{\frac{x}{K}}$$

D = water moved downward through the soil in mm,
v = water held in the profile at field capacity in mm,
x = depth of the profile in cm,
K = distribution factor in cm.

This solution of the Glueckauf-equation reduces the number of factors for the calculation of losses in a profile of x cm to three, of which two can be determined easily. These two are: D, the quantity of drain water that passed the profile, and v, the quantity of water held by the soil. The third factor, the distribution factor K, is not known and depends on the pore-space distribution in the profile.

The equation of Glueckauf consists of two parts. The first part is the relation of the cumulative probability distribution and the second part a correction upon this distribution. This correction will be smaller the higher the $\frac{x}{K}$ ratio is.

If the correction term is neglected as was done by VAN DER MOLEN (1956, 1958), then the equation of Glueckauf becomes the same as that of DAY (1956), in which mixing by the various pore-water velocities and molecular (or ionic) diffusion is lumped together.

Figure 1 demonstrates that under the same conditions of D, v, x and K, the results obtained using the equation of Glueckauf differ from those of the Day-equation, especially for the smaller values of $\frac{x}{K}$, thus at smaller depths and

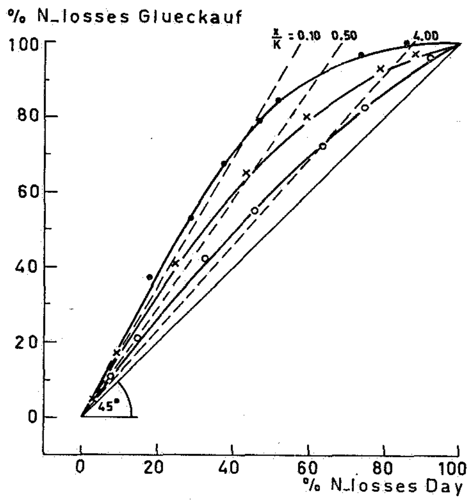


FIG. 1. A comparison of the N-losses by leaching computed by the equations of Day and Glueckauf at different $\frac{x}{K}$ ratios

greater distribution factors. As in practice we are interested mainly in profiles shallower than one meter, the equation of Glueckauf might be preferable to that of Day.

c. *Transformation of the equation of Day*

It is a drawback that the equation of Glueckauf is much more complicated than that of Day. Therefore we can ask ourselves whether it might be possible to introduce a correction factor in the upper limit z of the equation of Day, making the losses equal to those detected with the equation of Glueckauf at the same values of D, v, x and K.

Figure 2 demonstrates the relation between the upper limit value z according

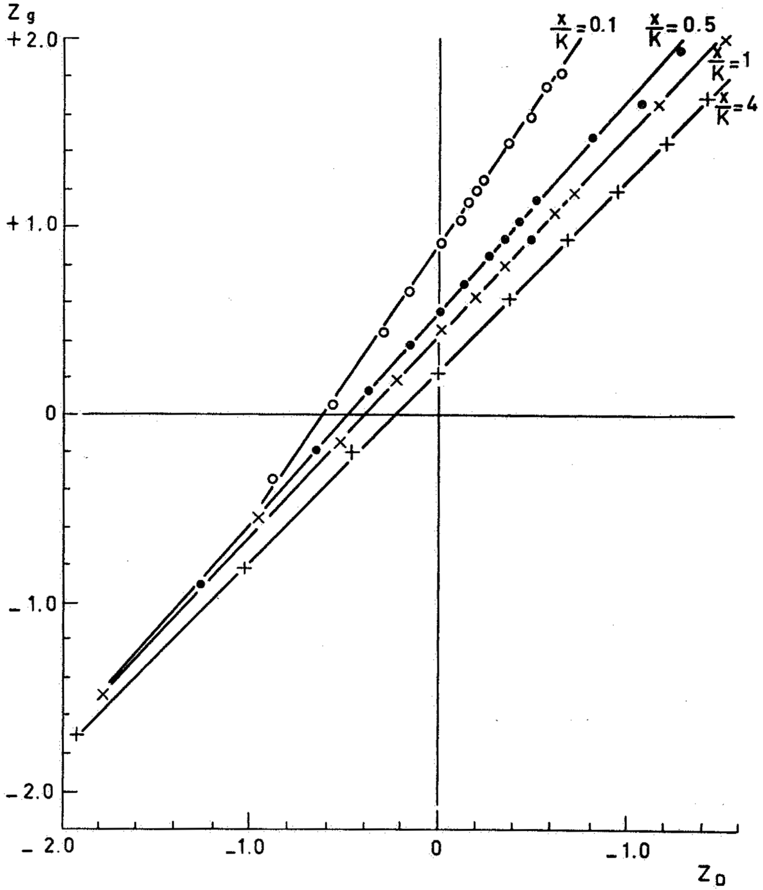


FIG. 2. Relation of the upper limit value (z_d) of the normal distribution in the equation of Day, and the corrected value of it (z_g) at different $\frac{x}{K}$ ratios

$$z_g = mz_D + q = \frac{P-1}{\sqrt{p}} \cdot \sqrt{m^2 \cdot \frac{x}{K}} + q \, .$$

to Day (z_D) and the corrected value z_g neccessary when the equation of Day should give the same losses as that of Glueckauf at equal values of D, v, x and K. Since this relation is linear we have: $z_g = m.z_D + q$.

The modified equation of Day can be written now as:

$$\text{Losses in } \% = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{z_g} e^{-\frac{1}{2}z^2} \, dz$$

and $z_g = \frac{\frac{D}{v} - 1}{\sqrt{\frac{D}{v}}} \sqrt{m^2 \frac{x}{K} + q}$

From table 1 and figure 3 the transformation factors m^2 and q can be read as a function of the $\frac{x}{K}$ ratio.

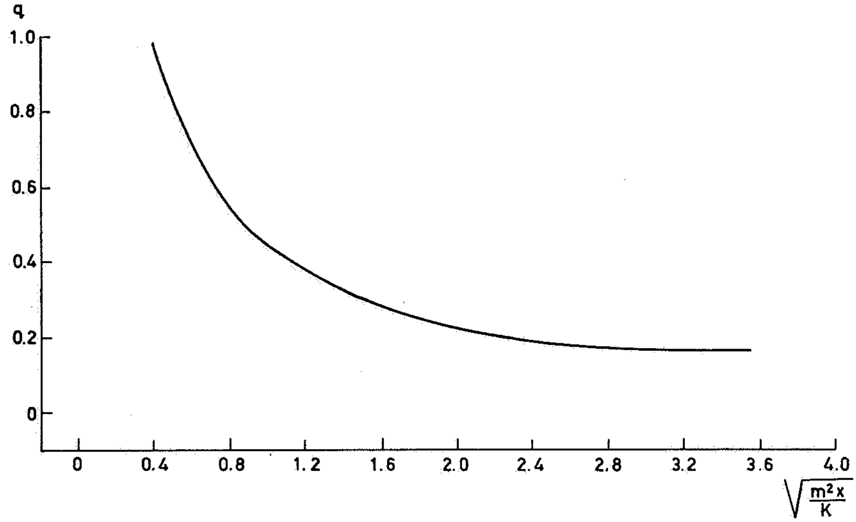


FIG. 3. Relation between the values of q and $\sqrt{m^2 \cdot \frac{x}{K}}$ for the assessment of the losses according to Glueckauf with the modified equation of Day

$$\% \text{ loss} = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{1}{2}z^2} dz$$

$$z_g = \frac{\frac{D}{V} - 1}{\sqrt{\frac{D}{V}}} \cdot \sqrt{m^2 \cdot \frac{x}{K} + q}$$

TABLE 1. Factors for transforming the equation of Day into an equivalent of the equation of Glueckauf

$\frac{x}{K}$	m^2	q	$\sqrt{m^2 \frac{x}{K}}$
0.10	2.04	0.90	0.45
0.20	1.69	0.75	0.58
0.50	1.23	0.55	0.78
1.00	1.14	0.43	1.07
2.00	1.08	0.30	1.47
4.00	1.04	0.23	2.04
7.00	1.00	0.18	2.65
12.00	1.00	0.17	3.64

3. Testing the modified equation of Day under field conditions

a. *Methods*

On a number of fallow trial fields the fate of the nitrate-ions after surface application of calciumnitrate was observed under more natural conditions than is possible in columns. The fields were of very different soil types, ranging from a pure sandy soil to heavy clay soils (approx. 60 % silt) and one reclaimed peat soil with undisturbed peat to 60 cm in the subsoil (figures 4, 5 and 6).

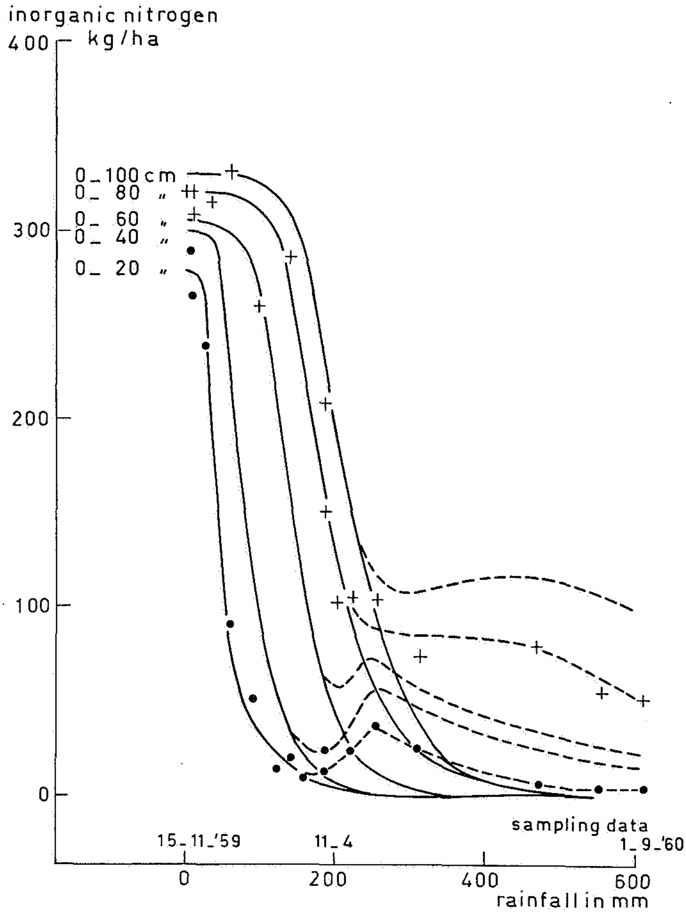


FIG. 4. Effect of leaching on the amount of inorganic nitrogen in a sandy soil in winter on profiles of different depths. Observed dots IB 522: • 0-20 cm; + 0-80 cm
——— calculated leaching curves (winter)
— — — hand-drawn curves (summer)

The nitrate was applied in autumn or spring at 150-250 kg N/ha. The fields were sampled in layers of 10 cm down to a depth of 100 cm with intervals of 14-30 days. In the laboratory the samples were homogenized immediately (or after storage at ca. 2°C) by rubbing through a screen, and subsamples were extracted with a solution of 1 % NaCl in water. In the extract the inorganic-nitrogen content was determined by the method of COTTE and KAHANE (1946). Hereby the nitrate nitrogen is reduced to ammonia. As the amount of ammonia in soil under normal conditions is low, the method is a measure for the amount of nitrate in the soil.

From each layer (10 cm) of the profile a complete pF-curve was constructed and since also the level of the water table was known, it became possible to calculate the amount of water in the layer, for each distance from the water table. The amount of water held in the whole profile (v) was found by summarizing the quantities in the layers.

The amount of drainwater (D) was calculated from rainfall (R) and evo-

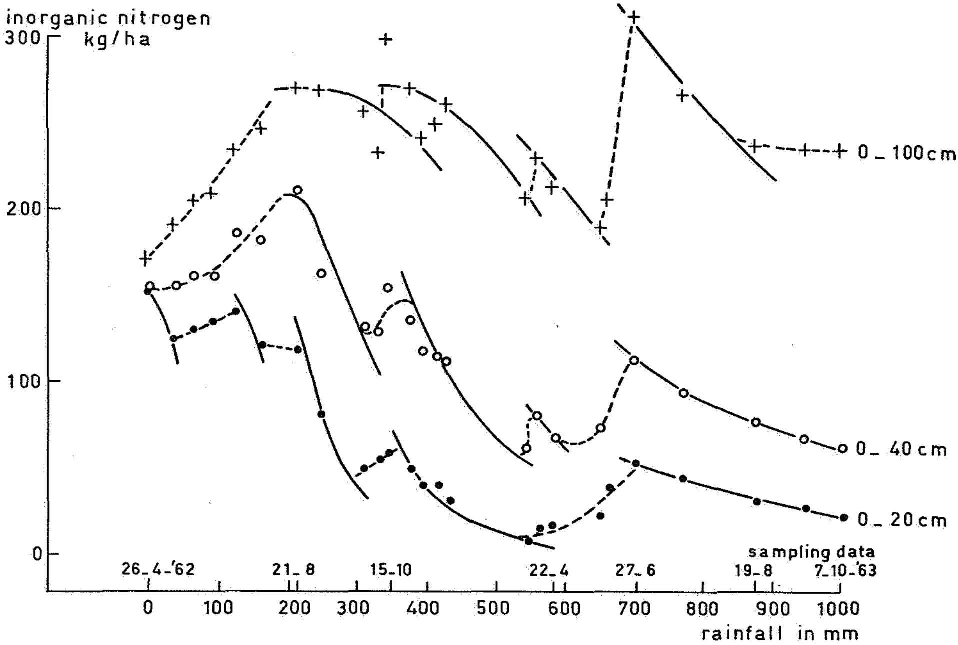


FIG. 5. The amount of inorganic nitrogen in heavy clay soil profiles of different depths IB 719:
——— calculated leaching curves
– – – – hand-drawn curves

poration (E). As rainfall values were used the official recordings of the meteorological stations as close to the field under investigation as possible. In late autumn, winter and early spring the evaporation is negligible. The rainfall in this period is a good measure for the drainwater production. Considering the evaporation in summer practically independent of the depth of the profile, the magnitude of this evaporation could be estimated with a reasonable probability. In the example of figure 5 the evaporation during the period April 26-August 21 proved to be about 190 mm.

b. *Results*

When the amount of water in the profile (v) and the production of drainwater ($D = R - E$) are known, we only must estimate the values $\sqrt{m^2 \frac{x}{K}}$ and q from figure 3, to get a leaching curve that describes the experimental results as good as possible. Figure 4 proves that the modified equation of Day gives a good description of the experimental results on a sandy soil in winter for profiles varying from 0-20 cm to 0-100 cm.

The downward movement of the wave through the "bottom" of the profile will find its expression in a nearly linear decrease of the amount of inorganic nitrogen within the profile. This decrease will be faster the smaller the length of the wave and the higher its top.

On heavy clay and heterogeneously reclaimed peat soils the interpretation of the results is not so easy as on sandy soils. The downward movement in such soils is slower due to the higher waterholding capacity and a higher dispersion factor. It therefore can happen that at the end of the winter the top of the wave has not yet passed the bottom of the profile. But by capillary suction in spring and summer the part of the wave beyond the bottom of the profile can return to the profile and bring about a rise of the amount of inorganic nitrogen. An extra complication in these types of soil is caused by the increase of the nitrogen level by mineralization of nitrogen in the upper layer of the profile in the year after application of the nitrogen.

In the next winter the top of the wave again may pass the bottom of the profile and the process of leaching will be continued. After a dry winter it is possible that the whole course will be repeated. That's why it will be possible to find in consecutive years different parts of the same leaching curve, partly overlapping each other. Figure 5 shows how some stretches of the curve can be recognized as parts of one leaching curve (fig. 6) that can be described with the modified equation of Day. It will be possible when the correct values of

$\sqrt{m^2 \frac{x}{K}}$ and q are found, to calculate the distribution factor K for different soil profiles.

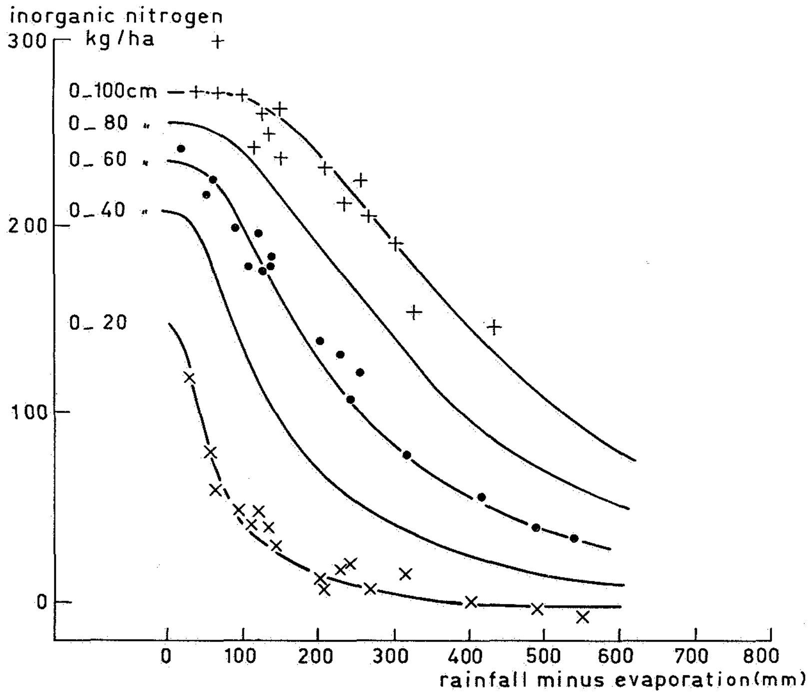


FIG. 6. Effect of leaching on the amount of inorganic nitrogen in a heavy clay soil in winter on profiles of different depths
Observed dots IB 719: × 0-20 cm; • 0-60 cm; + 0-100 cm
——— calculated leaching curves

c. *The distribution factor K*

From the two above mentioned extremely different examples, which can be amplified with several others, it is found that it is possible to give a description of the leaching losses under natural conditions with the modified equation of Day identical to that using the equation of Glueckauf. For practical use, however, it will be necessary to know the parameter K. Therefore we must know the relation between this distribution factor and a measurable factor of the soil. As the distribution factor depends on the mean pore size and the pore-size distribution, the air content of the soil at pF 2.0 may be a suitable measure. In table 2 the mean air content in the profile 10-100 cm is calculated. It is the mean air content of nine layers of 10 cm, each layer being supposed to have a pF = 2.0.

TABLE 2. The mean air content in a profile of 10-100 cm in vol. % per 10 cm at pF 2.0

	Soil type	% air
IB 523	Sandy soil	27.5
IB 522	Sandy soil	26.5
IB 731c	Loamy soil	22.0
IB 720	Reclaimed peat	14.0
IB 718	Sandy clay soil	12.0
IB 521	Sandy clay soil	7.5
IB 524	Light clay soil	4.5
IB 719	Heavy clay soil	2.5

It is apparent that there is a wide range over the different soil types.

Figure 7 gives the relation between the distribution factor K of different soils and the mean air content of the profile (10-100 cm). The relation can be expressed as:

$$K = \frac{4.5\,(x - 10)}{L^2} + 9$$

K = distribution factor in cm
x = depth of the profile in cm
L = mean air content in the profile (10-100 cm) in vol. %/10 cm at pF 2.0

The standard deviation of K (S_K) will increase considerably below an air content of 10 %. Calculating a mean standard deviation we must use the reciprocal value $\frac{1}{K}$, which has an equal variance over the range 0-30 % of the independent variate. The relation of S_K and $S_{\frac{1}{K}}$ can be expressed as:

$$S_K = S_{\frac{1}{K}} \cdot K^2$$

Since for $S_{\frac{1}{K}}$ was found 0.017 cm we have

$$S_K = 0.017 \cdot K^2$$

For K = 10 cm, S_K = 1.7 cm.
for K = 40 cm, S_K = 27.2 cm.

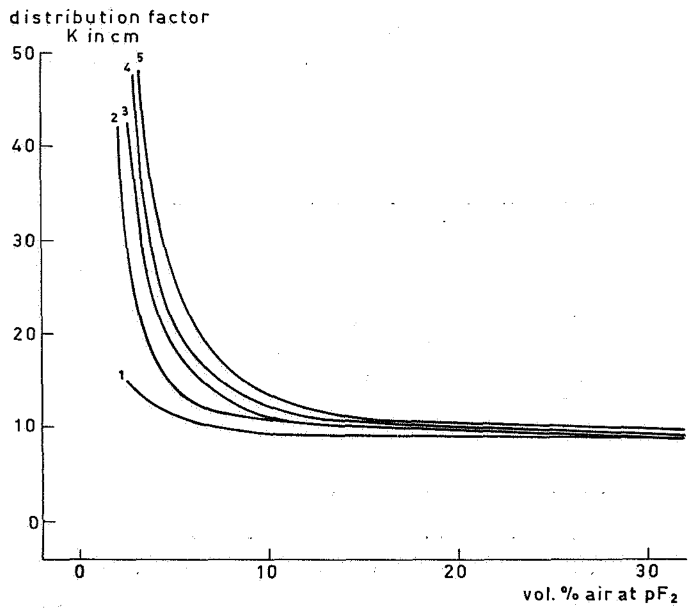


FIG. 7. The relation between the distribution factor K and the air content of the soil at pF 2.
Standard deviation: $S_K = 0.017.K^2$ cm

$$K = \frac{4\,.\,5(x - 10)}{L^2} + 9$$

Profile depth:
1. 0- 20 cm
2. 0- 40 cm
3. 0- 60 cm
4. 0- 80 cm
5. 0-100 cm

4. Discussion

From figure 6 it is found that above a mean air content of 10 % in the profile at pF 2.0 the distribution factor is about 8-12 cm. The influence of the depth of the profile is small. But below 10 % air there is a sharp increase in the value of K, which becomes higher the deeper the profile is. This is caused by the fact that such soils are clay soils with many cracks in the subsoil. A part of the nitrate is rapidly transported downward through these cracks. In the furrow the air content is high, even in heavy soils, due to repeated tillage activities. Consequently there will be little difference in the distribution factor in the 0-20 cm layer of different soils.

Comparing these results with those of other investigators, it becomes apparent that we must distinguish between experiments with filled-in columns and field experiments with undisturbed soils and low water velocities. In the first type of experiments with continuous leaching NIELSEN and BIGGER (1967) found for the value of K 2 cm. FRISSEL and POELSTRA (1967b) in a series of experiments with different rates of water flow obtained values between 1.7 – 0.17 cm, and in our own experiment on sandy and peat soil it was 6.3 – 1.4 cm. All together the values consequently vary between 6.3 – 0.17 cm with an average of about 3 cm.

In field experiments with intermitting leaching GARDNER (1965), using the results of WETSELAAR (1962) on clay soil, calculated for K the value of 44 cm, while VAN DER MOLEN (1956, 1958) found values between 5-15 cm on 5 different soils. The results of these experiments are in good agreement with those of figure 6.

The difference between column and field experiments must be caused by the difference in texture (pore-size distribution) and water flow. The latter is generally rather high in column experiments and that is why it is not possible to use the parameter K calculated from column experiments in field experiments.

The high values of K at a lower air content indicate that it is not advisable to simplify the equation of Glueckauf to that of Day by neglecting the second terms without any correction as was done by VAN DER MOLEN (1956 and 1958), as in clay soils the $\frac{x}{K}$ ratio then becomes too small.

In agreement with FRISSEL and POELSTRA (1967b) and NIELSON and BIGGER (1967) we must conclude that the equation of Glueckauf is preferable to that of Day, although the difference will be small at air contents higher than 10 % and profile depths greater than 0-40 cm.

5. CONCLUSIONS

1. Leaching can be described either by the equation of Glueckauf or by that of Day. The latter can be regarded as a simple form of the first. In shallow profiles and in clay soils, however, the equation of Glueckauf must be preferred to that of Day.
2. After a correction it proved possible to use the equation of Day even for clay soils as then the results of both expressions become nearly identical. For calculation practice this must be considered a great advantage.
3. The distribution factor K, a measure for the dispersion of soluble substances could be determined for different soil profiles and proved to be closely related to the air content of the soil at pF 2.0.

4. It is not possible to use the distribution factor, calculated from column experiments for field work. Under field conditions the distribution factor is about three times that in columns.

6. Summary

On eight different soil profiles the leaching of applied nitrate was studied under field conditions. This process can be described by the theory of Glueckauf. But after a correction it also proved possible to use the less complicated equation of Day.

Using this modification of Day the distribution factor K could be calculated for different soil profiles. This factor is a measure for the vertical dispersion of soluble substances in the soil profile. It was found that it is closely related with the air content in the soil at pF 2.0.

The value of K is about 8-12 cm at air contents higher than 10 %, with a small effect of the depth of the profile. Below 10 % air (clay soils) K increases strongly with the profile depth. This is caused by cracks in the subsoil.

In columns filled in with soil the value of K is about three times smaller. This makes it impossible to use the distribution factor of column experiments in field work.

LITERATURE

Cotte, J. and E. Kahane 1946. Sur une nouvelle methode de reduction pour le dosage des nitrates. *Bull. Soc. Chim. Fr. 9-10:* 542-544.

Day, P. R. 1956. Dispersion of a moving salt water boundary advancing through saturated sand. *Trans. Amer. Geophys. Union 37:* 595-601.

Frissel, M. J. and P. Poelstra 1967a. Chromatographic transport through soils. I Theoretical evaluations. *Plant and Soil 26:* 285-302.

Frissel, M. J. and P. Poeltsra 1967b. Chromatographic transport through soils. II Column experiments with Sr- en Ca-isotopes. *Plant and Soil 27:* 20-32.

Gardner, W. R. 1965. Movement of nitrogen in soil. Soil Nitrogen, Agronomy no. 10. Ed. W. V. Bartholomew and F. E. Clark. Madison, Wisc., U.S.A.

Glueckauf, E. 1949. Theory of chromatography. Part VI. Precision measurements of adsorption and exchange isotherms from column-elution data. *J. Chem. Soc.:* 3280-3285.

Molen, W. H. van der 1956. Desalinization of saline soils as a column process. *Soil Science 81:* 19-27.

Molen, W. H. van der 1958. The exchangeable cations in soils flooded with sea water. Diss. 's-Gravenhage.

NIELSEN, D. R. and J. W. BIGGER — 1967. Radio-isotopes and labelled salts in soil-water movement. Soil moisture and irrigation studies. Panel Proc. Series Intern. Atomic Energy Agency, Vienna: 61-76.

WETSELAAR, R. — 1962. Nitrate distribution in tropical soils III. Downwards movement and accumulation of nitrate in the subsoil. *Plant and Soil 16:* 19-31.

IV. SOIL WATER CONTENT IN RELATION TO NUTRIENT UPTAKE BY THE PLANT

L. K. WIERSUM
Institute for Soil Fertility, Haren-Groningen

1. INTRODUCTION

Besides the fact that water is the main constituent of a plant it is also consumed in enormous quantities in the process of transpiration. As such large quantities of this substance are necessary as nutrient and as growth factor it is no wonder that it is often the primary limiting factor in growth of the plant. Water, however, is also of importance as a fluid transporting substance to the plant and in the plant. Also numerous characteristics of its medium, mainly the soil, are strongly influenced by its content and movement of water. In these two latter respects it can have a profound influence on mineral nutrition.

In this discussion an attempt will be made to elucidate the manners in which a number of interrelationships between soil water content and nutrient uptake are effected. In many cases no more can be done than to indicate along which lines progress has been made in obtaining further insight into the separate problems. No attempt has been made at completeness. Many parts of this discussion are due to contributions given by my colleagues of the Institute and its contributions in this field will be stressed.

The uptake of nutrients can be considered as an interplay between the amounts available and the possibilities of utilization of the stock by the plant. On these grounds the interrelationships with water content can be divided into three categories.

First of all we can consider in which manner water content influences the amount and the character of the available nutrients. A second aspect is the replenishment of nutrients at the root surface, where depletion occurs as a result of absorption. Modes of transport from source to sink will be discussed. In the third viewpoint the utilization will be stressed. Discussion will be focussed on the development of the absorbing root system, in its relation to water content of the soil. A few remarks concerning climatological effects which may affect nutrient uptake by different manners will also be given.

2. WATER CONTENT IN RELATION TO AMOUNT AND MODE OF OCCURRENCE OF READILY AVAILABLE MINERAL NUTRIENTS

The stock of available nutrients in the soil can be considered to occur in two fractions. One fraction consists of the nutrients "bound" in some way or other, either adsorbed, fixed, undissolved or unmineralized. The second fraction consists of the dissolved nutrients. No sharp distinction can be made on account of exchange processes. An important distinction between these two fractions is their difference in mobility, which is very restricted for the first and large for the second.

Except for the possibility of direct "contact exchange" (JENNY and OVERSTREET, 1939) contributing to uptake to some extent, the main primary source of the nutrients is the soil solution. Its reaction to changes in water content will be our first point for discussion.

As the water content of the soil increases the concentration of the soil solution will diminish. An almost inverse relationship between amount of water in the soil and concentration can generally be expected for the anions NO_3^-, $SO_4^{=}$, Cl^-, because almost the whole stock of these ions is in the solution. For the phosphate ions the situation is different. Here an intricate interplay of equilibria occurs with "bound" phosphate and the result will be that dilution is partly counteracted by release of phosphate ions (METWALLY and POLLARD, 1959).

In considering the behaviour of the cations of K, Na, Ca and Mg the situation becomes more complicated. More moisture in the soil will bring about a certain dilution. But the amount of dilution will differ according to the ion species. One of the main operating factors is the valency effect. This will result in a relative increase of the monovalent K^+ and Na^+ ions in the soil solution in comparison to the divalent Ca^{++} and Mg^{++} ions. This latter phenomenon can be described by a simplified equation derived from Eriksson's formulation. This relationship can be expressed by:

$\frac{j^+}{j^{++}} = G \frac{C_o^{\ +}}{\sqrt{C_o^{\ ++}}}$ in wich j^+ and j^{++} are the amounts of mono-, respectively divalent cations adsorbed (in m.e.); $C_o^{\ +}$ and $C_o^{\ ++}$ are the concentrations of these cations in the equilibrium solution (mol/liter) and G is the Gapon exchange constant. (VAN SCHOUWENBURG and SCHUFFELEN, 1963; LAGERWERFF and BOLT, 1959).

Recent data given by Moss (1964) show that the ratio K/Ca + Mg in the soil solution decreases from 0.20 to 0.13 as the pF value rises from 0 to 3 for the soil used. This shift in the soil solution is also evident in the mineral content of the plants used in the experiments (radish and *Brassica sinensis*). Under field conditions the same effect may be detected (fig. 1). In elaborating the results of 71 experimental fields on clay soils in which *K*-fertilizing experiments on potato were performed, MES (personal communication) found that leaf *K*-content was positively correlated with the amount of rainfall preceding the data of sampling

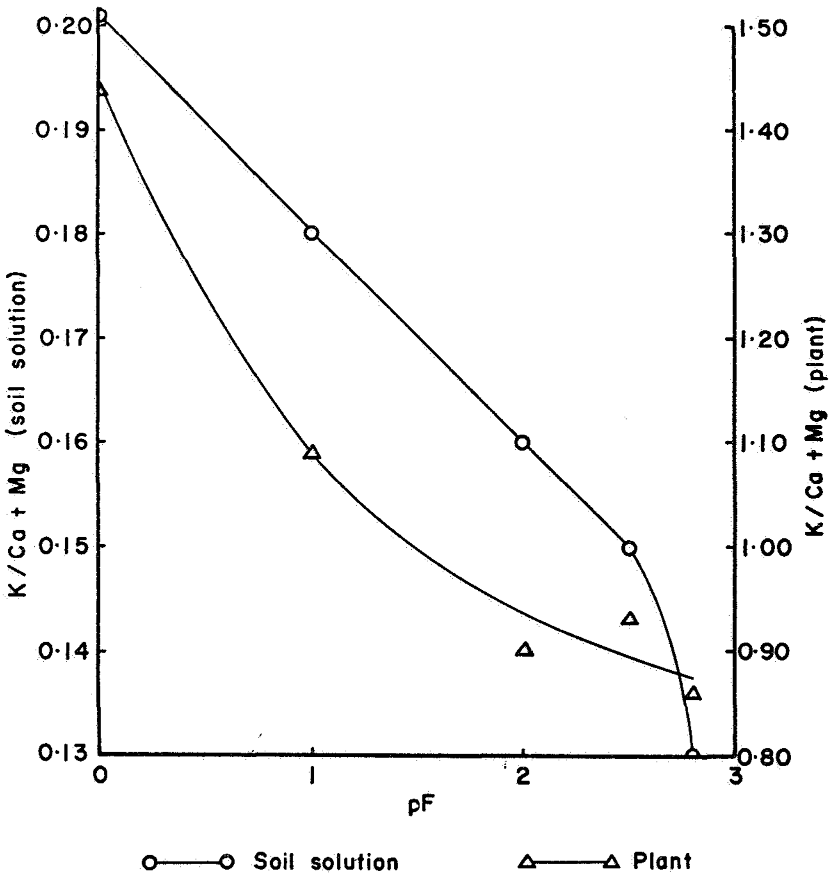


FIG. 1. The effect of dilution on the cation ratios of the soil solution and those absorbed by radish

up to a period of 45 days. Averaged over a period of 25 days each 10 mm rainfall effected a 0.25 % increase in K_2O-content of the potato-leaves. The same type of response with potatoes has also been observed by VAN DER PAAUW (1958). It has also often been observed that Mg-deficiency is more liable to occur in wet years (BROWN et al., 1960).

Few data are available concerning variations in concentration of the minor nutrients along with moisture content of the soil in the range of pF 1 — 4,2. Results of OLIVER and BARBER (1966a) suggest that with increasing water content B concentration diminishes while Fe, Zn and Al concentration may rise. In a number of cases the interaction of water content and soil aeration becomes a decisive factor. As moisture content in the soil rises an increasing number of the smaller capillary pores are filled with water. Also the thickness of the water films increases. As both diffusion of oxygen, and carbon-dioxide is enormously slowed down – O_2 by a factor 10^4 – in solution in comparison to in gas phase the p O_2 diminishes and bicarbonate content rises. The most extreme situation of reduction and high bicarbonate content will occur in flooded soil.

Taking the above-mentioned relations into consideration the question may be put what the requirements are for soil structure to allow a reasonable aeration at higher soil moisture contents, i.e. up to field-capacity (pF 2). This is the more important as lack of aeration does not only influence chemical soil equilibria but also profoundly effects root growth. If the air content at pF 2 decreases below 10, 15 or about 25 % for respectively heavy clays, silt soil, or sandy soils lower crop yields occur (BOEKEL, 1963; PATT et al., 1966). But if the water table is at a depth less than 100 cm these values may not be attained because of the lower pF and soil structure requirements are very high (BOEKEL, 1966). As these responses of the crop are effected by means of lack of optimal aeration of the root system this means that certain aspects of soil chemistry will also be affected.

Manganese availability may already be enhanced under conditions of low oxygen supply under normal moisture conditions (LABANAUSKAS et al., 1962).

Excess of water in the soil, however, can bring about far more important variations in availability of the minor elements. This excess of water is only important from an agricultural viewpoint for most crops if it only occurs incidentally, for a continuously anaerobic soil will not possess living roots. Temporary water saturation of the soil is, however, no uncommon feature.

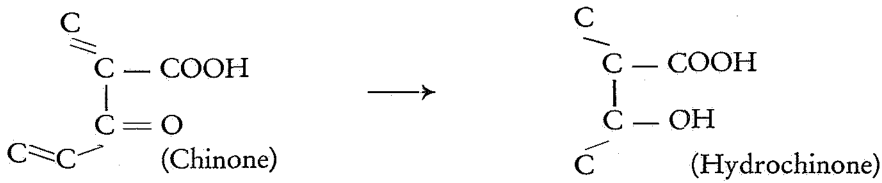
The rise in bicarbonate content, especially in calcareous soil, can impede Fe absorption by the roots as a result of inactivation of enzymes.

The anaerobic conditions result in reduction of MnO_2 to Mn^{++}, especially on acid soils (GRASMANIS and LEEPER, 1966). The amount of exchangeable manganese can increase enormously, resulting in toxicity (MIDDELBURG, 1967). According to GRAVEN et al. (1965) available Mn rises from 9 to 235 units after 144 hours of flooding on a Kellner loamy sand. However, there is another reaction, which may occur, and which has a contrary effect. The possibility of formation of a hydratation complex, which is not plant available, also exists according to the following equation:

$$x\,MnO + y\,MnO_2 + 2\,H_2O \rightleftarrows (MnO)_x\,(MnO_2)_y\,(H_2O)_2$$

Especially in cold and wet soils the latter product can be formed and Mn absorption is disturbed. Evidence for reduced Mn availability if this type has been observed in pot experiments with clay soils taken from recent deposits in estuaries (DE GROOT, 1963).

The reduction that occurs in the soil under anaerobic conditions can give rise to alterations in some organic compounds, resulting in enhanced chelate forming capacities. An example is the reaction:



If this occurs the solubility of Cu and Fe compounds is raised and availability is increased. Ultimately this may result in disturbances in the total minor element equilibria. For iron, however, the above mentioned possibility of toxic bicarbonate effects may counteract the result. Nevertheless the increase in soluble chelated Fe in the soil has been observed in pot experiments in wet soils (DE GROOT, personal communication). Under the anaerobic conditions due to waterlogging the reduction processes may also affect NO_3^- and $SO_4^=$. Formation of toxic nitrite can occur but does not seem to be agriculturally important. Complete denitrification may effect important N losses. Sulphide, however, can certainly produce toxic effects. The formation of organic acids in general is not enough to be deleterious (FORD, 1965).

The rather complicated effects of very high moisture content on the chemistry and availability of the nutrient ions make it extremely difficult to forecast the result in a special case. In most cases survival of the root system is far more important so that the occurrence of these extremes should be avoided as far as possible.

3. SOIL WATER IN ITS FUNCTION OF ION TRANSPORTING MEDIUM

Although a very large volume of soil is permeated by the total root mass of a crop the volume of soil in direct contact with the absorbing root and its root hairs is nearly always small in comparison. Calculated estimates (WIERSUM, 1961) have given evidence that for a field crop this soil-root contact volume is usually less than 3% of the total. Of the total amount of available nutrients in the soil the same small percentage will thus be at immediate disposition of the plant. The amount of nutrition with which the root comes into contact by root-interception (BARBER et al., 1963) is even smaller.

The result is that most nutrients will have to migrate to the root surface. Contact-exchange and surface migration as postulated by JENNY can be considered of negligible importance. The only other way in which migration is possible is in solution, either by diffusion or by mass flow. Thus water has an indispensable function in the nutrition of a plant.

As a nutrient is absorbed by the root its concentration at the surface will be lowered and a diffusion gradient will be established. Ions will move along this gradient. The resulting decrease in concentration will also induce replenishment of the nutrients in solution either by desorption or by dissolving. This process of diffusion is necessarily restricted to small distances, 1-3 mm, to be of any worthwhile value.

The second mode of transport of ions is the passive movement along with the soil solution. This "mass-flow", first postulated by BRAY (1954), of the soil solution is induced by the water requirement of the transpiring plant. Except for some minor effects, this mass flow carries along all dissolved substances indiscriminately. By this means of transport much larger distances are involved. They are the same as the distances encountered in extraction of water from the soil, which means that most of the soil volume permeated by the root system is involved in the supply (HSIEH, 1964; RICHARDS and WEEKS, 1957).

a. *The process of diffusion in relation to the water content of the soil*

The amount of ion migration by means of diffusion is dependent both on the concentration gradient and on the total cross area of the pathways of transport. Variations in soil water content have a large influence on the total pathway available for diffusion.

In our own experiments (WIERSUM, 1958) excised root pieces were embedded in sand containing a fixed amount of nutrients. In this case mass flow is negligible, because no transpiring plant is attached to the roots. It was found that the uptake of several nutrients was positively correlated with increasing water content of the sand. Exactly the same type of relationship was established for the adsorption by pieces of embedded ion-exchange sheets. The relationship between water content and absorption tends to be linear. The steeper gradient for the ion-exchange sheets may be related to their high rate of fixation, which induces a steeper concentration gradient. As the water content of the substrate increases, more and more of the capillary spaces are filled with water and thus the total cross section of available pathway rises. Another factor facilitating diffusion is the decrease in tortuosity as the substrate contains more moisture.

Numerous investigators are involved in recent research on ion diffusion in soil as related to moisture content. It has now become evident that the volume percent of water in the soil is the decisive factor. The relationships with the pF value are more intricate and show much more variation according to the type of soil (KEMPER and VAN SCHAIK, 1966). The speed with which diffusion occurs varies a lot for the different ions. The anions NO_3, Cl, and SO_4 can be considered as fast moving, while phosphate is verly slow. As far as the cations are concerned K and Na seem to move faster and cover slightly larger distances than Ca and Mg (TEPE and LEIDENFROST, 1958; COOKE, 1966; VAIDYANATHAN and NYE, 1966).

The effect of water content on diffusion rate can be illustrated by results obtained by OLSEN et al. (1965). The porous system self-diffusion coefficient (Dp) ranged from 0.4×10^7 to 15.5×10^7 $cm^2/sec.$ as the volumetric moisture content increased from 0.22 to 0.55. This is a nearly 40 times increase in rate of diffusion as soil suction is lowered from 6 to below 1 bar in a silty clay loam.

Generally a more or less linear relationship with soil water content is found (VAN SCHAIK and KEMPER, 1966; WESLEY, 1965; WIERSUM, 1958). Exceptions, however, have been found.

If, however, a higher water content of the soil results in a lowered concentration of a certain ion, e.g. Cl (PAUL, 1965), the enhanced possibilities for diffusion are more or less counteracted by a decrease in concentration gradient.

b. *The transport of ions by "mass flow"*

The water extracted from the soil by the plant carries along the substances dissolved in it towards the root surface. Interchange with adsorbed ions along the route will occur, but this has no influence on the overall process. If we conceive the soil solution as being in equilibrium with the solid phase of the soil, it is this solution that is transported.

If the amount of water consumed by a crop is known the amount of ions transported towards the root surface can be calculated if the constitution of the soil solution has been established. The amounts supplied are directly related to the amount of water transpired.

A generalized calculation (BARBER, 1962; WIKLANDER, 1965) immediately demonstrates the large differences in the amounts of the different ions transportable in this manner. Phosphate supply by this means is far below requirement, for potassium it is generally insufficient, while the amounts of Ca and Mg brought to the root surface are greatly in excess.

As the rate of uptake of any single ion is not directly linked with the rate of entry of water, this calculation of the contribution by mass flow is only of restricted value. However, nitrate is an exception. In the latter case we must regard the nitrogen supply of the plant to be dependent on this mode of transport. The distances involved are in the order of several centimeters.

An important consequence of this conception is that it has led us to the realization that the ionic composition at the root surface may be widely different from that in the normal soil solution. Substances supplied in excess of uptake will accumulate at the root surface and its immediate vicinity. This may result in secondary interactions.

None the less it will be evident that the more water the plant can extract from the soil the higher the contribution by mass flow will be. Alterations in composition of the soil solution as discussed earlier will have to be taken into account however. A reasonably high moisture content throughout the soil can be considered favourable for this mode of supply. The results of recent investigations have given us an idea of the relative contribution of the two modes of transport.

Except for the quantities contained in the organic matter, which are only slowly released by mineralization the whole stock of available nitrate and sulphate is in solution. Nearly the whole stock contained in the soil volume contributing water to the plant is thus supplied to the roots. The depletion of soil nitrate under a crop in midseason (HARMSEN and KOLENBRANDER, 1965) is clear evidence of this occurrence. Chloride supply to the root surface occurs in the same manner.

OLIVER and BARBER (1966b) have investigated the mechanisms governing the supply of Ca, Mg, K and Na to soybean roots in a silt loam soil. A significant contribution to uptake of Ca and Mg was supplied by means of massflow. For potassium, however 87-96 % of the absorbed substance was calculated to have reached the root by diffusion. For sodium supply the mass flow was in excess of uptake.

The necessity for diffusion arises if supply by mass flow is insufficient. Besides for potassium, this is still more the case for phosphate. The result of supply by diffusion is clearly evident from the occurrence of thin depleted layers of soil along the roots as can be made visible by autoradiography.

The formulation of a relationship between uptake of ions and water content of the soil seems to be easiest in the case diffusion is the dominating factor. We then may expect an enhanced uptake along with a rise in moisture content. This kind of effect has been described by MEDERSKI and WILSON (1960) for P and K with corn. The Ca content was found to be independent of soil moisture content, which is not surprising if mass flow supplies excessive amounts.

A clear contrast in behaviour is also found in the results published by FLOCKER and TIMM (1966). The phosphate content in the petioles of potatoes rises as water tension in the soil is lower. The behaviour of the nitrate content is just the opposite.

If soil moisture decreases to values in the vicinity of wilting point ion transport is severely hampered. The possibilities for mass-flow approach zero and diffusion becomes negligible. Maybe some contact-exchange absorption (JENNY and OVERSTREET, 1939) is still possible, but above pF 4.2 no significant uptake has ever been observed.

Summarizing we may come to the following general remarks.

It is evident that a high water content of the soil will be favourable as regards the supply of nutrients. In this respect we may refer to glass-covered horticulture where the growers aim at constant low water tensions in their soil. Of course leaching and development of anaerobic conditions must be prevented.

The question arises whether the discussed relationships can be formulated in a quantitative way. Here large difficulties are encountered. For the time being the most obvious way to tackle this problem seems to be the division of ions into two categories as regards their dominating mode of transport.

For those ions, such as phosphate, potassium, manganese, iron, and zinc, where diffusion is the main mode of supply a formula for diffusion process can be used. But the constant relating the diffusion rate to water content may vary for different ions.

When mass-flow accounts for the greater part of the supply water consumption by the crop is the regulating factor. This means that over a fairly large range of water contents the supply will be fairly constant. Only when transpiration is hampered in the dryer range the supply will decrease proportionally. But then the water itself will also become a very important factor.

Results obtained on corn under conditions of waterstress can illustrate this to some extent. The reduction in dry matter production (44 % of control) was accompanied by reduction of P content to 40 % and K to 71 %. Calcium however still accumulated to 93 % (JENNE et al., 1958). But in other research different results have been obtained. N content may be higher or lower.

4. THE ABSORBING ROOT SYSTEM IN RELATION TO WATER CONTENT OF THE SOIL

In more or less normal conditions growth of roots will occur during the greater part of the vegetative season. This continuous growth is more or less a necessicity as the amount of easily extracted water and that of available but immobile nutrients in the root vicinity will become exhausted. Flow of water in unsaturated soil is mostly too slow to comply with plant requirements. To obtain a steady supply thus a continuous shift of the absorbing zones into fresh soil is needed.

Root growth in soil is possible up to the wilting point. (SALIN et al., 1965). The rate of growth increases, along with an increase in water content, which facilitates extraction. A number of investigators have published data on ob-

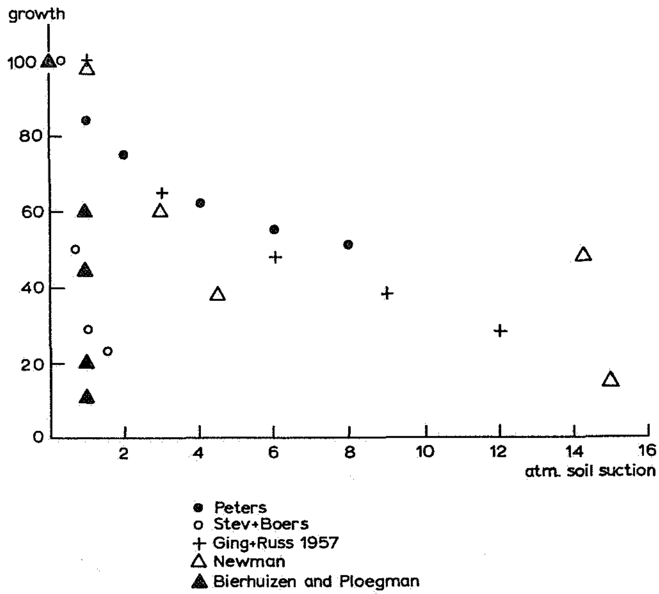


FIG. 2. Some of the data obtained on the relationship between soil water suction and root growth

served relationships between soil moisture tension and root elongation (GINGRICH and RUSSELL, 1957; PETERS and RUSSELL, 1960; RØNNIKE, 1957; NEWMAN, 1966; ROM and DANA, 1960; STEVENSON and BOERSMA, 1964; BIERHUIZEN and PLOEGMAN, 1958).

It is evident that the rate of elongation decreases as the water tension rises and that per unit of increase in tension the effects are usually higher in the range of low tension (PETERS, 1957). In figure 2 the results of a few investigations have been depicted to demonstrate the general trend.

The growth rate of a single root increases along with a rise in moisture content of the soil. This will go on till a condition is reached where lack of aeration becomes limiting (ROM and DANA, 1960). This lack of aeration is the result of decreased air-filled open pore space and also increase of waterfilm thickness on the roots (LEMON and ERICKSON, 1955). So in general roots will not penetrate downwards beyond the capillary fringe above the water table (WIERSUM, 1967). If the water table occurs at a shallow depth water suction in the soil will be less than pF 2. This will effect very poor aeration unless counteracted by a very favourable soil structure and a large total pore volume (BOEKEL, 1963).

Although rate of root growth is related to the ease of extraction of water the published results may partly be accounted for by an interaction with the pene-

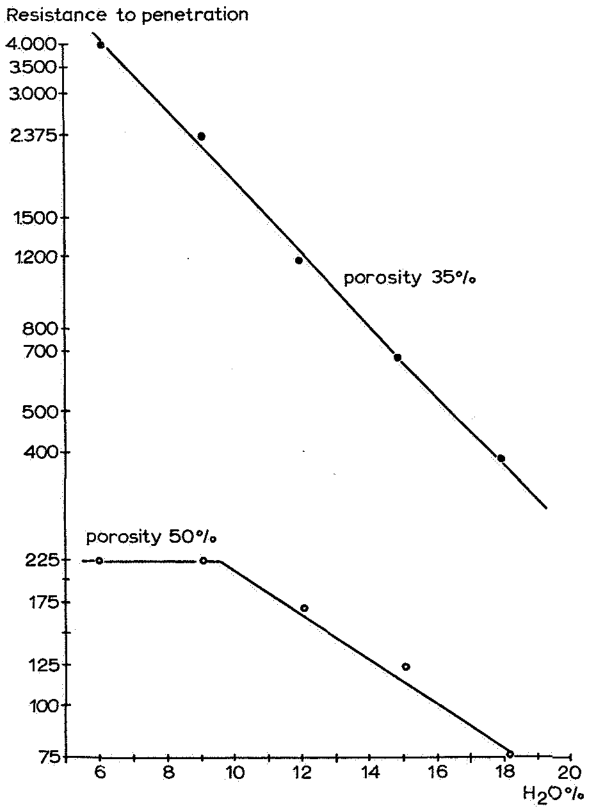


FIG. 3. An example of the relationships between penetrability of the soil and its moisture content at two different densities

trability of the soil. Penetrability of soil for roots is related to pore size (WIERSUM, 1957), density (SCHUURMAN, 1965; BARLEY et al., 1965) and ease of displacement of soil particles (WIERSUM, 1957). The ease of displacement of soil particles is a factor, which is influenced by moisture content. That resistance to penetration in a soil decreases along with a rise in water content has been clearly demonstrated (MAERTENS, 1964; TAYLOR et al., 1966; fig. 3).

So in general it can be concluded that an increase in soil moisture content enhances root growth rate both by means of a direct and an indirect effect. Water contents higher than those at field capacity may, however, soon become deleterious on account of insufficient aeration unless a favourable soil structure occurs.

5. Climatological aspects

Heavy rainfall in excess of evapotranspiration losses will result in loss of nutrients by percolation. The most important is the leaching of nitrate, of which process the characteristics have been dealt with by Kolenbrander (III). Losses of other nutrients, however, will also occur.

Another effect of periods of high rainfall may be the progressive destruction of soil structure. There are indications that the long lasting high moisture contents may result in reduced N mineralization. Van der Paauw (1962) has clearly demonstrated that the cumulative depressing influence on yields of a sequence of wet years must be mediated by the soil.

6. General remarks

Having given this review of the manner in which way the water content of the soil effects the separate processes involved in nutrient extraction from the soil, the question arises if this knowledge can be of use to the agronomist. It is especially related to circumstances where regulation of water supply (drainage or irrigation) is of prime importance and chemical soil fertility has been taken care of.

What can be considered of general applicability?

Which soil moisture regime is to be considered best in relation to nutrition?

A continuous presence of available water in the whole rooted profile must be preferred. Loss of nutrients by leaching should be prevented. Keeping the soil as moist as possible, as long as aeration is sufficient to attain a sufficient depth of rooting. Then we may expect the most intensive utilization of soil nutrients, because of favourable conditions for mass flow, diffusion of ions, rate of root growth and mineralization.

We may have a look at management of soil moisture in protected horticulture. The rapid growth of the crops is facilitated by striving to obtain continuous very low soil moisture tensions.

What one should try to prevent is fluctuations of the groundwater level within reach of the root system. Roots will strive to penetrate downwards in periods of low water level, only to be killed by asphyxiation when it again rises. Another unfavourable condition to be aware of is temporary anaerobic conditions caused by pore saturation with water in the superficial layers as the result of heavy rains or irrigation.

If a subsoil occurs, which is penetrable for roots and which contains nutrients and sufficient moisture a temporary dessication of the topsoil need not be deleterious to the crop and even enhance aeration of the subsoil. Own research (WIERSUM, 1967) has corroborated the fact that deeper situated roots can be as effective per unit of weight as the more superficial roots. A profile with these favourable characteristics will make water management easier.

On more or less saline soils one should be especially careful to avoid anaerobic conditions within rooting depth. Not only the roots may be impaired but low aeration may effect a loss in selectivity of the roots and a strong rise in sodium uptake (LABANAUSKAS et al., 1966).

The high moisture content leading to the poor aeration also results in a relative increase of the sodium concentration in relation to the divalent ions on account of the valency effect.

In some circumstances water management may have a profound influence on minor element nutrition. A too high moisture content could result in increased Mn availability and even toxicity. The other minor elements may also be effected, especially if the pH also changes.

At the end of this review it seems appropriate to mention the possible existence of relationships in this field, which would have general applicability. From the foregoing it will have become clear that water content of the soil can have an effect on nutrient uptake in quite a number of different manners. Soil chemistry, mode of supply and root behaviour are all involved.

The most clearcut relationship is that between moisture content and diffusion of ions in the soil. In this respect the available results of specialized investigations seem to offer good possibilities for a more generalized formulation.

Somewhat less strict is the relationship between rate of root growth and moisture content. Still all evidence shows that also in this case a higher moisture content is favourable, unless it leads to anaerobic conditions.

The relationship between water content of the soil and the ratio of mono-divalent ions in solution can also be expressed in an equation. A rise in moisture content of the soil will always favour a relative preponderance of the monovalent ions in solution.

The supply of ions by mass-flow should be more dependent on the fertility level than on water content directly.

At this moment it seems impossible to suggest any more fundamental relationships of general applicability. But a better general understanding of the phenomena involved should stimulate further research. As more quantitative data become available more factors and parameters can be used in descriptive models, which would allow us to forecast the effects.

LITERATURE

BARBER, S. A. 1962. A diffusion and mass-flow concept of soil nutrient availability. *Soil Sci. 93:* 39-49.

BARBER, S. A., WALKER, J. M. AND VASEY, E. H. 1963. Mechanisms for the movement of plant nutrients from the soil and fertilizer to the plant root. *J. Agr. Food Chem. 11:* 204-207.

BARLEY, K. P., FARELL, D. A. AND GREACEN, E. L. 1965. The influence of soil strength on the penetration of a loam by plant roots. *Austr. J. Soil Res. 3:* 69-79.

BIERHUIZEN, J. F. EN PLOEGMAN, C. 1958. Wortelgroei en waterhuishouding. *Meded. Dir. Tuinb. 21:* 484.

BOEKEL, P. 1963. Soil structure and plant growth. *Neth. J. Agric. Sci. 11:* 120-127.

BOEKEL, P. 1966. De bodemstruktuur van klei- en zavelgronden in verband met de ontwatering. *Landbode 20,* 40: 1047.

BRAY, R. H. 1954. A nutrient mobility concept of soil-plant relationships. *Soil Sci. 78:* 9-22.

BROWN, D. A., PLACE, G. A. AND PETTIET, J. V. 1960. The effect of soil moisture upon cation exchange in soils and nutrient uptake by plants. 7th Int. Congr. Soil Sci. Madison, part IV, 56, 443-449.

COOKE, G. W. 1966. The availability of plant nutrients in soils and their uptake by crops. *Fert. Feed Stuffs J. 63:* 823, 824, 827.

FLOCKER, W. J. AND TIMM, H. 1966. Effect of soil moisture tension and physical condition of soil on utilization of water and nutrients by potatoes. *Agron. J. 58:* 290-293.

FORD, H. W. 1965. Bacterial metabolites that affect citrus root survival in soils subject to flooding. *Proc. Amer. Soc. Hort. Sci. 86:* 205-213.

GINGRIČH, J. R. AND RUSSELL, M. B. 1957. A comparison of effects of soil moisture tension and osmotic stress on root growth. *Soil Sci. 84:* 185-194.

GRASMANIS, V. O. AND LEEPER, G. W. 1966. Toxic manganese in near-neutral soils. *Plant and Soil 25:* 41-49.

GRAVEN, E. H., ATTOE, O. J. AND SMITH, D. 1965. Effects of liming and flooding on manganese toxicity in alfalfa. *Soil Sci. Soc. Amer. Proc. 29:* 702-707.

DE GROOT, A. J. 1963. Mangaan toestand van Nederlandse en Duitse holocene sedimenten in verband met slibtransport en bodemgenese. *Versl. Landb. Ond. 69. 7:* 1-164.

HARMSEN, G. W. AND KOLENBRANDER, G. J. 1965. Soil inorganic nitrogen, in Bartholomew W. V. and Clark, F. E. Soil Nitrogen pag. 43-92. Amer. Soc. Agron. Madison, U.S.A.

HSIEH, J. J. C. 1964. A technique for controlling soil moisture content in the vicinity of root hairs and its application to soil-water-plant studies. Diss. Abstr. 25, 2150.

JENNE, E. A., RHOADES, H. F., YIEN, C. H. AND HOWE, O. W. 1958. Change in nutrient element accumulation by corn with depletion of soil moisture. *Agron. J. 50:* 71-74.

JENNY, H. AND OVERSTREET, R. 1939. Surface migration of ions and contact exchange. *J. Phys. Chem. 43:* 1185-1196.

KEMPER, W. D. AND VAN SCHAIK, J. C. 1966. Diffusion of salts in clay-water systems. *Soil Sci. Soc. Amer. Proc. 30:* 534-540.

LABANAUSKAS, C. K., LETEY, J., STOLZY, L. H. AND VALORAS, N. 1966. Effects of soil-oxygen and irrigation on the accumulation of macro- and micronutrients in citrusseedlings. *Soil Sci. 101:* 378-385.

LABANAUSKAS, C. K., STOLZY, L. H., KLOTŽ, L. J. AND DE WOLFE, T. A. 1962. Effects of soil temperature and oxygen on the amounts of macronutrients and micronutrients in citrusseedlings (Citrus sinensis var. Bessie). *Soil Sci. Soc. Amer. Proc. 29:* 60-64.

LAGERWERFF, J. V. AND BOLT, G. H. 1959. Theoretical and experimental analysis of Gapon's equation for ion exchange. *Soil Sci. 87:* 217.

LEMON, E. R. AND ERICKSON, A. E. 1955. Principle of the platinum microelectrode as a method of characterizing soil aeration. *Soil Sci. 79:* 383-392.

MAERTENS, C. 1964. La résistance mécanique des sols à la pénétration, ses facteurs et son influence sur l'enracinement. *Ann. agron. 15:* 539-554.

MEDERSKI, H. J. AND WILSON, J. H. 1960. Relation of soil moisture to ion absorption by corn plants. *Soil Sci. Soc. Amer. Proc. 24:* 149-152.

METWALLY, S. Y. AND POLLARD, A. G. 1959. Effects of soil moisture conditions on the uptake of plant nutrients by barley and on the nutrient content of the soil solution. *Journ. Sci. Food and Agric.* 632-636.

MIDDELBURG, H. A. 1967. De wet der verminderende meeropbrengsten. *Landbouwk. Tijdschr. 79:* 55-61.

MOSS, P. 1964. Some aspects of the cation status of soil moisture V. The effect of soil moisture tension on growth and cation uptake by plants. *Plant and Soil 20:* 271-287.

NEWMAN, E. I. 1966. Relationship between root growth of flax (Linum usitatissimum) and soil water potential. *New Phytol. 65:* 273-284.

OLIVER, S. AND BARBER, S. A. 1966(a). Mechanisms for the movement of Mn, Fe, B, Cu, Zn, Al, and Sr from one soil to the surface of soybean roots (Glycine max). *Soil Sci. Soc. Amer. Proc. 30,* 468-470.

OLIVER, S. AND BARBER, S. A. 1966(b). An evaluation of the mechanisms governing the supply of Ca, Mg, K and Na to soybean roots. *Soil Sci. Soc. Amer. Proc. 30:* 82-86.

OLSEN, S. R., KEMPER, W. D. AND VAN SCHAIK, J. C. 1965. Self-diffusion coefficients of phosphorus in soil measured by transient and steady-state methods. *Soil Sci. Soc. Amer. Proc. 29:* 154-158.

VAN DER PAAUW, F. 1958. Relations between the potash requirements of crops and meteorological conditions. *Plant and Soil 9:* 254-268.

VAN DER PAAUW, F. 1962. Periodic fluctuations of soil fertility, crop yields and of responses to fertilization effected by alternating periods of low or high rainfall. *Plant and Soil 17:* 155-183.

PATT, J., CARMELI, D. AND ZAFIR, J. 1966. Influence of soil physical conditions on root development and on productivity of citrus trees. *Soil Sci. 102/2:* 82-85.

PAUL, J. L. 1965. Influence of soil moisture on chloride uptake by wheat seedlings at low rates of transpiration. *Agrochimica 9:* 368-379.

PETERS, D. B. 1957. Water uptake of corn roots as influenced by soil moisture content and soil moisture tension. *Soil Sci. Soc. Amer. Proc. 21:* 481-484.

PETERS, D. B. AND RUSSEL, M. B. 1960. Ion uptake by corn seedlings as affected by temperature, ion concentration, moisture tension and moisture content. 7th. Int. Congr. Soil Sci. Madison, IV, 58. Trans. Vol. III, 457-466.

RICHARDS, S. J. AND WEEKS, L. V. 1957. Moisture movement in soils. *Calif. Agric.* (April) 24, 27.

ROM, R. C. AND DANA, M. N. 1960. Strawberry root growth studies in fine sandy soil. *Proc. Amer. Soc. Hort. Sci. 75:* 367-372.

RØNNIKE, F. 1957. On the growth of roots and hypocotyls of lupine plants cultivated in substrata with different water contents. *Physiol. Plant. 10:* 440-444.

SALIN, H. M., TODD, G. W. AND SCHLEHUBER, A. M. 1965. Root development of wheat, oats and barley under conditions of soil moisture stress. *Agron. J. 57:* 603-607.

VAN SCHAIK, J. C. AND KEMPER, W. D. 1966. Chloride diffusion in clay-water systems. *Soil Sci. Soc. Amer. Proc. 30:* 22-26.

VAN SCHOUWENBURG, J. CH. AND SCHUFFELEN, A. C. 1963. Potassium-exchange behaviour of an illite. *Neth. J. Agric. Sci. 11:* 13-22.

SCHUURMAN, J. J. 1965. Influence of soil density on root development and growth of oats. *Plant and Soil 22:* 352-374.

STEVENSON, D. S. AND BOERSMA, L. 1964. Effect of soil water content on the growth of adventitious roots of sunflower. *Agron. J. 56:* 509-512.

TAYLOR, H. M., ROBERSON, G. M. AND PARKER, J. J. 1966. Soil strength-root penetration relation for medium- to coarse-textured soil materials. *Soil Sci. 102:* 18-22.

TEPE, W. UND LEIDENFROST, E. 1958. Ein Vergleich zwischen pflanzenphysiologischer, kinetischen und statischen Bodenuntersuchungen. I. Die Kinetik der Bodenionen, gemessen mit Ionenaustauschern. *Landw. Forsch. 11:* 217-230.

VAIDYANATHAN, L. Y. AND NIJE, P. H. 1966. The measurement and mechanism of ion diffusion in soils. II. An exchange resin paper method for measurement of the diffusive flux and diffusion coefficient of nutrient ions in soils. *J. Soil Sci.* (Oxford) *17:* 175-184.

WESLEY, D. E. 1965. Phosphorus uptake by oat seedlings from phosphorus fertilizer applied to a subsoil as affected by soil moisture. *Diss. Abstr. 26:* 206.

WIERSUM, L. K. 1957. The relationship of the size and structural rigidity of pores to their penetration by roots. *Plant and Soil 9:* 75-85.

WIERSUM, L. K. 1958. Influence of watercontent of sand on rate of uptake of Rubidium-86. *Nature 181:* 106-107.

WIERSUM, L. K. 1961. Utilization of soil by the plant root system. *Plant and Soil 15:* 189-192.

WIERSUM, L. K. 1967. Potential subsoil utilization by roots. *Plant and Soil 27:* 383-401.

WIKLANDER, L. 1965. The composition and ecological importance of soil solution. *Grundförbättring 18:* 71-89.

V. RULES OF TRANSFER OF WATER MANAGEMENT EXPERIENCE, WITH SPECIAL REFERENCE TO THE ASSESSMENT OF DRAINAGE DESIGN CONSTANTS

W. C. VISSER
Institute for Land and Water Management Research, Wageningen

1. INTRODUCTION

In the countries, where water management projects have already been in existence for a long time, a vast knowledge is available concerning the rules and constants governing the reaction of the growth and productivity of crops on soil and water conditions. This knowledge is partly founded on soil physical and plant physiological experiments and observations, another part rests on experience gained in the field. Properties of importance for the design but varying from field to field as permeability and moisture retaining capacity, generally will be measured. Properties with a regionally more constant nature as rainfall and evaporation, often will be dealt with along empiric lines.

Often the project engineer will have to make plans for areas where the validity of design constants derived from empirical experience is no longer ensured. This will not only occur within the Netherlands, where water management primarily was developed for arable clay soils and now is applied to other conditions as sandy soils, horticultural land or orchards. Here the earlier experience will not necessarily hold. The soils may differ considerably and more expensive crops will require more intensive and more costly solutions. Even more poignantly does the problem of transfer of knowledge and experience show up in projects in the developing countries, where soils and hydrology, climate, crops and economy are vastly differing from the situation in the country where the experience is gained. Here the project planner has to decide what part of his experience and knowledge still will hold.

The answer that all the research for these different conditions will have to be done all over again is not acceptable. It is of importance therefore to question what the rules of transfer of existing knowledge to other environments are and what can be done to shape the research in countries with advanced water management experience in such a way, that transfer to areas where this experience is lacking is possible. For such a transfer it will not only be necessary that the result is sufficiently accurate, but it also will have to satisfy requirements of simplicity and manageability. The last requirements limit to a large extent the freedom of evolving theories which allow an easy transfer.

2. General rules of transfer

The classic rule of transfer is, to reduce relations to accurate and generally accepted functions or approximations and to avoid systematic errors. As an instance may be mentioned the incompressability of water and the linear Darcy-law on which the hydrology is based. Another rule is, that the constants should be reduced to absolute physical constants or should be based on direct measurements. This minimises the random errors.

In water management research, as in all comprehensive problems, the influence of the availability of time, money and specialists will have to be added to the usual requirements of the classic type of research. The gain from additional accuracy has to be set against the additional time that will be required or against the availability or the cost of a better expert to carry out the research. This may change the characteristic of selection of the method from those of scientific elegance to those of an acceptable increment in accuracy.

In general the scientifically more accurate formula will provide a result with a higher degree of reliability. But it is known, that two formulae of vastly different complexity may yield nearly the same results over the whole range of variations. Further, the most accurate determination will often render the highest certainty of a correct result. But it is also known that results may prove to be very insensitive to errors of part of the parameters, whilst the sensitivity for errors in other parameters may be high. In such cases, it will not be difficult to select the more efficient formula or to decide on the amount of work to be spent on the accuracy of determination of the parameter with a large or small effect. The more difficult decision is, to assess which complexities or difficulties in the method a designer is able and willing to deal with and what may be considered to be entirely the task of specialists or scientists. The wide range of problems, present in any comprehensive project, sets a limit to the intensity of the attention which can be given to each problem. Wide applicability of the knowledge to be transfered will require a measure of attention for each aspect which holds a proper relation to the economic importance of that aspect.

The expectation that it will be possible to use data from one area in designs in other areas, will not often come true. What can be transfered, however, is the functional relation between causes and effects. The constants in this relation have to be assessed in the area of the project. What further can be transfered is the best way to assess such constants. This concerns not only the type of observations that give the best results with the smallest amount of specialist training, time and money. It also deals with the methods of adjustment, which make it possible to extract reasonably accurate values for the constants from observations of restricted accuracy. It seems advisable that closer attention should be given to the way in which observations are condensed to the desired information. Attention is also needed for the way in which conclusions as accurate as possible are drawn from inaccurate data. In the transfer of water management experience emphasis should not only be laid on technical and physical aspects, but also on the treatment of the observational data.

3. The diagram of relevant aspects

A water management project is based on four main aspects, depicted in figure 1. The part, indicated with A, comprises soil hydrology. This deals with the properties governing groundwater flow and with the properties upon which the relations of soil moisture and soil air in the unsaturated zone are based. Part B

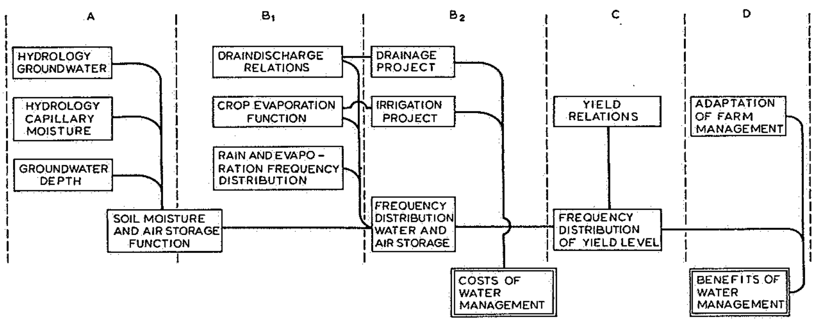


Fig. 1. Diagram of the aspects and interrelations of a water management project

deals with the depletion of the soil moisture stock by drainage and evaporation and its increase by rain or by application of additional water. Part B can be split up in B_1, which describes the water balance, and B_2 describing the technical measures developed on account of the data from part B_1. This part B_2 is today very much the main core of the water management design and derives its importance from the fact that the costs of the project are based on these informations. In part C the prognosis of the results on crop yield is listed, which is derived from the considerations in the parts A and B_1. In part D are indicated the effects of the change in the availability of water on farm management and the benefits that will be derived from the change in the water management situation due to the measures taken. Comparison of the costs in column B_2 with the benefits in column D makes it possible to assess the efficiency of the proposed measures and to evaluate the measures as to their feasibility. The aim should be to determine with what detail and what margin of intensity the project should be carried out to ensure the optimum economic effect.

Comparing the course of investigations as depicted in this diagram with the usual practical approach, part C and D require the most active attention. These parts represent the most unpredictable incertainties. The yield prognosis in part C, however, has the favourable property that very much is known about plant growth and that it is based on invariant plant physiological rules, applicable the world over. The influence of farm management in part D is far less well-known and – as it is based on human behaviour – is not invariant. The adaptation of farm management to the moisture status of the field will in many areas only be known rather superficially and will often be the limiting factor for the accuracy of the expected results of water management design.

This part of the research, which is making steady progress, is generally based on the elaboration of information obtained with questionaires. This technique is not applicable everywhere, however, so that this subject will not be discussed in this paper.

4. The rules of transfer for the prediction of crop response

The law of Darcy, basis of the worldwide application of the rules in hydrology, is also the basis – together with the formally identical law of diffusion – for the laws of plant response. This application of the linear laws of transport of matter on other growth factors than water is less commonly known and applied and will be discussed in detail. These crop-yields relations deserve attention because of the limiting position that yields have in comprehensive water management planning.

An important point is that a law of plant growth represents with a few additional relations an economic production function from which it is possible to derive the order of feasibility of improvement measures, or the marginal intensity of each separate improvement activity. In its original shape it shows how growth factors cooperate and how beneficial effects – for instance draining of excess of water – can be evaluated against the harmful effects due to moisture deficiency caused by such draining away of moisture.

The laws of the response of crops to water management measures are also valid for the solution of the normal problems of soil fertility management and fertilizer application and cannot without loss of accuracy be separated from this soil fertility aspect. Because the laws of plant growth constitute the area of contact between the technical and the agricultural specialist, this also requires a discussion in some detail.

5. General aspects of plant response

Usually it is assumed that the plant reacts on the depth of the groundwater table. What the biological effect of this groundwater table might be — in the soil itself at this level no other effect than that of a water tension equal to the atmospheric pressure is present — has never been stated and a direct effect does not seem to exist. The plant reacts on the moisture stress and the moisture content in the root zone and on the rate of exchange of oxygen and carbondioxid between the root zone and the atmosphere. Because there is a fixed relation between the moisture content and the moisture stress, as well as between the air content and the air exchange coefficient for each separate soil and soil structure condition, the momentary reaction of the crop on water management measures can be largely explained by the moisture and air content of the root zone.

The plant, however, is not a constant entity in this relation, but can adapt itself to gradually changing situations. If the groundwater table draws down gradually, the roots follow the water table and the rate of growth will not be affected much. The more or less quick variations of the moisture conditions, superimposed on this slow lowering of the water table, have more influence. Experiment fields with a constant groundwater depth generally show optimal growth at very shallow, but constant, water tables which would cause grave trouble if used in practical design.

In figure 2 the result of an experiment on the groundwater level is shown, where the constant depth of the groundwater table allows tulips to give an optimal growth at a very shallow groundwater depth *. Such a result shows what problems the design engineer will be up to, if he relies on scientifically conducted experiments with constant water depth and would construct in his project area a drainage system ensuring an optimum water depth as obtained on his experiment field. The first rainshower would convince him, that a field experiment without the variations in the groundwater table which normally occur, is not a good guide in water management design. These sudden changes vary from drought damage due to dessication, to moisture excess due to inundation. Whilst the slow variations in moisture relations are sufficiently characterized by the water depth in summer and winter, a description of the variation in moisture condition of short duration is required in addition. This is done by recording the moment and length of moisture excess or deficiency.

Next to a distinction in slow and rapid variations, another distinction has to

---

* Valk, G. G. M. van der and J. A. Schoneveld: De reactie van tulpen op grondwaterdiepte en profielopbouw. *Meded. Dir. Tuinbouw 27,* 12: 631-639 (1964).

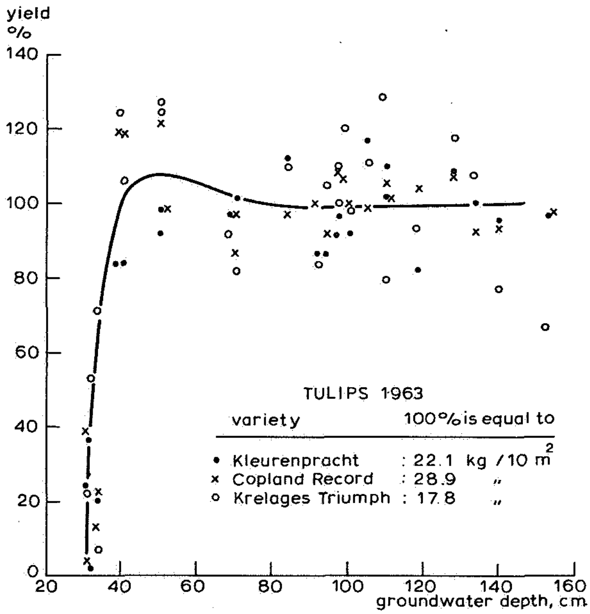


FIG. 2. Crop growth, depending more on air diffusion than on groundwater depth, reaches its optimum at low values of the depth of drainage if water drains readily from wide pores at low moisture stresses

be made in reversible and irreversible damage. A small degree of shortage or excess of water will lower the rate of growth, but as soon as the unfavourable situation is lifted, the plant grows on at the original rate. The reduction of the growth rate is reversible. If, however, the unfavourable situation is of a high intensity, impairing the production mechanism of the plant, improvement of the unfavourable situation is at best followed by a slow recovery of the growth rate. If the production mechanism can still be restored, the damage is slowly reversible, but otherwise irreversible with the death of the plant as ultimate limit.

In figure 3 an instance of this irreversible reaction is given. For a sprinkled and a non-sprinkled object the daily increase in dry weight is given by the curves A, respectively B. The curves C and D show the daily evaporation. The rainy month of May shows, that dry matter increase and rate of evaporation on the two objects are the same. June was very dry up to 18th and on the non-sprinkled field the evaporation rate and the daily dry matter production decreased rapidly. In the last 5 days the moisture tension in the non-sprinkled soil dropped till pF 4.5. Then a rainshower of 60 mm restored the soil moisture status. Line D

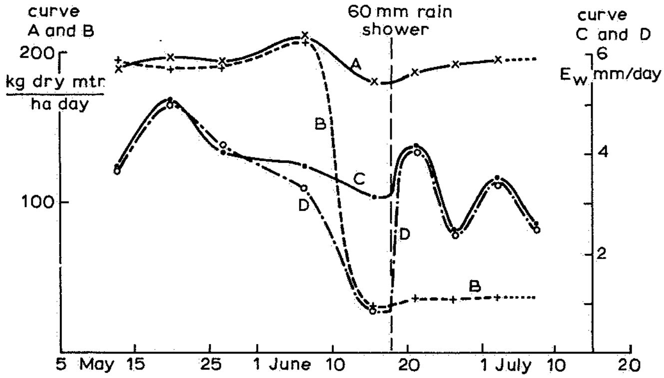


FIG. 3. Heavy irreversible damage was done to wheat on non-sprinkled plots (curve B and D) by a dry week, reducing the daily increase in yield, which after restoring the soil moisture conditons, does not — in contrast with evaporation — return to its previous level

for the non-sprinkled field rises to the level of the sprinkled field and the following month, due to repeated rainfall, the two experiment plots show an equal evaporation. The dry matter production of the non-sprinkled field, however, does not return to its original level, as line B shows. In the dry week the production mechanism was apparently severely damaged and in the following three weeks of the experiment this damage was not repaired, notwithstanding that the crop still lived and evaporation went on at a normal rate. A small amount of water between 12 and 18 June presumably could have prevented the irreversible damage and would have given a very satisfying ratio between amount of water given and yield increase obtained.

The distinction between steady versus unsteady water relations and the distinction between reversible and irreversible damage is presumably of more decisive importance for project design than up to now has been thought. But although the unsteady and the irreversible effects are of more importance for crop growth than the steady and the reversible effects, the latter effects are much easier to counteract. The primary aim of project design should, however, be to prevent the ill effects of unsteady conditions and the irreversible effects. In this respect it should always be remembered that field experiments on moisture relations and crop yield often deal with steady effects which are of restricted value in project design. The better the moisture conditions were kept constant in the experiment, the more the results should be used with reserve.

6. A PLANT PHYSIOLOGICAL BASIS OF WATER MANAGEMENT

The law of plant response can be based on three fundamental relations. The growth promoting factors are taken up by the plant via a linear process of transportation, which may be the Darcy law for moisture flow or the law of Fick for diffusion *. The transportation velocity is given by:

$$v = \frac{x_2 - x_1}{R_{12}}$$

The flow resistance R tends to be constant. The rate of growth q is directly related to the transportation velocity v and the factor c, describing the ratio of growth rate q to uptake rate v, also is nearly a constant.

The following relations hold:

$$q = v/c \qquad\qquad q = \frac{x_2 - x_1}{cR_{12}}$$

$$1/c\ R_{12} = a \qquad\qquad a - \frac{q}{x_2 - x_1} \approx 0$$

The value of a, equal to the inverse of the product of two magnitudes which tend to be constant, is nearly equal to the ratio of the growth rate divided by the gradient.

That the inverse of the ratio between x and q has to be taken, meaning that it is not a resistance but a conductivity which tends to be constant, has to be understood as follows. The supply of the growth factor $a(x_2 - x_1)$ is the independent factor, the growth rate q is the dependent factor. The plant reacts according to a ratio of the yield per unit value of the nutrient supply. Therefore the reaction is governed by the magnitude of $q/\ (x_2 - x_1)$ and not – as might be assumed as alternative – by $(x_2 - x_1)\ /q$.

The difference $a - q/\ (x_2 - x_1)$ can be given for any growth factor to be inserted in the yield equation. The significance of such difference is, that it represents a stress, which the plant has to overcome in taking up a satisfactory amount of each separate growth factor. The larger the difference is, the larger

---

* Visser, W. C.: Ein Ertragsmodell für günstige und schädliche Umweltfaktoren. Studia Biophysica 1968. In press.

Visser, W. C.: Anwendung der parametrischen Biologie auf praktische Probleme. Studia Biophysica 1968. In press.

this stress becomes. Now it is assumed that the sum of the deviations $a - q/ (x_2 - x_1)$ – the size of which indicates the degree of intensity of the struggle for homogeneous growth – if expressed in a relative scale to account for differences in magnitude, will be zero. This supposition means that this struggle leads to an equilibrium situation with respect of the combined stresses. This equilibrium defines the magnitude of the excesses and deficiencies, which govern the ultimate growth rate q.

This minimum stress is defined by:

$$\sum_{i=1}^{n} \frac{d\left(a_i - \dfrac{q}{x_{i2} - x_{i1}}\right)}{\left(a_i - \dfrac{q}{x_{i2} - x_{i1}}\right)} = 0$$

Integration provides an equation in which the maximum of the growth rate or of the uptake capacity due to the genetic properties, can be inserted by assuming that the uptake of nutrients, leading to maximum growth Q, is proportional to the value of this Q. So a growth equation can be obtained reading:

$$\left(1-\frac{q}{Q}\right)\left(1-\frac{q}{a_1 x_1}\right)\left(1-\frac{q}{a_2 x_2}\right)\ldots\ldots = F_1 \qquad (1)$$

The symbol F stands for the integration constant and has the meaning of a constant, depicting the flexability with which the plant can adapt itself to variation in the availability of the growth factors x_1, x_2 ... The formula should for theoretical reasons contain all growth factors, but for practical application the most important ones will do. The factors which cause damage to the growth mechanism of which the magnitude is represented by Q, should be inserted in the formula as some function reducing the value of Q.

The formula describes a growth rate or a dry matter increase per unit time. Field experiments generally work with yield over the full growth period and to use these data it is usually assumed that the factors a_i are constant over this period. Is this true, then the equation can be used as a yield function.

7. Assessment of the constants

Graphically represented, the law of plant growth takes the shape as depicted by figure 4. The curves approach an oblique and a horizontal asymptote. This horizontal asymptote can be situated at different levels of q. In the simplest case

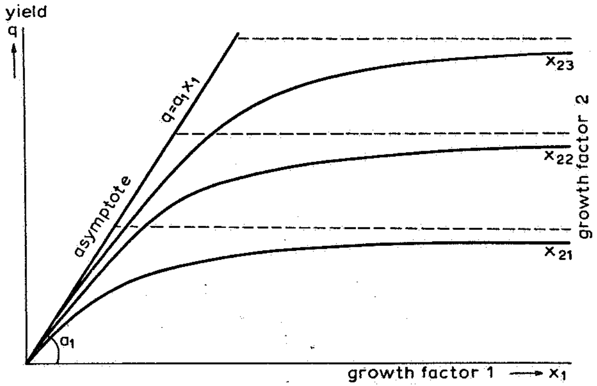


FIG. 4. Graphical representation of the yield function, identical to the representation of the law of the limiting factors or the growth model according to Blackman

the oblique asymptotes for increasing values of other factors coincide. The equation has the useful property, that the shape of the curves is practically identical. They only differ due to a translation parallel to the direction of the oblique asymptote.

In figure 5 upper half, the curves for the response of the crop to nitrogen, obtained from field experiments, are given as an instance. If these curves are shifted correctly, the observations become grouped along one single line, which satisfies the equation:

$$\left(a-\frac{q}{x}\right)\left(1-\frac{q}{Q}\right)=F_1$$

The level of the horizontal asymptote represents the value of Q. The inclination of the oblique asymptote represents the constant a. A few trials provide the value of F.

The project researcher generally will not have field experiments on soil moisture conditions and crop response available. He can, however, select in the field a number of spots with large differences in moisture relations. By collecting yields every week and determining the moisture conditions – groundwater depth or soil moisture content – at the same moment, data are available to solve the problem. For sufficiently narrow intervals of growth factor x_1, the yields q are plotted against x_2, and for intervals of x_2 the q is plotted against x_1. On the scatter diagrams of this type, the translation technique is applied and the constants can be found.

This elaboration makes it also possible to treat the problem when q depends on more than one growth factor x. Often the investigations will be sufficiently accurate if only one growth factor is taken into account. In figure 6 an instance

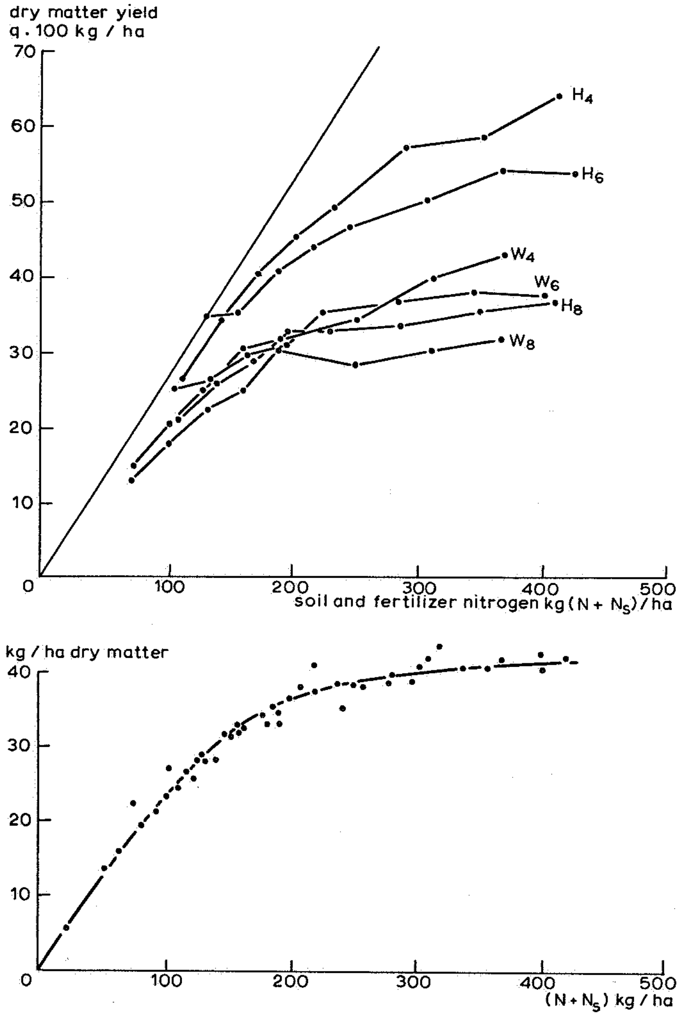


FIG. 5. With a good approximation, yield curves can be brought to coincidence by shifting along the oblique asymptote, or in case of differences in the growth factor from unknown sources, by an additional horizontal shift of which the lower graph presents the result

is given of the influence of the volume percentage of air on the growth of grass on peat soils *. This growth was determined during four successive cuts and the separate yields were plotted against the average air content observed during

* Titze, E.: Der Wasser und Lufthaushalt der oberen vererdeten Schicht des Klenzer Niedermoores und sein Einfluss auf den Ertrag. Inaugural Dissertation Rostock, März 1966.

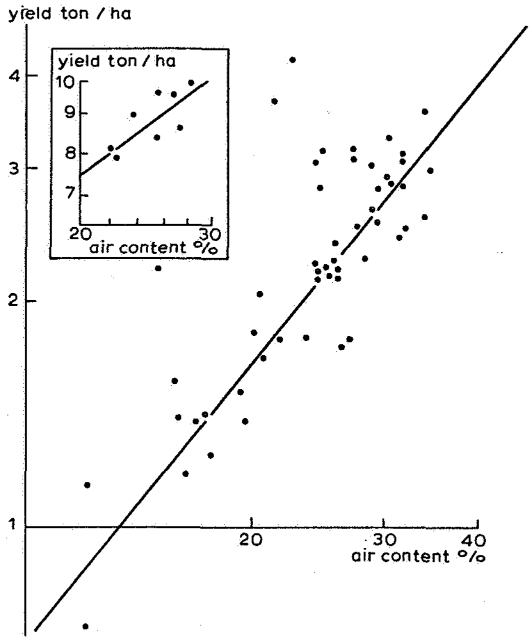


FIG. 6. Repeated harvests, plotted against the level of the growth factor in the time interval of growth, presents deeper insight into the growth relations that the total growth against the average level of the growth factor, as presented in the inserted graph

the growth interval. Because it is known, that moisture conditions do not influence growth according a linear, but according an exponential relation, the logarithms of yield and air content are plotted against each other.

The small graph, given as an annex, is shown as a proof that repeated harvests give a better result than total yields. In the annex the sum of the four cuts is plotted against the average air content over the entire growth period. This integration levels off the variation in the resulting scatter diagram and by decreasing the range of scatter gives far less convincing results. If one takes moreover into consideration that the growth relation is in reality an equation for the rate of growth and not for the total quantity of growth, the theory and the practical results both point in the direction of taking repeated yield determinations.

8. A PHYSICAL BASIS OF WATER MANAGEMENT

The management of the groundwater depth or the moisture content in the root zone aims at obtaining the optimum relation between crop yield and several other magnitudes. These may be the amount of water or the discharge capacities available or the costs of water management practices.

The water management conditions which should be attained, depend for their main aspects on four relations, rendered by the following formulae:

Discharge $$\left\{1-\frac{D}{\frac{8k_1\,d_1}{L_1^2}(z-S_1)}\right\}\left\{1-\frac{D}{\frac{8k_2\,d_2}{L_2^2}(z-S_2)}\right\}=F_2 \qquad (2)$$

Evaporation * $$\left\{g-\frac{E_r}{E_o}\right\}\left\{A-\frac{E_r}{(v^l-v^l_{wp})}\right\}=F_3 \qquad (3)$$

Soil moisture profile $$\left(1-e^{\alpha z_w}\right)\left(1+\frac{z_o-1/\alpha}{z_o+z_s}\,\frac{v_c}{k_o}\right)=(1-e^{-\alpha\psi})-\frac{1}{z_o+z_s}\,\frac{v_c}{k_o}\,z_w \qquad (4)$$

Desorption curve $$\psi=\frac{G(P^*-v)^n}{v^m} \qquad (5)$$

Equation (2) relates the discharges D to the pressure head existing between the groundwater level z_s and in succession the water level in a nearby shallow ditch S_1 and a more distant and deeper main water course S_2. All these groundwater levels are expressed as depth below soil surface. The insertion of two drainage bases in the formula is in accordance with the practical experience that generally two discharge effects can be observed, but a third level, if exerting an effect, has too small drainage capacity to allow determination. Third effects are therefore neglected here. However, limiting the discharge model to only one drainage basis would neglect effects of too large an importance. The relation between discharge and gradient is assumed to be linear. For drainage with deep impervious layers and large drain distances this often will hold good. In case of tile drainage a term of the second power of z_s can be added.

Equation (3) states that the evaporation rate depends on alternatively the evaporative capacity of the atmosphere E_o – a value which can be calculated, but often can more reliably be determined as pan evaporation – or on the moisture content of the root zone v **. The zero evaporation appears at a low moisture content v_{wp} known as wilting point.

---

* The word evaporation is used as a general description for the transition of liquid to vapour without any distinction of the process or origin of the evaporated moisture.

** Rijtema, P. E. An analysis of actual evapotranspiration. *Agric. Res. Rep. 659,* p. 1-107 (1965).

Formula (4) relates the height above groundwater z_w and the soil moisture stress ψ at that point, with the velocity of capillary flow v_c. In this relation a parameter z_o is inserted, which indicates the level at which the soil moisture is extracted.

Formula (5) shows the mathematical representation of the desorption curve, which relates the soil moisture stress to the soil moisture content.

The four formulae together account for the discharge, the amount of moisture in the profile and the evaporation, which, together according to the water balance equation, add up to the rainfall. Further represented are the water level in the soil, in ditches of a first and second order and the moisture content in the root zone. Problems on drainage or on water application can be solved, but also the discharge data, integrated for a catchment area, may be used as a basis for river regulation designs. Because further the crop reaction depends on the air and water content of the soil, the equation for the desorption curve represents the link between the hydrology of the soil and the plant response with respect to this hydrological condition. The four formulae together allow to calculate a large number of cross relations between important variables. The main problem, however, is what values the many constants should be given. The determination of the constants will be the problem to be discussed next.

9. Determination of the soil moisture parameters

Two methods are available with which even in conditions under which no laboratory is at hand or specialist assistance is available, the water management situation can be analysed. These methods are based on soil moisture determination or on groundwater depth readings. The determinations of the soil moisture content represent a valuable tool in studies on fields, where the groundwater table is deep, whilst the determination of the groundwater depth is most useful in studies on more shallowly drained fields.

The determination of the soil moisture content, to be expressed as a volume percentage, requires soil augers with which cores of a known volume can be taken and asks for drying and weighing. This can be done cheaply and simply, as described by Bourrier *. A roman balance can be constructed at very low cost, the drying can be done by mixing the soil with common household spirits which, when lighted, evaporates the soil moisture.

A further valuable information is comprised in the desorption curve. Although this curve is not decidedly necessary, its availability can be helpful. At lower values of the moisture stress up to pF 2.7 the determination can be done

* Bourrier, J.: Bulletin Technique de Génie Rurale. Nr. 61, mars 1963.

with the sand tank method as described by STAKMAN.* At higher stresses the extraction of water by sunflowers provides a simple and practical method to determine the wilting point at pF 4.2. The point for pF 6.0 can be obtained by determining the soil moisture content of a soil which, put in a dish, is left to reach equilibrium with the atmosphere in the laboratory. At least 5 points of the desorption curve should be assessed to obtain it with reasonable accuracy.

The soil samples for soil moisture content determination should be taken once a week in some four successive layers of 20 cm thickness during a sufficiently long period to ensure that the moisture relations are known under different conditions of rain or drought, heat or cold, cropped or bare soil. The accuracy of the moisture determination should be tested by comparing the observations of successive layers or weeks of sampling.

The groundwater depth readings should be made in a tube, constructed of clay drain tiles, plastic drain pipes or perforated metal pipe. The observations have to be done on a weekly basis. Together with the observation of the groundwater depth, the level of open water should also be read in the nearest water course to which the groundwater drains. If no water course is present and the groundwater flow is determined by a gradient in the terrain, the direction of this gradient has to be determined by levelling the groundwater depth at a number of points. The gradient in this case has to be determined as the difference between the water levels at two points situated on the line of maximum groundwater slope. The observation wells should reach to a depth in excess of the deepest groundwater level to be expected, and should be repeatedly checked on silting up or decrease of the depth of the bottom of the tube.

10. THE WATER BALANCE DERIVED FROM MOISTURE CONTENTS

The soil moisture contents are first plotted for the successive layers against each other – as given in figure 7 – or against the total moisture content in the part of the profile that was sampled. These curves provide a first indication of the moisture content at field capacity and wilting point for the upper layers, in figure 7 of the order of 27 and 7.5 %. Considerations of the following type should be taken: in the linear right hand part of the line the moisture contents of the two layers vary in relation. At a moisture content of 17 % the data diverge due to evaporation in the top layers. Would this evaporation not occur, then the moisture content could only lower due to drainage. And a lowest

* Stakman, W. P. and G. G. v. d. Harst: Soil moisture retention curves I Range pF 3.0-4.2. Harst, G. G. v. d. and W. P. Stakman: Soil moisture retention curves II Range pF 0-2.7. Nota 159 and 81, Inst. for Land and Water Management Research.

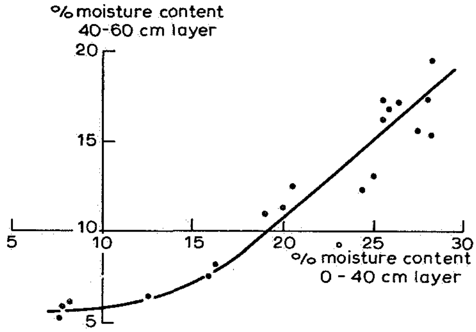


FIG. 7. The moisture content in successive layers bear a certain relation to each other, which can be used for adjustment of erroneous or lacking data, for assessment of accuracy of determination and for obtaining some indication as to the shape of the desorption curve

moisture content of the lower layer of 5.5 % would match with a lowest moisture content in the upper layer of 14 % and represent an approximate equilibrium situation, depending on the depth of the water table of some 10 m. This would be therefore the moisture content at 10 m moisture tension or pF 3.0. This example may show that moisture contents of successive layers are able to convey a first impression as to the soil moisture retaining properties.

The moisture content data are used to determine the terms of the water balance in a way as indicated in the following example. The moisture contents of the layers are added and the sum represents the moisture volume v_T of the profile over the full depth of sampling. Also the average moisture content v_c of the main root zone is calculated. The following table is then constructed:

			from:
Moisture volume v_T, 5 May	143.0		analyses
Moisture volume v_T, 16 May	126.4		analyses
Stored moisture	16.6		calculated
Rainfall 5-16 May	28.3		measurement
Sprinkling irrigation	0.0		application
		44.9	calculated
Moisture content root zone v_r	28.1		analyses
Pan evaporation	36.6		measurement
Multiplication factor $n = E_r/E_p$	1.15		calculated
Real evaporation $E_r = nE_p$		42.1	calculated
Deep drainage		2.8	calculated
Extraction from subsoil		nil	

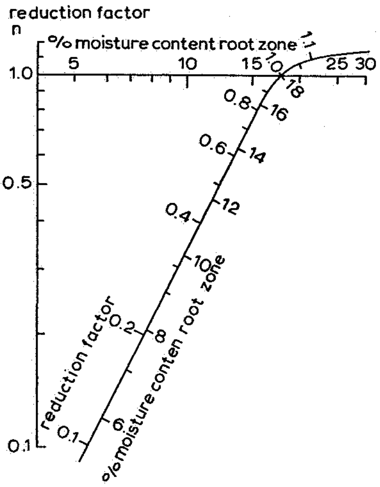


FIG. 8. The constants of the evaporation function are assessed by plotting the log E_r/E_0 values against the log of the soil moisture contents and determining the intercept of the two asymptotes and the inclination of the oblique asymptote

The only magnitude in this example which is not known and has to be deducted is $n = 1.15$. This is done by drawing a graph as in figure 8, with axes representing log v_r and log n. In this graph a curve has to be constructed consisting of a sloping and horizontal asymptote, linked together with a curved transition. It is known that the angle of the sloping part often is of the order of 3. The point of intersection of the two asymptotes is not difficult to assess. Periods with abundant rain will show the maximum value of n and the lower limit of the moisture range over which the climatological situation alone determines the rate of evaporation is found by plotting all the intervals with abundant rain along the moisture content axis and determining the lower limit of these data. This lower limit of the moisture contents along the horizontal line constitutes the upper point of the sloping asymptote.

Then the slope of the line of reduced evaporation is found by a step by step procedure. First it is assumed that at wilting point some 10 to 20 % of the potential evaporation will still be possible as evaporation from the soil. The transpiration by the plant will at this low moisture content have become negligeable. With this second point of the sloping line the first approximation of the curve in figure 8 is drawn, and the data of the series of moisture content observations are processed as in the example of calculation just discussed.

Then the results for the deep drainage and extraction are considered by inspection as to their acceptability. If an indication is found that the data could improve by increasing or decreasing the rate of evaporation, then the curve of figure 8 is slightly altered till acceptable deep drainage and extraction values are obtained. As the rainfall and storage are known, data for the deep drainage and the evaporation data complete the soil moisture balance.

11. THE WATER BALANCE DERIVED FROM GROUNDWATER DEPTH OBSERVATIONS

The assessment of the water balance terms starts with splitting up the data in groups with increasing values for the difference in the level of groundwater z_s and that of the water in the ditch. For each group the data for the winter, when the evaporation is small, or the wet season, when the evaporation is a constant fraction of the pan evaporation, are plotted by marking along the horizontal axis the values Δz, the difference between successive groundwater readings, and along the vertical axis rainfall R minus an estimated value for the real evaporation E_r^*. If the amount of water stored is described as $\mu\Delta z$, the storage coefficient μ multiplied with the change in water level Δz, then the water balance equation becomes:

$$(R - E_r^*) = D + \mu\Delta z$$

As shown in figure 9 the values $(R - E_r^*)$ and Δz are approximately linearly related and the value of D and μ can be assessed for each group $(z - S)$. By

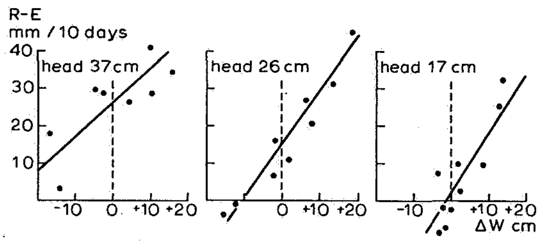


FIG. 9. The preliminary elaboration of groundwater depth observations is carried out by plotting for winter observations rainfall minus estimated evaporation against the change in groundwater depth. The intercept with the $\Delta W = 0$ line represents the discharge, the inclination the storage coefficient

plotting D against $(z - S)$ and μ against z_s, as depicted in figure 10, an average relation is constructed. This first approximation gives first values for E_r and μ.

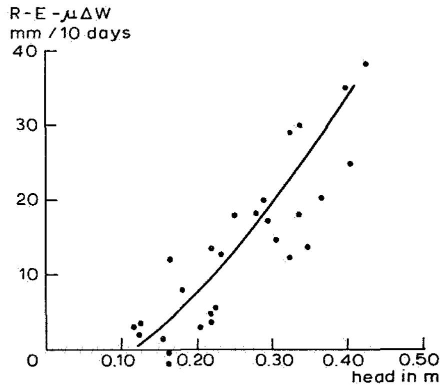


FIG. 10. By plotting winter rainfall minus evaporation and storage against the pressure head, the drainage discharge curve, valid for winter and summer, is obtained

The next step is, to calculate the discharge D for each time interval and plot for each month $(R - D)$ against Δz according the equation:

$$(R - D) = E_r + \mu\Delta z$$

In this way for each month an average value of E_r is obtained as represented in figure 11.

The adjustment of E_r is somewhat complicated. The values of μ plotted against z_s provide an indication of the air content for a depth of the groundwater level equal to z_s. The moisture content can be calculated as pore space P minus the storage coefficient μ. The relation between E_r and the moisture content in the root zone equal to $v_r = P - \mu$ is then calculated as described for the elaboration of the data in the paragraph for the water balance derived from moisture contents.

A few difficulties have to be overcome with the elaboration of groundwater readings. Often the observations are lacking in accuracy. A reading error of 5 cm on a depth of 1.50 m seems trivial, but at this water depth the value of μ may be 0.2 or more and the small error in depth means an error of 10 mm in evaporation and makes the observation useless. Water depth recorders may simplify considerably the adjustment of the data and the solution of E_r and μ.

A second point is the complex character of the relations between storage as well as evaporation on one hand and groundwater depth, capillary movement of the water, evaporative capacity of the atmosphere and influence of the stand

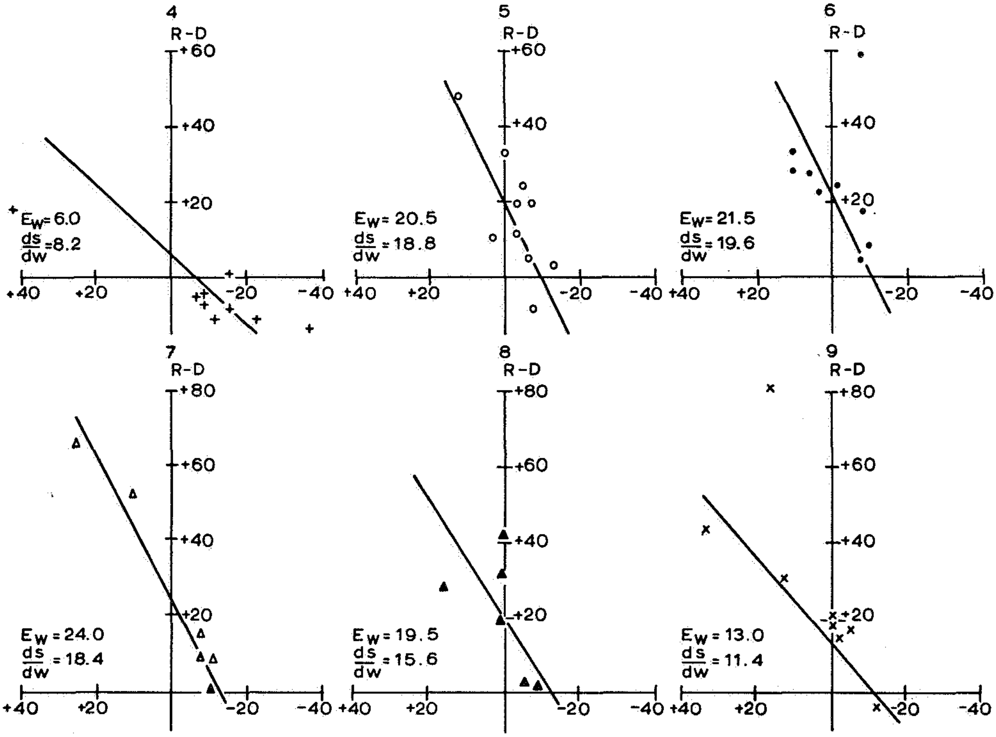


FIG. 11. The rainfall excess *R-D* is plotted against the change in groundwater depth ΔW for the summer months April (4) to September (9). The evaporation E_w as intercept and the storage coefficient μ are found

of the crop on the other. As an approximate knowledge of the water balance often is sufficient as a basis for the design of a project, these difficulties may be of a minor nature. If, however, a higher accuracy is desired or if moisture conditions have to be reconstructed for moments for which no observations are available, then the results of a first approximation have to be adjusted with the help of the available physical functions and with further supporting observations.

So is the curve, obtained by plotting μ against z_s for a period with no evaporation practically identical with the lower part of the desorption curve and could be supported by laboratory determinations of the desorption curve. The difficulty in separating the storage from the evaporation leads to complicated adjustment problems. A simultaneous determination of the depth of the groundwater level and the soil moisture contents provides data for the storage and may simplify the elaboration of the data considerably.

For research workers which have computer facilities available, the elaboration can be done entirely mathematically. The formula for adjustment in its simplest shape is:

$$R = az_s + bz_s^2 + cz_s^d \Delta z + gE_p + f$$

Here $az_s + bz_s^2$ represent the drain discharge, the cz_s^d represents part of the desorption equation and is equal to the storage capacity μ. The exponent d has to be chosen for the adjustment and changed till the smallest mean error is obtained. The value of g has to be taken constant over the year and is a rather crude approximation. If data on rainfall, pan evaporation and groundwater measurements are available over several years, then a monthly g as an average over the years can be obtained. If a precise result, dependent on the moisture content of the soil is desired, then also data about the density of the canopy and the length of the crop should be available. The adjustment will become difficult and enters the province of fundamental science at which this article was not aimed.

12. Methods of curve fitting and assessment of parameters

The benefit to be derived from using physical relations is firstly the possibility to obtain acceptable results from data of restricted accuracy and secondly the calculation of the water balance from generally available data as rainfall and calculated evaporation. Often it is supposed that formulae only make sense if the data are accurate, but in such a case a graphical representation is far more advantageous, because it can more easily be grasped, interpolated and used for assessing the value under different conditions.

For inaccurate data, the formulae are used to assess what scale functions should be selected along the axes to ensure the easiest fitting of curves through the scatter diagram. The following example can give an insight into the construction and use of an often applicable nomogram to handle all adjustments to formulae that can be reduced to the type:

$$ax + by + cz = 1$$

Between wilting point and a moisture content that approximates field capacity, a relation exists which defines the real evaporation E_r by a formula of the type:

$$E_r = A\,(v^l - v^l_{wp}) \qquad \text{or with } Av^l_{wp} = C$$

or $(E_r + C) = Av^l$

The assessment of the exponent l requires the use of logarithms. This transforms the equation to:

$$\log(E_r + C) = \log A + l \log v$$

In this equation the adjustment becomes complicated, because of the position in the formula of the wilting point influence v^l_{wp}. Often this effect can be neglected, because it is only of importance in case of low evaporations. In wetter climates the dry conditions are often of restricted practical importance.

The formula can be represented graphically on three parallel axes. On the first axis is plotted $\log (E_r + Av^l_{wp})$, on the second $\frac{\log A}{1 + l}$ and on the third $-\log v$. The distances between the axes are $l/(1 + l)$ and $1/(1 + l)$ as shown in figure 12, on the first and third axis one unit on the scale represents for instance 10 cm and on the second axis $1/(1 + l)$ units. The zero line linking the $\log (E_r + C)$

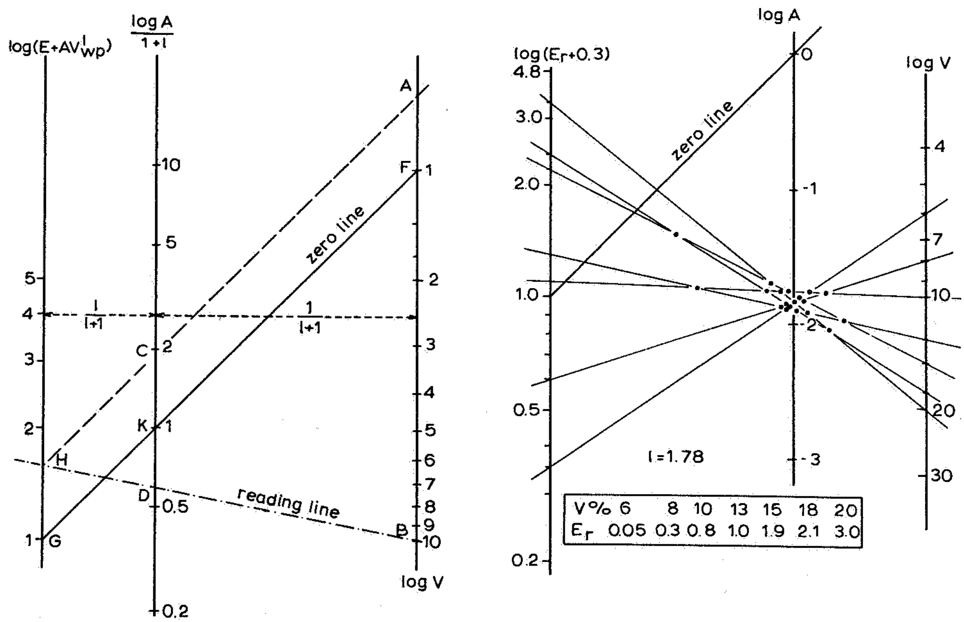


FIG. 12. Nomogram of the formula $E_r = A(v^l - v^l_{wp})$ for calculation as well as adjustment of the constants. Example of the use of nomograms for the assessment of constants

scale at the value of $E_r + C = 1$ with the log v scale at the value $v = 1$ may be given any desired slope by shifting the zero points along the axes and is chosen in such a way that the values on the E-axis and those on the v-axis are marked at about the same height.

If in figure 12 the point on the E-axis is H, and the one on the v-axis is B, then the following relation holds for GH equal to AF equal to CK:

$$\frac{AF + FB}{1} = \frac{CK + KD}{l/(l+1)} \text{ or } \frac{\log(E_r + C) + \log v}{(1 + l)} = \frac{\log(E_r + C) + \log A/(1 + l)}{l}$$

$$l \log (E_r + C) + l \log v = \log(E_r + C) + l \log(E_r + C) + \log A$$
$$\log (E_r + C) = - \log A + l \log v$$

If $\log(E_r + C)$ is plotted with a few well chosen values of $C = Av^l_{wp}$, and $\log v$ is plotted, the fact that A is a constant ensures that all the reading lines – linking the E_r and v-values which belong together – will intersect in one point situated on the log A-axis at a point equal to log A. The distance along the log A-axis to the zero-line is now measured. If a certain value of C was chosen which is not the correct one, or in case the observations are not absolutely accurate, the points of intersection will scatter, but the mean point of this scatter will be an estimate for the position of the log A-scale and will provide an approximation for l, A and v_{wp}.

An example is given in figure 12 for the following series of observations:

v %	6	8	10	13	15	18	20
E_r mm	0.05	0.3	0.8	1.0	1.9	2.1	3.0

The observations are plotted with the same logarithmic scale along the two axes, $(E_r + C)$ is plotted in an upward, v in a downward direction. The value of $C = Av^l_{wp}$ is chosen arbitrarily. The zero-line is chosen with such a slope, that the reading lines form a more or less symmetric sand glass shaped image. The points of intersection are marked, 21 in number for 7 pairs of observations and in horizontal and vertical direction the position of the 11th point in horizontal and vertical order is marked as coordinates of the average. Through these coordinates the third axis is drawn and the point of intersection with the zero-line is determined. Now the distances DK and $l(l + 1)$ can be measured and the values of l, A and v_{wp} can be calculated.

Is this construction made for different values of C, then the l and A can be assessed which produce the most credible value for v_{wp}. The following table shows what kind of result can be expected:

C	=	0.0	0.1	0.2	0.3	0.5	1.0	3.0	5.0	6.5
l	=	2.45	2.41	1.99	1.78	1.32	1.10	0.515	0.346	2.282
A	=	182.10^{-5}	245.10^{-5}	871.10^{-5}	155.10^{-4}	537.10^{-4}	0.134	1.14	2.58	3.78
v_{wp}	=	0.0	4.67	4.84	5.30	5.38	6.17	6.53	6.79	6.82

The result shows that a small range of v_{wp}-values, together with sets of interdependent values of l and A, covering a wide range, are able to give a good adjustment of the data. That the value of C is difficult to assess means, that the point of zero evaporation occupies a very insensitive place in the plant-soil moisture relation.

13. The relations in the unsaturated zone

The relations in the unsaturated zone are described by two characteristics, the desorption curve, defining the moisture content-stress relation, and the conductivity curve, which gives the relation between the capillary conductivity and the moisture content. Behind these curves are the curves for the pore size distribution, as give in figure 13. The pore size distribution is a two apex curve, because the pore sizes are related to two origins. The large pores are the result of cracks or root holes, the small pores are the voids between the soil particles. The two origins of pore size distribution show up in two frequency curves, which in fig. 13 A are drawn as separate probability distributions, but they may overlap.

The desorption curve is the integration curve of the pore size distribution. The shape of this curve is given in fig. 13 B. The curve in fig. 13 A consists of three parts *AB, BC* and *CE,* and in fig. 13 B these three ranges can also be distinguished. In the distribution curve a certain pore size will define the largest pore present. This maximum size will be of less than infinite radius. Because between the capillary stress ψ and the pore radius a relation exists reading:

$$\psi = \frac{a}{r}$$

the presence of a maximum pore size means that a minimum value of ψ can be distinguished, which can be used as indication of the presence of this maximum pore size. This is the air entry stress ψ_a, the stress at which the first quantities of air start to enter the soil, provided that no macro-porosity is present. If macro-porosity has to be taken into account, there are two of these points, the air entry point A for the macro-pores and point C for the micro-pores. The point A is, however, situated at a moisture stress that is too small to be determined.

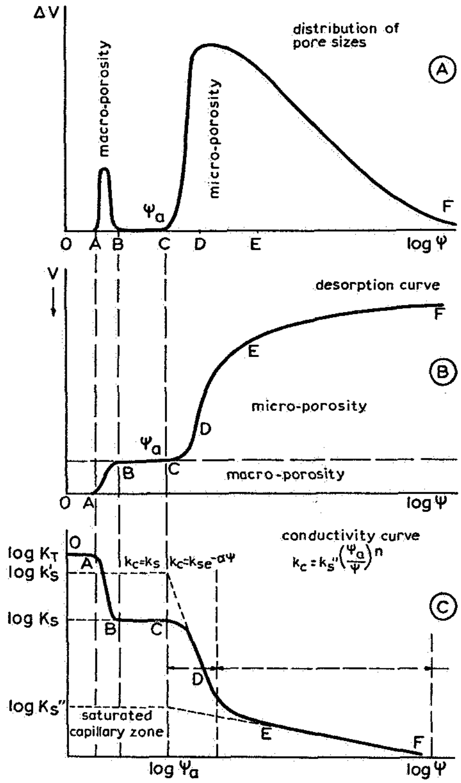


FIG. 13. Explanation of the qualitative relations between the curves for the pore size distribution, the desorption curve as integration of the latter and the conductivity curve as influenced by macro- and micro-porosity and the interjacent pore size range with zero pore probability

The air entry point determined in the laboratory conforms with point *C*. The volume of the macro-pores generally is also small and will normally be overlooked. It is, however, because of its lager pore diameter of decisive importance for the permeability.

The law of Poisseuille states that the amount of water flowing through a capillary pore is proportional to the fourth power of the pore diameter. The macro-pores therefore contribute largely to the conductivity, the microporosity contributes far less.

The capillary conductivity is the sum of the contributions of all the pores which contain water and allow moisture to flow. These will only be pores below the size which just can hold its moisture against the stress resulting from the degree of saturation. The curve for the capillary conductivity will follow from the pore size distribution. The size has to be brought to the fourth power and these values have to be integrated to give the conductivity curve, as depicted in fig. 13 C. In the range *OA* and *BC*, where no pores are present, the conductivity will not increase. In the range *AB*, where in fig. 13 B the increase is small, the conductivity will increase quickly, in the range *EF* this is just the reverse as a consequence of the small pore sizes.

Taking into account that the range *OB* is too small to allow the determination of ψ-values – capillary stresses of a few mm cannot be determined in undisturbed samples of a few cm thick – one will find for the conductivity curve a simplified shape. The saturated conductivity in fig. 13 C will coincide with point K_T. The highest unsaturated conductivity will be situated on the line *BC* where, dependent on the soil, a certain constant value will be found. In the range *CD*, a more or less straight line relation will be found for the lower end if log K_c is plotted against ψ. In the range *EF* also a straight line can be constructed, but

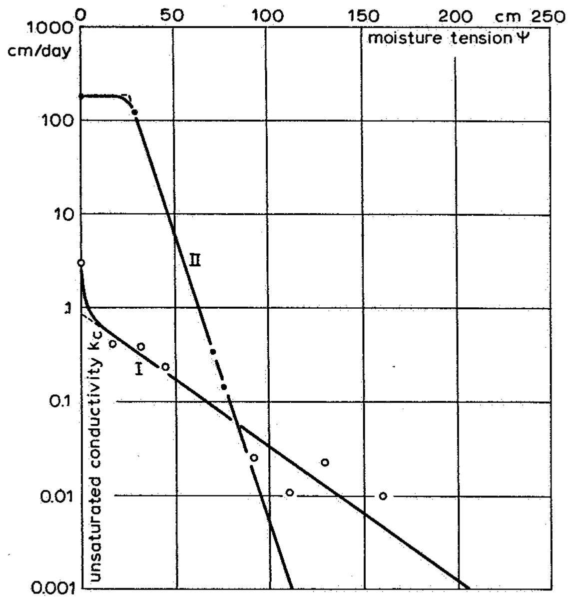


FIG. 14. Example of the possible aspects of the curves for capillary conductivity. Curve I has a low zero stress capillary conductivity and influence of macro-porosity. Curve II has a high zero stress capillary conductivity but a clearly indicated saturated capillary zone

now if log K_c is plotted against log ψ. The precise nature of the relation between the desorption curve and the conductivity curve is not known. The Poisseuille equation was mentioned, but does not correctly allow for the effect of the variable diameter of the pores, for the tortuosity and the ramification of the pore system and for the presence of air blocks. The Poisseuille relation, however, is important as a basis of explanation why the small volume of macro-pores often accounts for the larger part of the saturated conductivity, and why the saturated conductivity, plotted against the moisture stress, often has no clear position on the curve for the unsaturated conductivity. In figure 14 an example of a laboratory determination of the curve for the unsaturated conductivity is given.

14. The desorption curve

The data for moisture content and moisture stress, if analysed in detail, provide not only information for the pore size distribution. If the air entry point is assessed and the total pore space is measured, and further a fluent line is drawn or calculated through the points depicting the stress and moisture content observations, then four desorption characteristics are available, which are of interest. Figure 15 explains the pore space characteristic.

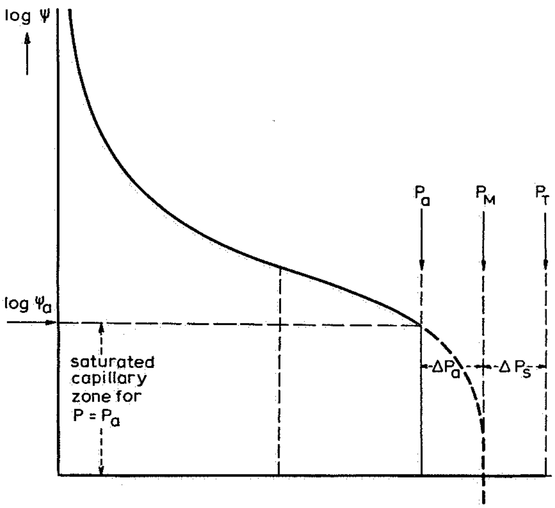


Fig. 15. Influence of the presence of a saturated capillary zone with pore space P_a and of macro-porosity with pore space P_T on the desorption curve and the position of the pore space P_M found by mathematical adjustment. $\Delta\ P_s$ can be positive or negative but its negative value cannot exceed $\Delta\ P_a$

One can distinguish the capillary pore space P_a which goes with the air entry stress ψ_a. The non-capillary pore space ΔP_s is the difference between the capillary and the total pore space P_T. The mathematical pore space P_M is the value of P which gives the best fitting fluent line, depending on the presence of the macro-porosity as distinguished in figure 13, and is higher than the value for P_a but can be smaller as well as larger than P_T. The value of P_T is the value of the pore space determined in the laboratory. The difference $P_T - P_M = \Delta P_s$ is positive in case macro-porosity is present. In case the micro-porosity P_s is zero, the laboratory analysis provides a positive difference $P_M - P_a = \Delta P_a$. In case this positive value is obtained, the air entry stress ψ_a can be deduced from the desorption formula and compared with the laboratory determination. Often the laboratory determination proves to be somewhat higher.

The desorption formula, of an empirical nature which holds well for undisturbed not swelling soils, is:

$$\psi = \frac{G\,(P_T - v - \Delta P_S)^n}{v^m} \qquad (5)$$

or $$\log G - \log \psi = m \log v - n \log (P_T - v - \Delta P_S)$$

The air entry value is $\psi_a = \dfrac{G\,\Delta\,P_S^n}{v^m}$

In the following discussion, the distinction between ΔP_S and ΔP_a, only differing in sign, will be neglected.

The formula will often be used in the shape of

$$b\,(G^* - pF) = p \log v - (1 - p) \log (P^* - v) \qquad \begin{aligned} G^* &= \log G \\ P^* &= P_T - \Delta P_a \end{aligned}$$

As will be shown, a major problem with respect to the use of the formula is to obtain in an easy way an indication of the value of $(P_T - \Delta P_S)$ and of ψ_a, a difficulty which arises from the inaccuracies in the determination of the data.

15. Assessment of the constants

For the solution of the desorption equation as well as for curve fitting three solutions are available.

The first and second solution use the nomogram with three parallel lines, see figure 16. In fig. 16 A the right x-axis represents in an upward direction the log v-values, but is marked with the values of v itself. The left y-axis is calibrated

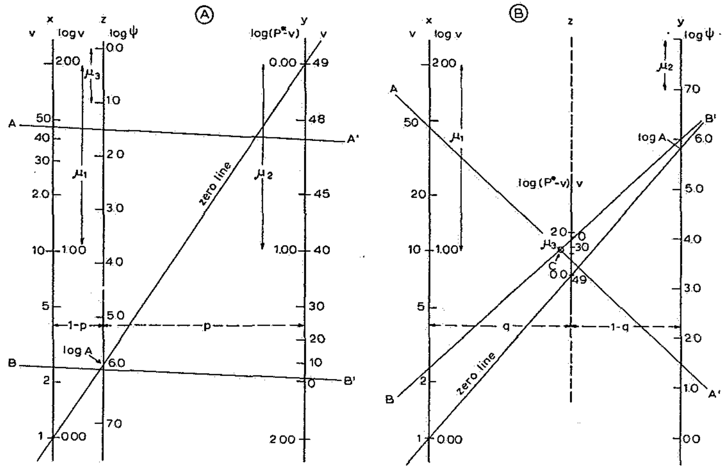


FIG. 16. Construction principles of the nomograms for the formula b (G-log ψ) $= p$ log v — (1-p) log (P-v) for calculating ψ or v and adjustment of the constants b, G, p and P. The nomogram in fig. 16B is more specially advocated for assessment of P

in a downward direction with log (P^* — v), but also indicated with v-values. In this diagram the reading lines A-A' and B-B' for log Ψ-values of 1.5 and 6 are drawn. These lines link the points for $v = 2.4$ and $v = 47.5$ % moisture, which are the moisture contents obtained by analysis going with the stresses log $\psi =$ 1.5 and 6.0. If other, but identical moisture content values on the x- and y-axes are connected, then at the intercept with the z-axis the matching log ψ-value is indicated.

When constructing the nomogram, the position and calibration of the z-axis is, however, not yet known. The construction is as follows: The vertical distance between the two reading lines has to be divided in the log ψ-intervals of the observations. The line for log $\psi = 3$ is drawn at (3 — 1.5) / (6.0 — 1.5) or 1/3 of the distance between the two lines — from the A-A' line, the line for 4.2 is situated at (4.2 — 1.5) / (6.0 — 1.5) part of the distance between the lines from the A-A' line. This system of lines is indicated in the nomograms of figure 17 as the ψ-lines.

Next a second system of lines is constructed, indicated in figure 17 as v-lines, which link the v-values on the two axes which match with the successive log ψ-values. The points of intersection of the drawn ψ-line and the dashed v-line for the values of the analyses are marked with a circle and through these circles the vertical log ψ-axis is visually adjusted. The intersection with the A-A' line is marked with log $\psi = 1.5$, the intersection with the B-B' line with log $\psi =$

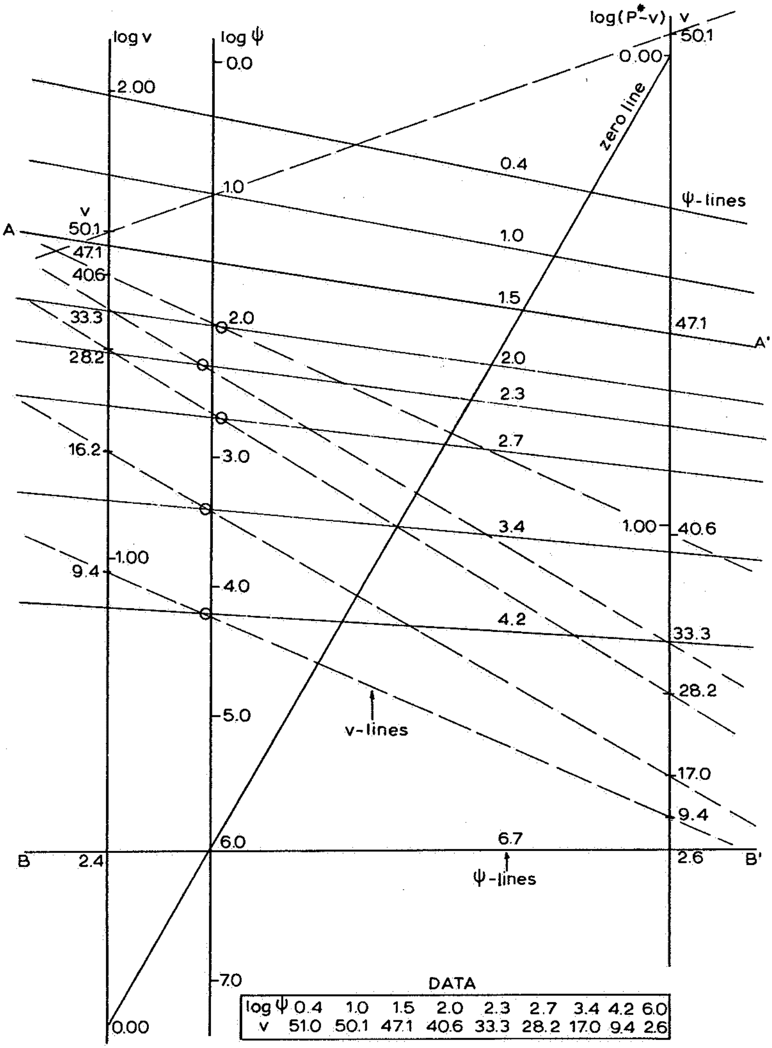


FIG. 17. Example of adjustment of the given data, according to the nomogram of fig. 16A in which for every value of P to be tried a new sheet has to be worked out

6.0. The ψ-scale is constructed as a metric scale between these two points, the value of b is calculated as the ratio $\mu_{\psi} = L/(6.0 - 1.5)\ \mu_v$ in which L is the length along the log ψ-axis between the A-A' and B-B' line, μ_v is the scale unit of the log v and log $(P^*\text{-}v)$ axes and $(6.0 - 1.5)$ is the number of log ψ-units between the A-A' and B-B' lines. The nomogram can be used for fitting the formula to the observations, but with the three axes correctly calibrated, each reading line linking two equals values of v on the outer axes with the value of ψ on the middle axis forms a solution of formula 5. In this way the same nomogram is used for assessing the constants as well as for solving the formula.

DATA

$P_r = 50.2$ log ψ	0.4	1.0	2.0	4.2	6.0
V	48.5	48.3	47.2	30.8	7.1
P = 49.1 P^*-V	0.6	0.8	1.9	18.3	42.0
48.9	0.4	0.6	1.7	18.1	41.8
48.8	0.3	0.5	1.6	18.0	41.7
48.7	0.2	0.4	1.5	17.9	41.6
48.65	0.15	0.35	1.45	17.85	41.55
48.6	0.1	0.3	1.4	17.8	41.5

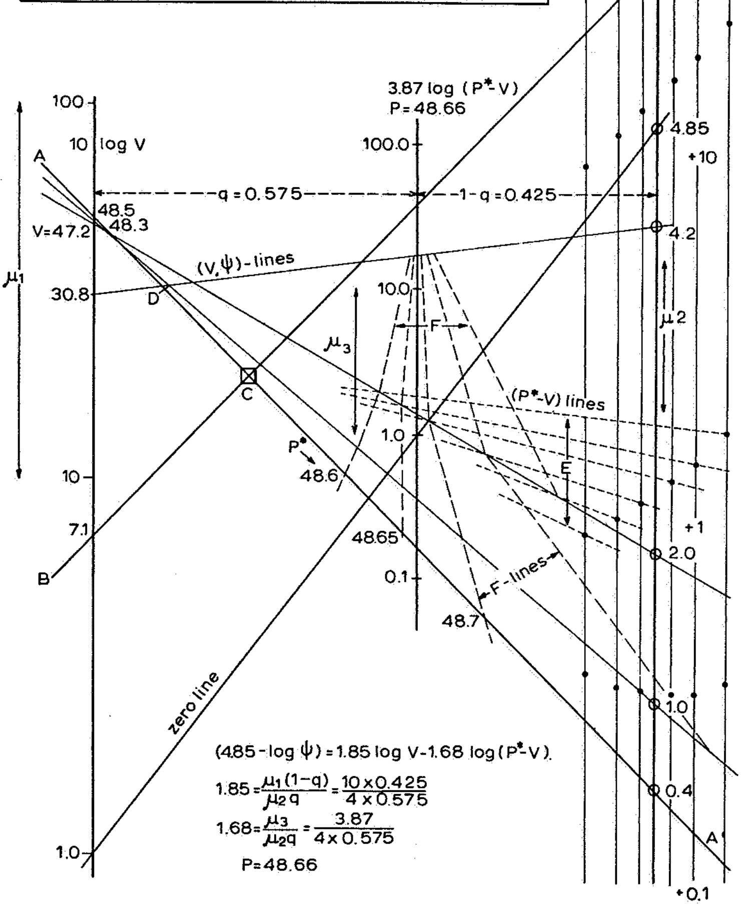


FIG. 18. Example of adjustment of the given data according to the nomogram of fig. 16A in which a number of attempts with different values of P can be constructed on the same sheet

This nomogram is simple, but has the disadvantage that the assessment of the value of P^* requires the repeated construction of the whole nomogram. The necessity of repeated construction can be evaded by calibrating the outer axes both in upward direction with $\mu_1 \log v$ and $\mu_2 \log \psi$ in which the ratio μ_1/μ_2 is selected in such a way that the observations for $\log v$ and $\log \psi$ cover about the same length of each axis. Figure 18 shows how this nomogram is made. Often a ratio $\mu_1/\mu_2 = 3$ is suitable. The $\log v$-axis is again indicated with v. The two reading lines *A-A'* and *B-B'* for $\log \psi$-data of appropriate value – here 0.4 and 6.0 – are drawn, which intersect at *C*. Now between these two lines on vertical distances equal to $\log (P^*\text{-}v)$ and plotted at a convenient scale, the values of $\log (P^*\text{-}v)$ are marked in such a way that the values of $\log (P^*\text{-}v)$ for $\log \psi = 0.4$ and 6.0 are situated on the *A-A'* and *B-B'* lines. A set of lines is constructed for successive values of P^*. These lines are in the top right hand side of the nomogram indicated as $10 \log (P^*\text{-}v)$ lines.

Now two sets of lines are constructed. The dashed $(P^*\text{-}v)$ lines connect the $(P^*\text{-}v)$ values of the analysis as marked on the arbitrary $\log (P^*\text{-}v)$ axis with point *C*. The third set of drawn v, ψ-lines connects the values of matching v and ψ-values and intersects with the $(P^*\text{-}v)$ lines. The points of intersection of the matching $(P^*\text{-}v)$ and v, ψ-lines – belonging to the same observation – are marked and these markings should be situated on a vertical line. In case the value of P^* is not correctly estimated, then for lower values of $(P^*\text{-}v)$ – or higher values of v – the points fan out to the left if P^* was taken too low, or to the right if P^* was taken too high. A new value of P^* is selected and a new arbitrary $\log (P^*\text{-}v)$ axis of the set of $10 \log (P^*\text{-}v)$ axes is drawn. Because the distance between the values $(P^*\text{-}v)$ to be situated on the *A-A'* and *B-B'* lines varies, the new axis will not coincide with the former one and the construction can be repeated on the same sheet of paper, with only the $(P^*\text{-}v)$ lines changing. Figure 18 gives an example of the construction of the successive approximations of the $\log (P^*\text{-}v)$ axis.

The intersections of the vertical line through the constructed points with the *A-A'* and *B-B'* lines again provide two points of the $3.87 \log (P^*\text{-}v)$ scale and the calibration can be constructed, the magnitude of a scale unit can be assessed, the zero line through the points v and $(P^*\text{-}v)$ equal 1.0 can be drawn. At the intersection of the zero line with the $\log \psi$-axis the value of G can be read.

The formula can now be calculated by determining:

$$m = \frac{\mu_1 (1 - q)}{\mu_2 q} \quad \text{and} \quad n = \frac{\mu_3}{\mu_2 q}$$

The values of μ_1, μ_2 and μ_3 are the scale units for the $\log v$-axis, the $4 \log \psi$-

axis and the 3.87 log (*P**-*v*) axis. It is advisable to indicate the scale not only with the variable — for instance (*P**-*v*) — but also with the function — log (*P**-*v*) — as well as with the length of the scale unit applied — therefore 3.87 log (*P**-*v*).

The advantage of this nomogram is that on one sheet of paper the solution for a number of *P*-values can be worked out and comparison of the shape of the *F*-lines, in figure 18 obtained in the successive solutions, allows more readily to make an estimate of the final solution for *P*.

The disadvantage of the two nomograms is, that in case of rather inaccurate observations, the solution becomes difficult. Inaccuracy of the values for log Ψ = 6.0 is troublesome, because the solution is sensitive to this value. The same holds for the lower observation, providing line *A*-*A'*, for which the value of Ψ has to be chosen above the tension of the air entry point and this value is often not known.

A third solution which in the case of inaccurate data may be helpful is the one in which log ψ is plotted against — log (*P**-*v*) as well as against +log *v* as depicted in figure 19. It can be proved, that the line *EF*, linking the points of intersection of each curve, has relative to the log ψ-axis an inclination equal to *b*.

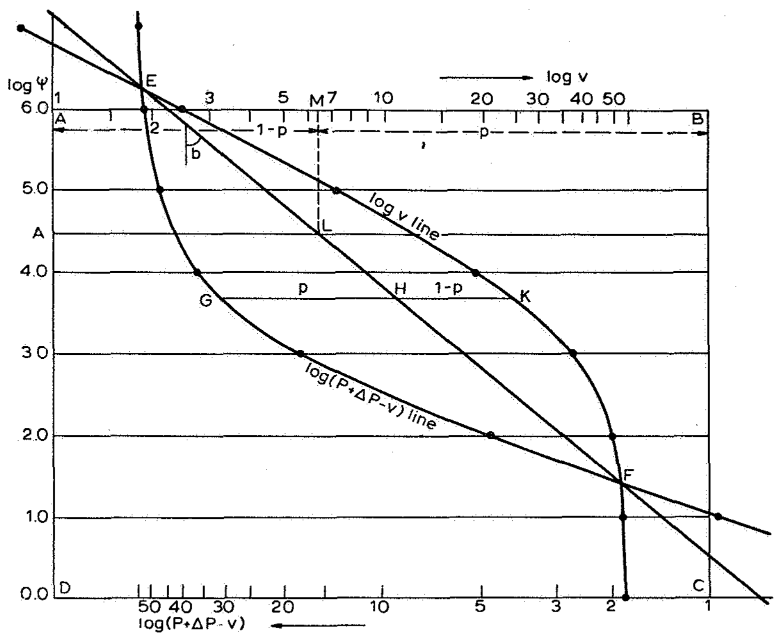


FIG. 19. Example of a method for adjustment of desorption data, which may be helpful in case of inaccurate observations

The line EF divides each horizontal line GK according a ratio p to $(1\text{-}p)$. The distance AB between the arbitrarily chosen zero points of the log v and log $(P^*\text{-}v)$ axis, if divided in a ratio

$$\frac{BM}{AM} = \frac{p}{1\text{-}p}$$

provides a point of intersection L of a vertical line through M and the oblique line EF. This point L indicates on the log ψ-axis the value of A. Further, the tangent lines on the curved log v-line in E and the log $(P^*\text{-}v)$ line in F provide values for the approximation of the desorption curve:

$$\psi = G_1\,(P^* - v)^{m1} \qquad \text{and} \qquad \psi = G_2\, v^{m2}$$

for the dry and wet ends of the moisture stress - moisture content relation. The last equations are used if a simplified mathematical relation for the lower or upper part of the desorption curve is considered acceptable.

16. The soil moisture profile

The moisture profile of the soil is related to the soil moisture stress that prevails at the point of sampling according the relation that was discussed in the paragraph dealing with the desorption curve. If at any layer of the profile this moisture stress ψ is equal to the height z above the groundwater table, then the moisture distribution in the profile is in equilibrium and no capillary flow will occur.

If any flow is present, this means that the difference $(\psi - z)$ will depart from zero and will vary in upward or downward direction. Moisture will be extracted or stored in the successive layers of the soil and the moisture stress ψ will the more diverge from the values z for the height above ground water, the higher the rate of flow v_c or the lower the unsaturated conductivity k_c of the soil is. This divergence can be appreciable in case of upward capillary flow and soil moisture extraction. For downward flow the divergence from the equilibrium profile is much smaller and, due to the inconstancy of the rain as compared with the far less variable evaporation, lasts much shorter. The discussion will therefore centre on the upward capillary flow.

The extraction v_c of soil moisture from the profile should be described by a non-steady flow equation. Because, however, these equations are rather cumbersome, the use of an approximation is proposed, assuming that the extraction from each layer is the same. This is described by:

$$v_z = k_c \left(\frac{d\psi}{dz} - 1\right)$$

$$\frac{dv_z}{dz} = a\, v_c$$

or $$v_z = (az + b)\, v_c = \frac{z + z_o}{z_s + z_o}\, v_c$$

z_s = the height of the soil surface above the groundwater table
z_o = a parameter governing together with z_s the linear increase of the quantity of water that flows upward
v_z = the flow at the heigt z
v_c = flow at the soil surface z_s, often equal to the real evaporation E_r
k_c = capillary conductivity at height z

This moisture flow is also dependent on the capillary conductivity k_c which may be described by:

$$k_c = k_o\, e^{-a\psi}$$

The value of k_o is obtained by calculating the value of k_c for $\psi = 0$.
The equation from which the soil moisture profile can be deducted can be written as:

$$\frac{z + z_o}{z_s + z_o}\, v_c = k_o e^{-a\psi} \left(\frac{d\psi}{dz} - 1\right)$$

Here $\frac{d\psi}{dz}$ is the gradient in the unsaturated zone, by -1 the gradient due to gravity is given. The differential equation can be solved and after some rewriting becomes *:

$$(1 - e^{-az}) \left\{ \left(\frac{z_o - {}^1/a}{z_s + z_o}\right) \frac{v_c}{k_o} + 1 \right\} + \left\{ \frac{1}{z_s + z_o} \frac{v_c}{k_o}\, z \right\} = (1 - e^{-a\psi})$$

* The assumption of a linear increase of the extraction is a simplication. The equation can be transformed into:

$$\frac{de^{-a\psi}}{dz} + e^{-a\psi} = -\frac{a v_c}{k_o}\, f(z)$$

or $$\frac{dx}{dz} + Px = -Q \qquad P = +a \qquad Q = -\frac{a v_c}{k_o}\, f(z)$$

This is a well-known equation which can be solved if $f(z)c^{-az}\, dz$ can be integrated.

The shape of the curves, which follow from this equation, are given in the following table:

Constants	z_0 / z cm	0	150	∞
	20	20.0	20.2	20.5
$v_c = 0.4$ cm/day	50	50.4	51.2	52.0
$k_o = 20$ cm/day	100	104	107	111
$z_s = 150$ cm	150	188	202	218
	160	244	311	
	166	∞		
	159		∞	
	158			∞

A quantity v_c of 4 mm/day is flowing upward under influence of the gradient due to moisture extraction at the soil surface. Dependent on the distribution of the extraction over the profile the increase in moisture stress, as compared with the equilibrium stress $\psi = z$, changes. The more the extraction is concentrated in the upper layers of the profile, the higher the moisture at a certain rate v_c of upward flow can be lifted. The difference between z_{max} for $z_o = 0$ and $z_o = \infty$ is 8 cm for $v_c = 4$ mm/day, but this difference becomes larger the lower the rate of upward flow.

If this equation is used for the assumption that the flow of water through the profile has the same value in any layer, meaning that the capillary rise consists of water drawn from the groundwater, the situation is defined by taking $z_o = \infty$. This results in

$$(z_o - {}^1/\alpha) \ / \ (z_o + z_s) = 1$$

and $$1 \ / \ (z_o + z_s) = 0$$

and leads to the simplified equation (RIJTEMA, 1965 *):

$$\left(1 - e^{-\alpha z}\right) \left(1 + \frac{v_c}{k_o}\right) = (1 - e^{-\alpha \psi})$$

* Rijtema, P. E.: An analysis of actual evapotranspiration. Agric. Res. Rep. 659, p. 1-107 (1965).

A further simplification is possible. From the last mentioned formula may be derived the expression:

$$v_c = \frac{k_o\left(1 - e^{-\alpha(\psi - z)}\right)}{e^{\alpha z} - 1}$$

In cases where ψ is large compared with z, the value of $e^{-\alpha(\psi - z)}$ can be neglected. By putting $v_c = E_w$, the expression for the real evaporation, assumed to be a steady flow, can for conditions in which the availability of the soil moisture is the limiting factor, be derived by the use of the equation:

$$E_w = \frac{k_o}{e^{\alpha z} - 1}$$

In case of values of αz above 2.5, an easy assessment of α and k_o can be made by plotting ln E_w against z according

$$\ln E_w = \ln k_o - \alpha z$$

This is a straight line relation with intercept ln k_o and tangent α.

If – what is common – v_c is very small compared with k_o and v_c/k_o can be neglected against 1, the equation reduces to

$$z \approx \psi$$

This solution shows, that a large value of k_o results in a moisture stress profile which does not perceptively differ from the equilibrium profile. The rate of capillary rise then depends on the intensity of the real evaporation, which is, as will be shown in the next paragraph, a function of the moisture stress in the root zone.

This situation, for which the equation needs not to be used and only the desorption curve is of importance, occurs often. The cases, however, where the capillary supply of water is small, are agriculturally of importance and the treatment of observational data to solve the parameters, deserve closer attention. In figure 20 a graphical representation of the equation is given.

The fitting of the data for groundwater depth, evaporation and moisture stress to this formula will be influenced by the method of assessing the values of E and of the storage capacity μ. The value of μ is equal to the air content of the

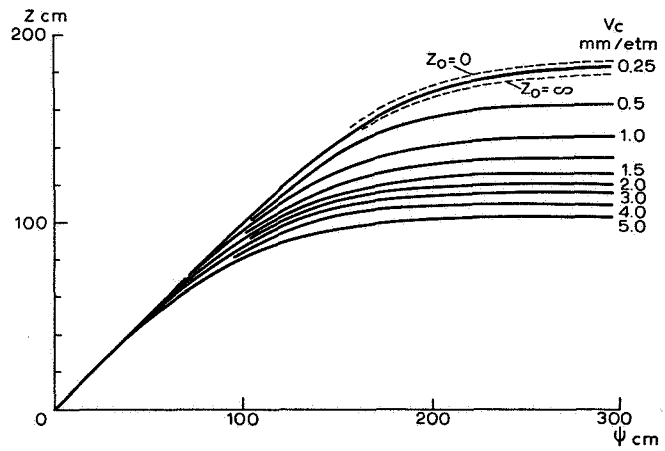


FIG. 20. Example of the relation between soil moisture stress ψ, velocity of capillary rise v_c and groundwater depth z for $k_o = 10$ cm, $\alpha = 1/30$ and $z_o = 150$ cm. The dashed lines are for $z_o = 0$ and infinite

top layer of the soil. Are these values obtained by an analysis of the groundwater depth, then in the equation for the moisture profile z is equal to z_s. Is the analysis done by studying soil moisture determinations from samples taken at successive depth, then z and z_s differ.

17. Calculation and assessment of constants

The assessment of the constants can be done with a nomogram, although the nomogram is complicated and the adjustment of the constants is not very efficient. The nomogram has, however, the advantage that no calculation errors have to be feared.

The nomogram consists of 8 parallel axes and 3 oblique zero-lines, which also are calibrated. In figure 21 the nomogram is represented. The significance of the values indicated along the axes is the following.

The scales along the axes are calibrated according to the construction of the formula, but the indication is done with the variables taken up in the formula. For axis 1 for instance, the values indicated numerically are calculated as αz. The calibration, however, is carried out for $20(1 - e^{-\alpha z})$. This axis is located at the zero-coordinate in the horizontal direction.

For each axis, in the table below, the number as indicated in the nomogram

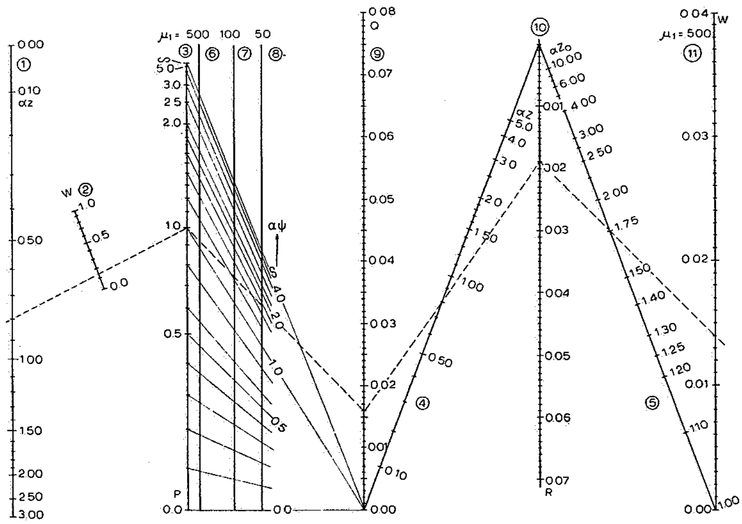


FIG. 21. Nomogram for the calculation of unsaturated upward flow for decreasing extraction at increasing depth. The axes 6, 7 and 8 should be used in case the scale along axis 11 is taken μ_1 = 500, 100 or 50

is given and the horizontal distance between each axis and axis nr. 1 is mentioned as the horizontal coordinate. In the third column the scale which is marked along the axis, is given. In the fourth column the values are indicated of which the numerals are used to mark the points of the scales.

Axis	horizontal distance	scale function	numerical value
1	0	$20(1\text{-}e^{-\alpha z})$	αz
2	zero line	$20(1+W)\ /\ (2.111+W)$	$W = (z_o-1)\,v_c/(z_o+z_s)\,k_o$
3	70	$18(1\text{-}e^{-\alpha\psi})$	$\alpha\psi$
4	zero line	$20\alpha z(\alpha z+1)$	αz
5	zero line	$20(2\alpha z_o-1)$	αz_o
6	74.7	$16.8(1-e^{-\alpha\psi})$	$\alpha\psi$
7	88.5	$13.5(1-e^{-\alpha\psi})$	$\alpha\psi$
8	99.3	$10.46(1-e^{-\alpha\psi})$	$\alpha\psi$
9	140	pivot line	immaterial
10	210	pivot line	immaterial
11	280	$500\ W$	$W = \dfrac{a\ (z_o - l)}{\alpha\ (z_o + z_s)}\ \dfrac{V_c}{K_o}$

A zero-line is an oblique axis which links the zero-points of the two adjacent parallel axes; a pivot line is an arbitrarily calibrated axis on which the reading lines intersect. The value, which might be read from such an axis is, however, as an intermediate result of calculation, immaterial for the solution.

The axes 7 and 8 are given in addition for the cases when higher values of W have to be used, surpassing the highest values indicated on scale 11. For values of W as indicated on axis 11, the value of $\alpha\psi$ should be read on scale 6. If the values along axis 11 are multiplied by 5 or 10, then the $\alpha\psi$ should be read on scale 7 or 8. The dashed reading lines drawn in the nomogram as an example, are constructed for $W/10$ as appears by comparing the values indicated at the points of intersection on the axes 2 and 11. These values are 0.14 and 0.014. This points at the use of a smaller modulus. Because the nomogram is not used with modulus $\mu_1 = 500$ but with $\mu_1 = 50$, the solution for $\alpha\psi = 1.6$ has to be read from axis 8.

The nomogram can be used for adjustment of the constants α, z_o and k_o. The values of z, z_s and $v_c = E_r$ will be available and ψ will be solved from the known soil moisture contents with the aid of the desorption curve. The adjustment is done by assuming a value for α, z_o and k_o. If for each observation the reading lines are drawn, using the observed values of z, z_s, v_c and ψ, then with correct values of α and k_o the lines will all intersect on axis 5 for αz_o. The value assumed for z_o to calculate W must compare with the average of the values read at the intersections on axis 5. If these values are not equal, other combinations of α and k_o have to be tried out till the data fit sufficiently with the observations. This fitting of values to the equation of the soil moisture profile is rather complex, but the results will show that often some of the constants can be neglected. In case of a good pervious soil the value of k_o is high and this means as was already mentioned, that the formula simplifies to $z \approx \psi$.

This simple solution is, however, of restricted use if the equation is intended to help determining at what value of z the capillary rise becomes too small to supply the plant with sufficient water. In this case the aim of the investigation is, to assess to which extent the soil dries out to a moisture content lower than the equilibrium moisture profile. This is shown by the value of Ψ, which then is larger than z.

18. Evaporation and soil moisture content

The moisture needed for the evaporation by plants is derived from the main root zone. The root zone is replenished, if not by rain, then by capillary supply from the subsoil. Between the capillary supply v_c of the previous paragraph and the real evaporation E_r exists a direct relation.

The evaporation, as part of the transport process with respect to the uptake of substances needed for plant growth, is based on the same laws of linear flow and minimum stress as the uptake of plant nutrients and the identical basis leads to an equation of similar shape. In this formula the soil properties define together the flow resistance parameter A, which was assessed to read as follows *:

$$A = \frac{4\, L k_o\, \psi_e^n}{(n-1)\, d^2 \left\{ \ln \left(\frac{d}{r}\right)^2 + \left(\frac{r}{d}\right)^2 - 1 \right\}}$$

d = radius of moisture extraction for a single root
r = radius of the root
L = thickness root zone
k_o = capillary conductivity k_c extrapolated to $\psi = 0$
ψ_e = air entry stress
n = exponent in equation $k_c = \left(\frac{\psi e}{\psi}\right)^n k_s$
k_c = capillary conductivity at moisture stress ψ

Because plant properties as the thickness L of the main root zone, the density of the root system $1/d^2$ or the average root diameter $2r$ are difficult to assess in the soil, the value of A will usually be determined by an adjustment technique and not from direct measurements. The equation may, however, be useful to transfer experience from one set of conditions to another.

The evaporation is calculated from an equation which is similar to the growth equation and which reads as follows:

$$\left(g - \frac{E_r}{E_o}\right)\left(A - \frac{E_r}{v^l - v^l_{wp}}\right) = F_3$$

The equation is represented graphically by figure 22, assuming that the moisture content v_{wp} at wilting point may be neglected, or the omission being compensated by correcting the factor A and the exponent l as was done in the paragraph 12 on methods of curve fitting and assessment of parameters. As value for the potential transpiration, a calculated value of E_o can be used, but often data of an evaporation pan are more practical.

---

* Visser, W. C.: Moisture requirements of crops and rate of moisture depletion of the soil. Inst. for Land and Water Managem. Res. Techn. Bull. 32 (1964).

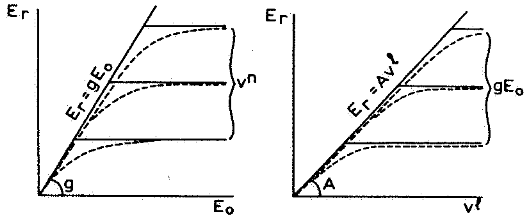


FIG. 22. Shape of the relation between real evaporation E_r, potential evaporation E_0 and soil moisture content v according formula 3

19. ADJUSTMENT OF CONSTANTS

In the adjustment of the constants g, A, l, v_{wp} and F_3 one will have to concentrate on the first three. The importance of the value of F_3 is restricted and by taking $F_3 = 0.05\ gA$, not much need for further adjustment will remain. The adjustment is carried out by making use of the property of the equation that two curves, given graphically and relating v to E_r, for two values of E_0 can be brought to coincidence by shifting the curves along the oblique asymptote $E_r = A(v^l - v^{wp}_{l})$. In the same way two curves for E_r against E_o for different values of v, can be brought to coincidence by shifting the curves along the $E_r = gE_o$ asymptote.

This shifting is carried out in graphs, obtained by plotting against each other:

$$\log E_r - (\overline{\log E_o} - \log E_o) \text{ and } \log v - \frac{(\overline{\log E_o} - \log E_o)}{l}$$

as well as:

$$\log E_r + l\,(\overline{\log v} - \log v) \qquad \text{and} \qquad \log E_o + l\,(\overline{\log v} - \log v)$$

The values of $\overline{E_o}$ and $\overline{v}$ are levels of E_o and v to which the other sets of observations are reduced. They can be freely chosen.

For this shift a first approximation of l has to be made, to be able to calculate the correction terms, but then the value of the tangent l from the asymptote can be used for a second elaboration and the values of log g and log A are found as the intercepts on the vertical axis. In figure 23 the principle of this curve fitting technique is shown (BLOEMEN, 1966)*.

An elaboration with data of sufficient accuracy will show, that the value of g is not entirely constant, but will vary during the year. This variation depends on the degree to which the crop covers the soil and also in the height of the

* Bloemen, G. W.: The calculation of evapotranspiration from groundwater depth observations. Techn. Bull. I.C.W. 46 (1966).

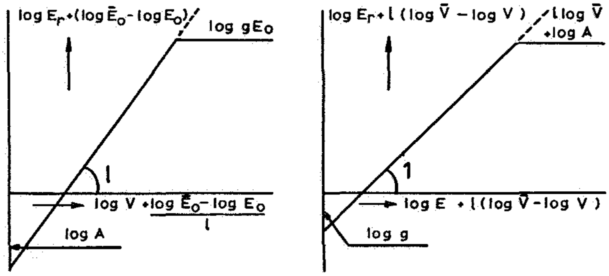


FIG. 23. Adjustment of formula 3 is carried out by an oblique shift, which brings for different levels of v or E_o the curves to coincidence. The shift is represented by the terms (log $\overline{E}_o$-log E_o) and (log $\bar{v}$ — log v)

crop effecting turbulence of the air. These effects will only be of importance if a high accuracy is needed. In this discussion they will be neglected. Another influence which is left out is the influence of variations in moisture content in the successive layers of the root zone. This can be treated by inserting in the equation for the evaporation the flow through n horizontal layers. The term T under consideration then takes the following shape:

$$T = \left[1 - \frac{E_r}{\sum_{i=1}^{n} A_i \, (v_i^l - v_{wp_i}^l)} \right]$$

By inserting this formula in equation 3 the moisture flow equation for a number of parallel directions of flow is given, with conductivity constants A_i and gradients $v_i^l - v_{wp_i}^l$ for each layer.

20. Evaporation and groundwater depth

The relation between soil moisture content and evaporation is a rather direct one, not accessable to disturbing influences. A point of practical interest often is however, the relation between groundwater depth and evaporation.

This relation can be determined, because the upward flow of moisture through soil, plant and atmosphere can be measured at four successive points of the flow path. Measurements can be carried out in the atmosphere by determining the vertical vapour transport. The measurement in the plant frequently used is the moisture transfer through the stomata. The equation for the moisture movement in the root zone was discussed in the previous paragraph.

The measurement of the capillary upward flow can also provide a basis for determination of the real evaporation. In the discussion concerning the soil moisture profile the formula relating groundwater depth to the velocity of upward flow was discussed. This equation only holds in the range of depth, where the soil moisture conditions represent the limiting factor for evaporation. For the range of groundwater depth, which includes the wetter conditions, the following formula holds:

$$\left(g - \frac{E_w}{E_o}\right)\left(k_o - \frac{e^{\alpha z} - 1}{1 - e^{-\alpha(\psi - z)}} E_w\right) = F_3$$

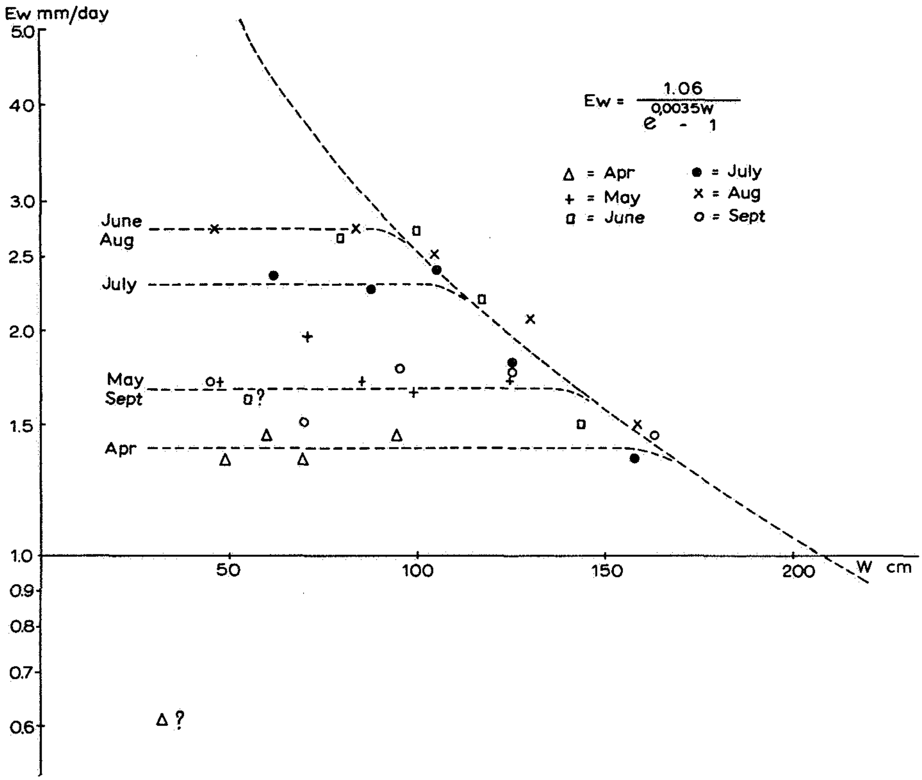


FIG. 24. Example of the adjustment of data on real evaporation with respect to the potential evaporation in case of limiting climatological conditions and to capillary flow in case of limiting soil moisture contents

In this formula further simplifications as already were discussed, can be applied. In figure 24 an example is given for sandy soils under normal farming conditions.

It should be remembered, that this equation only holds for situations of steady upward flow and should therefore not be used for conditions prevailing after rainfall. Because, however, in normal agricultural soils the rainwater is quickly evenly devided over the soil profile, the equilibrium conditions are sufficiently restored in one or two days. Therefore the equations can be used for assessing the evaporation if a time unit of a week or a fortnight is chosen, even if some of the days of the time-interval have been rainy.

21. Discharge and groundwater depth

Experience has shown, that in areas with an impervious layer at depth D and a wide spacing L of ditches and rivulets, the discharge equation is rendered with sufficient accuracy by:

$$A = \frac{8kd}{L^2}(W - S) = C(W - S)$$

W = groundwater depth
S = water level in ditch
k = conductivity
d = thickness of the pervious layer
L = drain spacing

$$C = \frac{8kd}{L^2}$$

The second power term $(W - S)^2$ of the common drainage equation can be neglected. What however cannot be neglected is, that generally at least two drainage bases can be assessed from the observations, a shallow and a deep one, the first consisting of furrows or field drains, the second of deeper water courses at larger distances. This shows up in the discharge curve as a more or less sharp bend, which has to be distinguished from the gradual transition from a flatter to a steeper part of the curve in case of a second power relation.

The combination of the effect of drainage bases on different levels can be achieved by multiplication of the terms for each drainage process. In such a formula the drainage equation should be written as a constant minus the ratio of flow to gradient, or as $C - D/(W - S)$. The product of two or more of such terms has to be constant. This is the same procedure as used for the yield equation and the equation for evaporation.

The formula becomes:

$$\left(\frac{8k_1\,d_1}{L_1^2} - \frac{D}{W - S_1}\right)\left(\frac{8k_2\,d_2}{L_2^2} - \frac{D}{W - S_2}\right) = F_2$$

and more of these terms of the same construction can be inserted if more drainage bases show up. For instance a subsurface flow to rivers at a considerable distance may be present, for which the gradient ΔW is constant. The thickness of the layer of flow d then depends on the upper limit of this layer and it varies with the depth of the groundwater W. The thickness of the layer is now inserted in the formula as $d - W$.

Such a term T, added to the previous equation, would read:

$$T = \left(k(d - W) - \frac{D}{\Delta W} \right)$$

The value of F_2 determines whether the transition from one branch of the discharge curve to the other is an abrupt or a gradual one. An example of such a discharge relation is given in figure 25. This example describes a case in which the drainage base – a distant river – varies in level as a result of variations in run-off.

The adjustment of the data obtained for instance from an analysis of the groundwater measurements, is carried out by plotting A and W or A and S for

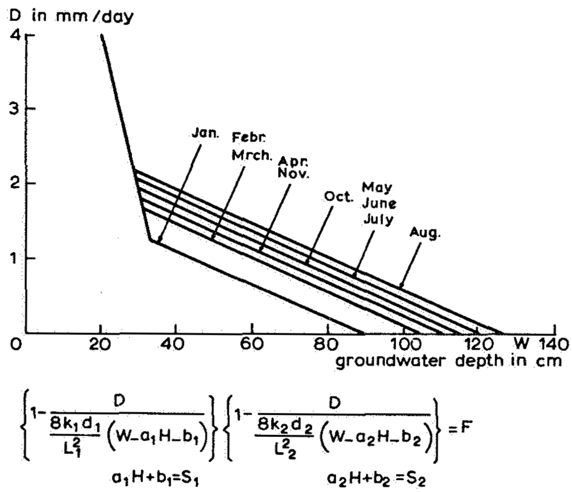


FIG. 25. In the water balance often the influence of two drainage bases is indicated, of which the lower one shows the effect of fluctuating water levels in the main water courses

different classes of S resp. W against each other and drawing straight lines through the scatter diagram.

22. Use of the formulae

The formulae may strike many designers of projects as rather complicated. The aim has been, however, to choose the simplest equations which can be applied over the largest range of hydrologic, climatic and agricultural conditions. And compared with the equations to which specialist studies often lead, the unwieldiness may probably be considered to be not too excessive.

The equations make it possible to use hydrologic soil properties to explain actual water balance situations. Also the response of crops or natural vegetation to moisture conditions can be predicted. One of the valuable points is, that the formulae allow to eliminate uninteresting variables and show that any magnitude can be expressed in each of the others. This may clarify relations which remain generally vague if one has not chosen them as object of basic study.

Groundwater levels are easy to determine and have a practical significance. Soil moisture stresses are an instance of a magnitude which is of restricted practical importance and is far less easy to determine. Still for scientific reasoning, the soil moisture stress is normally used and this makes the results, expressed as function of such a variable, so difficult to apply in practice. The equations obtained show how theoretical problems as evaporation, which are normally expressed as functions of ψ, now can be represented as functions of the groundwater depth. In the case of evaporation for instance the following result is obtained:

$$\sqrt{\frac{E_r\,(gE_o - E_r)}{(gA - F_3)\,E_o - AE_r}} =$$

$$\frac{-1}{\alpha}\ln\left\{e^{-\alpha z_s}\left(\frac{\alpha z_o - 1}{\alpha\,(z_o + z_s)}\cdot\frac{E_r}{k_o} + 1\right) - \left(\frac{\alpha(z_s + z_o - 1)}{\alpha(z_o + z_s)}\cdot\frac{E_r}{k_o}\right)\right\}$$

This relation is obtained by taking the real evaporation E_r equal to the rate of capillary supply v_c at the soil surface, where $z = z_s$. The equation shows that a direct relation exists between E_r and z_s, defined by a number of soil and crop constants. Included in the formula is E_o as the only variable independent of the groundwater depth z_s and it can therefore not be eliminated. In the same way the storage capacity can be expressed as a function of z_s, whilst the discharge is already given as a function of this technically important magnitude of the groundwater depth.

This possibility of expressing the water management problems as a function of z_s can be used in two ways. It can be used to study the influence of climatological conditions on the water balance for different drainage and irrigation situations. But is also can be used to predict the effect of these measures on crop production.

23. Prediction of water balance variations

If the correct constants in the formulae are found by some adjustment process, it becomes possible to calculate for each of the values of the water balance

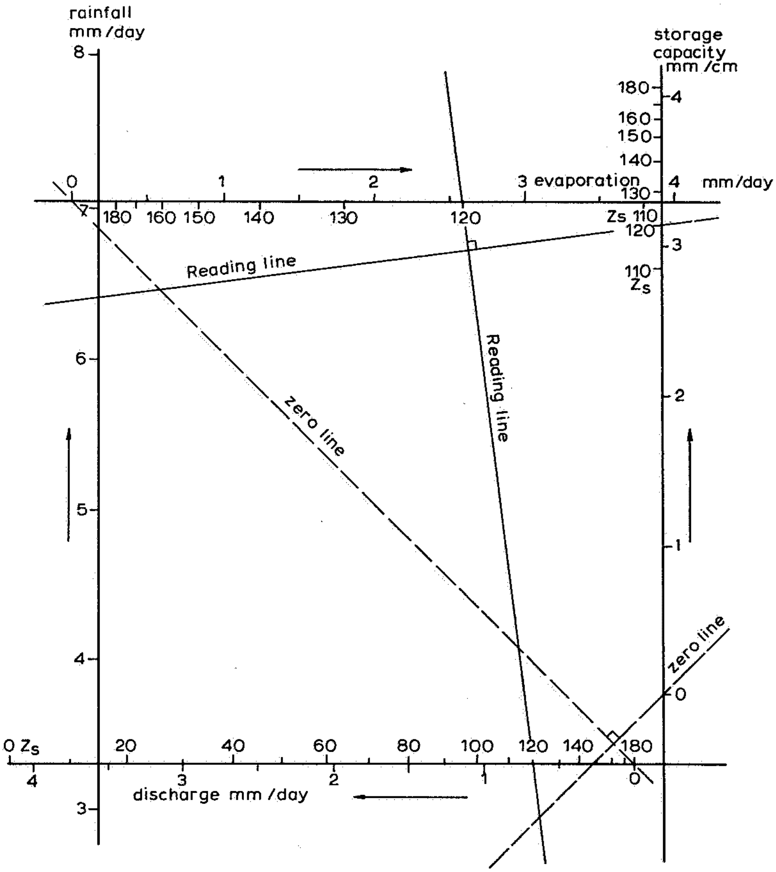


Fig. 26. Nomogram for the calculation of the response of the water balance terms in the course of time to the daily or weekly rainfall by assessment of ΔW

terms D, E_r and $\mu\Delta W^*$ with $\Delta W^* = 1$, what groundwater level matches with the intensity of each of the water balance terms. For ΔW, a unit value is taken to calculate what amount of rainfall provides, next to evaporation and discharge, an increase in storage of 1 cm. It is possible, by using the formulae, to calibrate four axes with the mm-value – using the same scale units for the various axes – at one side of each axis and – except for the rainfall axis – with the corresponding value of z_s at the other side. The result is shown in figure 26.

The four axes are united into a rectangular square, along which the direction of increasing mm is going clockwise, save for the axis for moisture storage, of which the direction of increase is anti-clockwise. This nomogram is read by a rectangular cross on transparant paper. If discharge and evaporation are marked on opposite axes, one leg of the cross is laid through two points of these two axes with the same value of z_s. Then the cross is shifted, with the first leg still intersecting at the same z_s-values on the A- and E_r-axes, till the second leg intersects the $\mu\Delta W^*$-axis at the same value of z_s. The mm of rainfall at the point of intersection with the fourth axis is read. This is the amount of rain R^* which would account for the discharge and evaporation obtained with this groundwater level and the change of storage of $\Delta W = 1$ cm.

The difference between the real rainfall R and this calculated rainfall R^* represents the actual rise or lowering ΔW of the groundwater level according to the relation $\Delta W = \frac{R - R^*}{\mu} + 1$, and by adding this value of ΔW to z_s, the groundwater table at the beginning of the second time interval is produced.

The nomogram has to be constructed for different values of the ditch water levels S of the discharge formula and for different values of E_o for the evaporation and storage formulae. This can be done by constructing cartesian side nomograms with the common rectangular axes, which allow to find for each S or E_o the values in mm for D, E_w and $\mu\Delta W$ which match with a certain value of z_s.

The nomogram enables one to calculate for an initial value of z_s what the change ΔW_1 is for a given rainfall, then to calculate the groundwater depth $z_{s2} = z_{s1} + \Delta W_1$ for the next interval and then again to assess the value of ΔW_2. This can be carried on for a sequence of climatical conditions, for instance a critical period, in order to find out what the moisture conditions will be before and after improvement of the drainage system, or for different moments and quantities of supply of irrigation water. Any alternative solution can be worked out and any strategy of using the management techniques, taken into consideration for actual construction can be sorted out in advance.

24. Prediction of crop response

The prediction of crop response depends largely on the ability to determine the coefficients for the successive stages of plant growth. Situations of excess or deficiencies of water which seldom occur, often are of great importance for the assessment of the profitability of a project. If data for periods with excessive

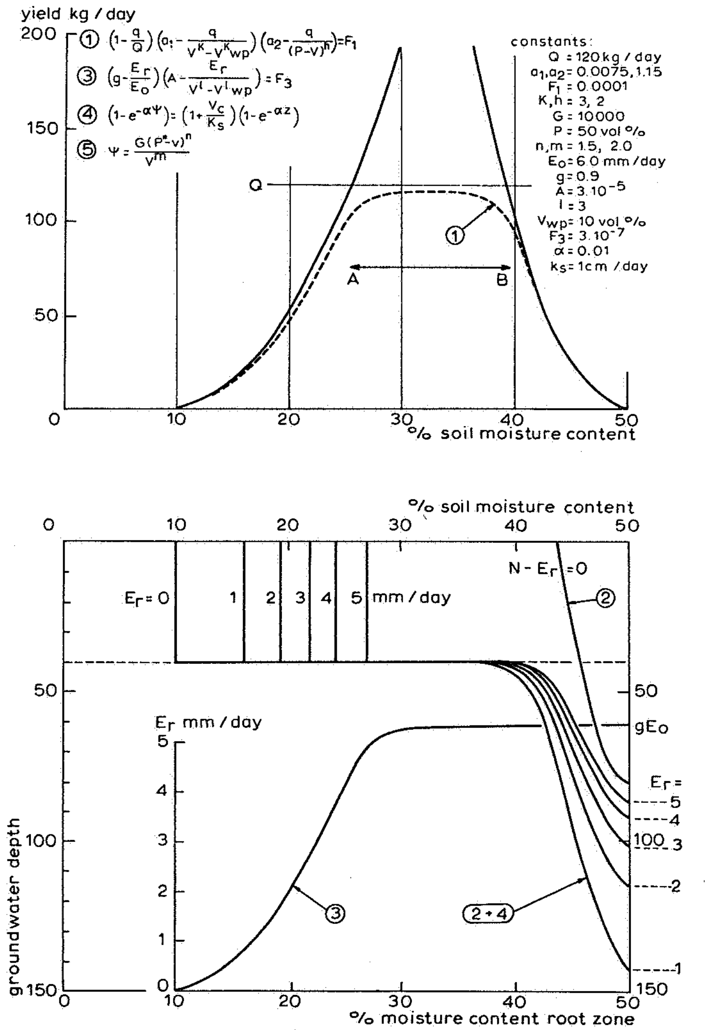


Fig. 27. Example of the response of the crop yield on groundwater depth, moisture content in the root zone, potential evaporation and capillary rise according the formulae 1, 3, 4 and 5

rainfall or prolonged drought are not available during the short time of preparation of a project, this will invalidate the resulting design. Therefore experiments and observations on crop growth should in support of a project preferably be started as soon as possible and be carried out as long as possible.

An example of such an elaboration of data is given in figure 27, in which, in order to simplify the problem, the discharge is left out.

The four remaining formulae and the constants which were used, are given. The formula for the moisture profile is used for $z_o = \infty$. This is the lysimeter formula for the case that the water which evaporated is directly replenished by subsoil infiltration. The moisture profile is assumed to be a two layer case, the root zone having a constant moisture profile and the subsoil a moisture distribution according the formulae 2 and 4 mentioned in figure 27. As common variable the moisture content in the root zone is taken for a change. It could have been the groundwater depth as well.

The arrow and number pointing at each curve give the formula which was used to calculate that curve. The depth below the soil surface, where the curves (2 + 4) for the soil moisture profile intersect the axis at the right hand, shows what groundwater depth z_s goes with each rate of evaporation E_w.

The lower half of the graph also shows, what relation exists between the moisture content in the root zone, the real evaporation and the groundwater depth. The upper half shows what the effect of these magnitudes is on crop production. The graph and the formulae deal as well with low moisture contents and water deficiency as with high moisture contents and water logging. The intermediate range *A-B* of moisture conditions with optimal growth in figure 27 is clearly the range at which the project should aim. The lower the maximum attainable yield Q, the wider the optimal range and the easier the design and management of the project. In areas with low production, a very crude assessment of the moisture relations will do. A high production requires a very exact handling of the water management measures on penalty of transgressing the narrow limits of maximum production, and stray off into the ranges of suboptimal growth.

25. Assessment of drain depth

The most accurate way to predict the required drain spacing and depth is the one, discussed in relation to figure 26. In the calculation of the variations in the water balance the elaboration can be carried out with a number of combinations for drain spacing and depth. For each combination, the sequence of groundwater depths can be assessed. By noting at the same time the moisture or air content on the $\mu\Delta W^*$-axis, the yield curve of a type as depicted in figure 27, if calculated with the proper constants, can be used to predict what yield depreciation will occur for each combination of drainage constants. This method is, however, the most laborious.

The depth of drainage depends on the point where in figure 27 the flat summit changes over in the slopes of the yield curve. These points of transition can be recalculated from moisture percentages into groundwater depths. The depth of drainage has to be taken equal to this groundwater depth, calculated from the moisture content, to which is added the average head of pressure between the middle of the field and the drain.

If the average runoff is equal to D_a, then the average head of pressure W_a is calculated as

$$D_a = \frac{aW_a + bW_a^2}{L^2}$$

The highest permissable drainage depth W_n then is the maximum groundwater level W_m according to the yield curve, plus this pressure head W_a required for draining away the rainfall surplus. The upper limit for the depth of drainage W_n is equal to

$$W_n = W_m + W_a$$

The lower limit depends on the lowest water level, acceptable according the yield curve, for which figure 27 gives a moisture content of the order of 25 %, an evaporation of 4.5 mm per day and a groundwater depth at the right hand side axis of the lower graph of 90 cm.

The upper level will require some rigid definition of what is intended with the drainage. If it is only spring drainage, then a certain air content in the root zone has to be indicated that should be present in order to start spring growth. The maximum growth rate in spring may be of the order of 25 kg per day, which goes, as depicted in figure 27 and formula 1, with an air content of 5 %. This, according to formula 2, means a groundwater depth of about 50 cm. If an air content had been required of 10 %, then a groundwater depth of 180 cm would have been calculated.

Would one centre the problem of drainage on the discharge of summer rainfall, then the required air content for unhampered growth at a high level of production would have been taken and an evaporation intensity would have to be defined which – together with the groundwater depth – governs the air content in the root zone.

If the evaporation is taken 5 mm and the required air content 10 %, then in figure 27 in the lower graph the value of the water depth on the right hand side axis is read to be 70 cm. The distribution of rainfall over the year and the response of the crop to the moisture relations will determine, what the depth of drainage should be, but it will be clear that for each year a slightly different value will be the best one. And during the year the results of the calculated optimum depth of drainage neither will be constant. The depth of drainage, due to its basic meaning, is an average value of wide variations, each of which has only a momentary validity.

26. Assessment of drain spacing

The drain spacing follows from the depth of drainage and the agricultural requirements. The actual spacing should be calculated by inserting rainfall data in the water balance formula, assessing the resulting water table height for a given drainage depth and spacing, and calculating the yield response with the productivity function. If this is considered to be too laborious, then this calculation is replaced by an elaboration which uses the rainfall frequency, a storage volume and a linear function for the integrated discharge. This latter assumption means that the discharge is constant and not dependent on the amount of drainable moisture, which is unsatisfactory, however. Therefore three acceptable formulae are suggested as a basis for this simplified solution for the drain spacing.

These formulae are:

a) $z = \frac{G\mu^n}{(P - \mu)^m}$ b) $-\frac{dS}{dt} = \frac{az + bz^2}{L^2}$ c) $\Sigma R = pt^q$

Equation a) is the desorption formula. If the value of μ does not vary too much, the denominator can be taken constant. Further it is known that the exponent n is often of the order of 1.0.

Formula b) is a drainage equation in which S is the volume of water that in the course of time can drain away. The formula especially is used as a function between L and z.

Equation c) gives for a certain probability K of transgression the rainfall sum as a function of the length of the time interval for which this rainfall sum and recurrence frequency are calculated. The exponent q and the constant p have for the shorter lengths of the time interval for a certain rainfall station a value as follows from figure 28.

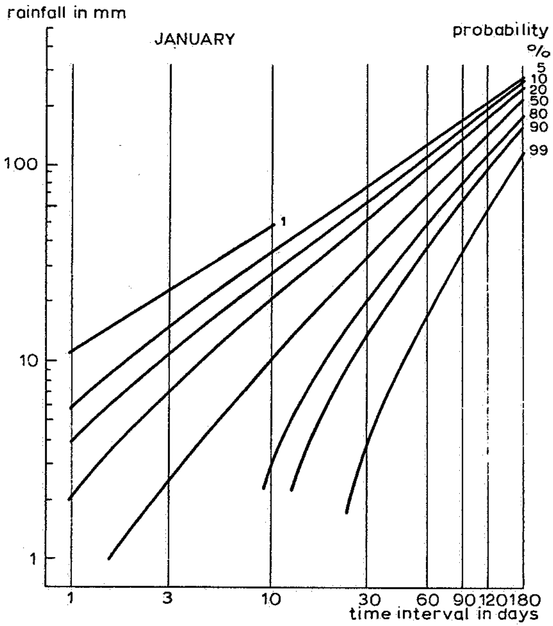


FIG. 28. Example of the rainfall probability in spring in its relation to the length of the time interval

The first formula will be used in its simplified form:

$$z = G^*\mu \qquad \text{or} \qquad \mu = \frac{dS}{dz} = \gamma\, z$$

From the latter formula follows:

d) $S = \dfrac{\gamma}{2} z^2$

In formula c) the value of ΣR is taken equal to S, meaning that the rainfall sum after t days with the given probality which determines p and t will just saturate the soil, bring the amount of drainable moisture to its maximum and build up the groundwater table to the soil surface. This is defined by the equations:

$$S = pt^q \qquad \frac{\gamma z_s^2}{2} = pt^q \qquad \frac{dS}{dt} = \frac{pt^{q-1}}{q}$$

In the latter formula z_s defines the water level at the surface with respect to the drains and represents therefore the depth of drainage.

Now several ways of calculation of the required drain spacing are open. It is possible to equate:

g) $$-\frac{dS}{dt} = \frac{az_s + bz_s^2}{L^2} \quad \text{and} \quad \frac{dS}{dt} = \frac{pt^{q-1}}{q}$$

In this case a drain spacing is calculated, which gives a runoff at the moment that the water table just has risen to the soil surface, equal to the intensity of the rainfall at the t^{th} day according to the probability function. This means that $\Sigma R = S_{max}$ and that the increase in ΣR per unit time dS/dt at that moment just can be drained away.

This means that for $z = z_s$:

e) $$L^2 = q\left(\frac{az_s + bz_s^2}{pt^{q-1}}\right)$$

But another solution is also possible. For this solution it is assumed that a period with average rain intensity $\overline{R}$ is succeeded by a heavy rainfall ΣR over t days. For reasons of easy mathematical solution it is assumed that the quantity ΣR of rain has fallen at the beginning of the t days. In the preceding period the $\overline{R}$ mm rainfall has built up a water level z_a above the drains and a matching amount of drainable water S_a. The t-day period adds an amount S_r of drainable moisture and a rise of the water level to z_s.

Now the requirement is made, that in the same t days the drainage system is able to drain away the amount of rainfall ΣR. The probability of recurrence of transgressions of this requirement – at which the water rises above the soil surface or the water cannot be drained away in the same t-days – is the dependent variable.

The latter solution requires the integration of the discharge, which is obtained as follows.

From formulae b) and d) the discharge sum can be deducted:

$$-L^2\frac{dS}{dt} = az + bz^2 \quad \text{or} \quad -L^2 d\left(\frac{\gamma\, z^2}{2}\right) = az + bz^2$$

$$-\gamma\, L^2\, z\frac{dz}{dt} = az + bz^2 \qquad\qquad -\frac{\gamma\, L^2}{b}\,\frac{dbz}{a + bz} = dt$$

From the formulae follows:

f) $$\frac{0.4343\ b}{\gamma\ L^2}(t_2 - t_1) = \log\left(\frac{a + bz_1}{a + bz_2}\right)$$

With the formulae b), c), d) and f) the design requirements can be solved.

As an example of the formulation of the requirements the following problem is raised:

A field under the influence of the average winter rain will have a discharge of $\bar{R} = 3$ mm, a groundwater level $z_a = 70$ cm and a matching amount of drainable water S_a. Then in a time interval of $t = 5$ days and a probability K of 0.5 %, due to rain an amount of moisture S_r, which can be calculated from these latter values, is added to the drainable moisture and a groundwater level z_s will occur. A further requirement is that the rainfall sum $\Sigma R = S_r$ has to be drained away in the same time interval $t = 5$, so that after t days the original equilibrium is restored, at which the original water level z_a a discharge of $\bar{R} = 3$ mm is obtained. Finally the time of $t = 5$ days has to indicate an optimum. An interval $t < 5$ will mean a water level that has not yet reached the soil surface. An interval $t > 5$ will indicate that the water level recedes from the soil surface because the drainage capacity exceeds the increase of the rainfall sum for an incremental increase in time.

As will be demonstrated, the drainage requirements mentioned are not simultaneously achievable. More requirements are aimed at than the number which will give a full solution. It is of importance, that one is conscious that often the practical requirements are converging on a generally desired goal, but that not all the requirements are converging on the same goal. One wishes more than is possible. An example will be worked out which shows the effect of these conflicting requirements and which at the same time gives an instance of how a solution is calculated.

The following values for the parameters are taken:

In formula b) $a = 10$ $b = 0.1$ which are valid for dS/dt in mm and L in m.
In formula c) $p = 14.3$ $q = 0.57$ for t in days, R in mm and the probability $K = 0.5$ %

In formula d) $\gamma/2 = 0.02$

The general parameters have values: $R = 3$ mm $\quad t = 5$ days
$z_s = 70$ cm $\quad R = S_s - S_a$

The available formulae allow to calculate the drain spacing in three different ways.

According formula f):

$$L^2 = \frac{0.4343\ bt}{\gamma \log \dfrac{1 + b/az_s}{1 + b/az_a}} = \frac{0.4343 \times 0.1 \times 5}{0.04 \log \dfrac{1 + 0.01 \times 70}{1 + 0.01\ z_a}} \qquad (1)$$

According to formulae b) and g):

$$L^2 = \frac{az_s + bz_s^2}{pt^q} \times qt = \frac{10 \times 70 + 0.1 \times 4900}{14.3 \times 5^{0.67}} \times 0.57 \times 5 \qquad (2)$$

According to formulae b), c) and d):

$$L^2 = \frac{az_a + bz^2}{\overline{R}} \qquad z_a^2 = z_s^2 - \frac{2pt^q}{\gamma}$$

$$z_a^2 = 4900 - \frac{2 \times 14.3 \times 5^{0.67}}{0.04} = 55.8^2 \qquad L^2 = \frac{10 \times 55.8 + 0.1 \times 3115}{3} \qquad (3)$$

The result according these three equations is:

(1) $L = 12.02$ m (2) $L = 9.75$ m (3) $L = 17.02$ m

By varying the probability of recurrence K or the storage γ, an identical solution of the 3 equations for L can be obtained, which proves that one requirement was mentioned above the number which allows a solution. For a value of $\gamma = 0.0164$ for instance a solution for $L = 9.75$ m is obtained. A smaller probability of surpassing the rainfall sum ΣE would also provide an identical solution of the three formulae for L at more than twice the rainfall sum used in this calculation and would produce for L the value of 12.02 m.

As was already stated, the drainage requirements which were mentioned are overdefining the problem. The calculation can only lead to a clear result if one knows exactly what one aims at. A disadvantage of the solution is, that the assumption has to be made that the rainfall ΣR is concentrated at the beginning of the time interval t. It means that the solution becomes less applicable the longer the time interval is. It is, however, not difficult to write down the differential equation for an even distribution of the rainfall ΣR over the interval t. The necessary mathematical treatment of such a formula makes this solution uninteresting however. A solution by trial and error would in that case probably be the most advisable.

27. Summary

The knowledge about water management relations has grown in the latter years to such an extent, that the limiting factor is no longer situated in the field of analysis. The accuracy of the design and the remunerativity of the project becomes more and more linked up with the accuracy of the constants used and the way in which the available knowledge is integrated. If comprehensive planning is advocated strongly these days, it is seldom realized that this means optimizing complicated functions with scores of unknowns, it also means to get the better of a propagation of errors which requires a careful adjustment of observations to available knowledge.

This assessment of the correct constants is, as is commonly known in mathematical circles, a formidable job. It will not be solved by neglecting the difficulties of a correct design, or the deterioration of costs-benefit ratio rising from the omittance of the specialized knowledge needed to solve just these complicated problems.

It is neither an advantage to study the details of the integrated problem along lines of scientific technique without considering how to combine the results into a practical solution, or to seek solutions with a vast amount of constants which may be difficult to derive on the construction site. It also is of slight avail to further the knowledge of one aspect of an integrated problem and neglect the large errors or lack of details in other aspects. The accuracy of the ultimate result depends on the largest error in the chain of relations.

Finally the computer is often presented as the solution of all difficulties. It should, however, not be forgotten that, besides the fact that these instruments are not generally available, a computer requires correct formulae and constants. And in case simplifications are applied, it is more difficult to control what is going on inside the computer, than to check deviations during a non-mechanized elaboration.

From these considerations follows, that it still is useful to select formulae which constitute a compromise with respect to wieldiness, accuracy and transferability. There is a strong need for simplified methods to adjust constants. Further ways of integrating the results of scientific reasoning should be divised, which lead to methods which are able to deal with practical – often multivariate – units of actual project construction. There are not yet many projects carried out in which the computer is used along lines resulting from physical and plant physiological reasoning. It should be remembered that the linear relations which are often used in computer programs do not preclude that the trees grow into heaven or that benefits decrease below the costs.

The main point of concern with respect to the transfer of the water management experience is, however, that so little use is made of the vast body of knowledge available during the design period or on the construction site. This gap will have to be bridged from both sides, scientific as well as practical.

In this article, the principal idea was to construct a method of solving water management problems along lines which can be followed by anybody who has only the simplest means available of soil moisture research, of yield determination and of mathematical elaboration. Much attention was therefore given to curve fitting techniques, to adjustment of constants and to methods of graphical solution. It is thought to be of considerable importance that a project designer is able to select the best value of a constant from a number of more or less reliable observations. He also should be able to design his own nomograms, in order to get an insight in complicated relations. He finally should master methods to calculate what influence a small variation of an independent variable has on the dependent variable and to check the accuracy of the relations by considering the credibility of the result at extreme values, which often allow the best comparison with practical experience.

The paper aims at showing how formulae can be joined to obtain an integrated solution. The elaboration of alternative solutions is done by varying the values of the parameters of those properties which are accessable to change by technical means. The constants of the drainage formula constitute an example. They enable one to insert a continuous infinite sequence of alternatives in the solution. These alternatives can be expressed in units of discharge, of evaporation, storage, groundwater depth or of plant production as desired and can give a sufficient basis for the assesment of the optimum desirability of any special case in the continuum of differing project designs.

The solution can be shaped to deal with more details by adding other formulae for further aspects. The considerations with respect to accuracy warn, however, that refinement of some details looses its importance as soon as the overall accuracy is limited by other details, known or unknown. It is, for instance, known that rainfall measurements are rather inaccurate. A lack in our knowledge is also how to deal adequately with surface runoff. Further it cannot be expected that the inhomogeneity of the soil profile will be taken up in great detail in the calculations of the optimum alternative. If this is so, these points will set a limit to the overall accuracy and beyond a certain number of aspects further items cannot be taken up in the integrated study with much expectation of improving the project.

The aim of the present paper was, to show that water management studies are based on 6 formulae for

1. Plant response: $\left(1-\frac{q}{Q}\right)\left(1-\frac{q}{a_1 v_1^k}\right)\left(1-\frac{q}{a_2(P\text{-}v)^b}\right)\ldots = F_1$

2. Discharge: $\left(1-\frac{D}{a(z-S_1)}\right)\left(1-\frac{D}{b(z-S_2)}\right) = F_2$

3. Evaporation: $\left(g-\frac{E_r}{E_o}\right)\left(A-\frac{E_r}{v^l - v^l_{wp}}\right) = F_3$

4. Soil moisture profile: $(1-e^{-\alpha z})\left(1+\frac{z_o - {}^1/\alpha}{z_o + z_s}\frac{v_c}{k_o}\right) + \frac{z}{z_o + z_s}\frac{v_c}{k_o} =$
$= (1 - e^{-\alpha\psi})$

5. Desorption curve: $\psi = \frac{G(P^* - v)^n}{v^m}$

6. Rainfall frequency: $\Sigma R = pt^r$

From the use of these 6 formulae, each relation between moisture conditions and plant response can be derived. Simplified formulae were discussed especially with respect to the equations 4 and 5. Further, some examples of calculation were given.

It has been tried to find a compromise between all the conflicting requirements as correctly optimizing of results, of hours of work for design against construction and of the degree of attention available for the physical-physiological background of the project on the one hand and the necessary attention for organization or for the social changes to precede or to follow the project on the other. It has further been tried to find an elaboration of water management problems for areas where practical experience, derived from actual projects, is insufficiently available. The project designer, often working with a minimum of scientific and mathematical help, has in such cases to solve the problems on his own. The methods here explained were developed to give him some tools for his job.

It is considered that the basic relations and the mathematical treatment of methods to be used in such cases require an increased attention along the lines as set forth in the preceeding pages.

COMMISSIE VOOR HYDROLOGISCH ONDERZOEK T.N.O.

Verslagen en Mededelingen

No. 1. Verslagen van de Technische Bijeenkomsten 1-6 (with summaries in English, avec des résumés en français), 1952.

1. Het waterhuishoudkundig onderzoek in de Rottegatspolder
2. De watervoorziening der gewassen I
3. Waarneming van grondwaterstanden
4. Lysimeteronderzoek in Nederland
5. De watervoorziening der gewassen II
6. Het vraagstuk van de verzouting van grond- en oppervlaktewater in Nederland

No. 2. Verslagen van de Technische Bijeenkomsten 7-10 en Verslag inzake het verdampingsonderzoek in de Rottegatspolder over de jaren 1947-1952 (with summaries in English, avec des résumés en français), 1955.

7. Bewerking van regenwaarnemingscijfers
8. Modelonderzoek van grondwaterstromingen
9. Metingen en verbeteringen in het stroomgebied van beken
10. Geo-electrisch bodemonderzoek

No. 3. Verslagen van de Technische Bijeenkomsten 11-12 (with summaries in English, avec des résumés en français) en Rapport inzake de lysimeters in Nederland (in de Engelse taal), 1958.

11. Watervoorziening van zandgronden
12. Kwaliteitseisen van oppervlaktewater

No. 4. Verdampingssymposium Agrohydrologisch Colloquium C.O.L.N. en Rapport inzake de lysimeters in Nederland II (with summaries in English), 1959.

No. 5. Verslagen van de Technische Bijeenkomsten 13-14 (with summaries in English), 1960.

13. Grondwaterstanden en grondwaterbeweging in de Nederlandse zandgronden
14. Het water in overzadigde grond

No. 6. Verslag van de Technische Bijeenkomst 15 (with summaries in English, avec des résumés en français), 1961.

15. Enige onderzoekingen ten behoeve van de grondslagen van het beheer van de Rijn, het IJsselmeer en het Zeeuwse Meer

No. 7. Verslag van de Technische Bijeenkomst 16 (with summaries in English), 1962.

16. Het droge jaar 1959

No. 8. Verslag van de Technische Bijeenkomst 17 (with summaries in English), 1963.

17. De stromingswetten van het grondwater en de toepassing daarvan in de praktijk

No. 9. Verslag van de Technische Bijeenkomst 18 (with summaries in English), 1963.

18. Wateroverlast

No. 10. Steady flow of ground water towards wells, compiled by the Hydrologisch Colloquium, 1964.

No. 11. Verslag van de Technische Bijeenkomst 19 (avec des résumés en français, mit Zusammenfassungen in Deutsch), 1964.

19. Geo-hydrologische karteringen

No. 12. Water balance studies, Proceeding of Technical Meeting 20, 1966.

No. 13. Recent trends in hydrograph synthesis, Proceeding of Technical Meeting 21, 1966.

No. 14. Regenwaarnemingscijfers (II), Verslag van de Technische Bijeenkomst 22, en Rapport inzake de lysimeters in Nederland (III) (with summaries in English), 1968.

COMMITTEE FOR HYDROLOGICAL RESEARCH T.N.O.

Proceedings and Informations

No. 1. Proceedings of Technical Meetings 1-6 (with summaries in English), 1952.
1. Invcstigations into the water balance of the Rottegatspolder
2. The water supply for crops I
3. Observations of groundwater levels
4. Investigations by dreain gauges in the Netherlands
5. The water supply for crops II
6. The problem of the increasing salinity of ground and surface water in the Netherlands

No. 2. Proceedings of Technical Meetings 7-10 and Report on the evaporation research in the Rottegatspolder 1947-1952 (with summaries in English), 1955.
7. The study of precipitation data
8. Model research on groundwater flows
9. Measurements and improvement works in basin of brooks
10. Geo-electrical research

No. 3. Proceedings of Technical Meetings 11-12 (with summaries in English) and Report on the lysimeters in the Netherlands (in English), 1958.
11. The water supply of sandy soils
12. Quality requirements for surface waters

No. 4. Evaporation Symposium and Report on the Lysimeters in the Netherlands II (with summaries in English), 1959.

No. 5. Proceedings of Technical Meetings 13-14 (with summaries in English), 1960.
13. Groundwater levels and groundwater movement in the sandy areas of the Netherlands
14. Water in unsaturated soil

No. 6. Proceeding of Technical Meeting 15 (with summaries in English), 1961.
15. The regimen of the Rhine, the Ysselmeer and Zealand lake

No. 7. Proceeding of Technical Meeting 16 (with summaries in English), 1962.
16. The dry year 1959

No. 8. Proceeding of Technical Meeting 17 (with summaries in English), 1963.
17. The laws of groundwater flow and their application in practice

No. 9. Proceeding of Technical Meeting 18 (with summaries in English), 1963.
18. Water nuisance

No. 10. Steady flow of ground water towards wells, compiled by the Hydrologisch Colloquium (in English), 1964.

No. 11. Proceeding of Technical Meeting 19 (with summaries in French and German), 1964.
19. Geo-hydrological cartography

No. 12. Water balance studies, Proceeding of Technical Meeting 20 (in English), 1966.

No. 13. Recent trends in hydrograph synthesis, Proceeding of Technical Meeting 21 (in English), 1966.

No. 14. Precipitation data (II), Proceeding of Technical Meeting 22, and Report on the lysimeters in the Netherlands (III) (with summaries in English), 1968.