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Moisture requirements of crops and rate of moisture depletion of the soil

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The availability of moisture for a crop can best be defined by the number of hours during which the climate will allow the leaves to evaporate at the same rate as the roots are able to supply water. The stomata close as soon as the availability becomes limiting factor. The assimilation stops till the potential evapotranspiration decreases and an equilibrium is possible again. During the hours of the day with maximum radiation, the moisture supply may be insufficient (fig. 1). The severeness and length of a hampered water supply may follow from hydrological reasoning. In this way the problems of moisture requirement, moment of moisture replenishment or rate of moisture depletion may be solved. The formula is evolved in the following way (VISSER, 1962).

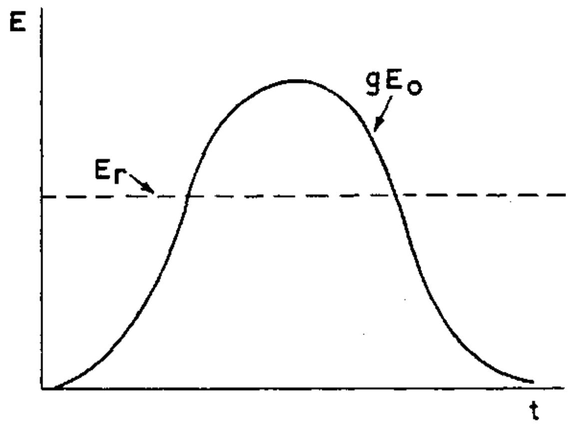

Fig. 1. During the daily variation of the potential evapotranspiration, gE_o, the capacity of the soil to provide water is only during part of the time sufficient. Assimilation will be hampered during the midday hours when the soil moisture availability is too low

The formula for soil moisture movement

The plant extracts moisture from a small soil cylinder around each root. The flow follows the formula of Darcy

$$q = k . F . d\psi/dx \qquad (1)$$

The quantity of flow. The amount of moisture q flowing through a concentric circle around h_r roots per plant depends on the area outside these circles, but inside the line of demarcation between the extraction area of the root under observation and the other roots. Taking this line of demarcation as a circle, the radius of this soil cylinder is d. The moisture extraction at a radius x is then equal to

$$q = \pi (d^2 - x^2)\, h_r\, E \tag{2}$$

Here E is the extraction per unit area, and h_r the number of roots per plant.

The capillary conductivity. The conductivity of the capillary zone k_c depends on the soil moisture stress (WESSELING, 1961; WIND, 1961) according

$$\log k_{c2}/k_{c1} = -m \log \psi_2/\psi_1 \tag{3a}$$

In this equation ψ_1 is the stress at which the soil is still entirely saturated, but where an increase in stress will bring the first quantity of air into the largest pores (fig. 2). This stress at air entry point is given the symbol ψ_e. The pores are entirely filled with water and the permeability of the soil is equal to the saturated permeability k_s. For the permeability we may therefore write

$$k_c = \left(\frac{\psi_e}{\psi}\right)^m k_s \tag{3b}$$

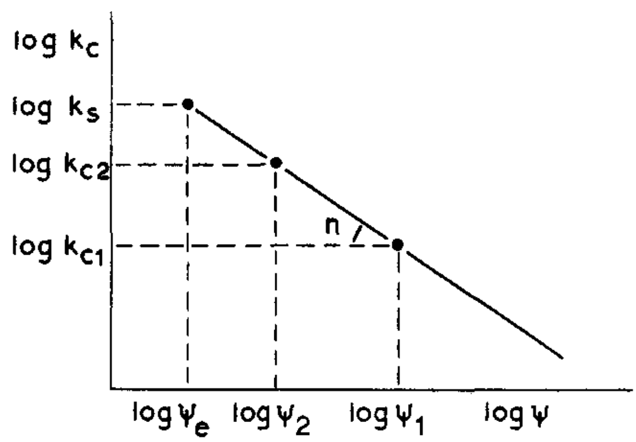

Fig. 2. The curve for the relation between the capillary permeability, k_c, and the moisture tension, ψ, is approximately a straight line with inclination n, it runs through the point for the saturated conductivity, k_s, and the ψ_e for the point where saturation is just met

The area of flow. The area of flow F is the area of the cylinder with radius x and length of the cylinder equal to the average length l_r of the roots. Therefore F is equal to

$$F = 2\pi . x . l_r \tag{4}$$

The plant and root density. The density of h plants per unit area and h_r roots per plant may be brought in connection with the total length l_r of the roots per plant, the radius d of the cylinder of extraction and the thickness L of the layer of extraction.

The total volume of the layer of extraction per unit area is L. This volume is occupied by $\pi d^2 l_r h_p$ volume units of the cylinder of extraction. But it is also equal to the number of plants h_p multiplied by the plant area O and the thickness L of the layer, or the number of roots $h_p h_r$ times the root area πd^2 times the thickness of the layer L.

Therefore:

$$L = h_p O L = \pi d^2 l_r h_p = \pi d^2 h_p h_r L \tag{5a}$$

We will need:

$$\frac{l_r}{h_r} = L \tag{5b}$$

In further formulae l_r and h_r will be expressed in h_p, L and d.

The integration. The values for q, k and F can be inserted in the equation of Darcy. This leads to the differential equation:

$$\pi (d^2 - x^2) E = \left(\frac{\psi_e}{\psi}\right)^m k_s \; 2\pi . x . L \frac{d\psi}{dx} \tag{6a}$$

$$\frac{E}{2 L k_s \psi_e^m} \int_r^d \left(\frac{d^2 - x^2}{x}\right) dx = \int_{\psi_r}^{\psi} \frac{d\psi}{\psi^m} \tag{6b}$$

$$\frac{E}{2 L k_s \psi_e^m} \left\{ d^2 \ln \frac{d}{r} - \frac{(d^2 - r^2)}{2} \right\} = \frac{1}{(m-1)} \left(\frac{1}{\psi_r^{m-1}} - \frac{1}{\psi^{m-1}} \right) \tag{6c}$$

Now we combine:

$$\frac{4 L k_s \psi_e^m}{(m-1) d^2 \left\{ \ln \left(\frac{d}{r}\right)^2 - 1 + \left(\frac{r}{d}\right)^2 \right\}} = A' \tag{6d}$$

in which equation $(\frac{r}{d})^2$ may be neglected, because of its small value.

The negative sign of moisture stress. The soil moisture stress is in reality a negative potential, but will mainly be used as a positive value to facilitate calculations. In formula (6c) in the right hand term for ψ the quotient may be constructed

$$\frac{\psi_{\ell}^{n}}{\psi^{n-1}} \text{ equal to } \left(\frac{\psi_{\ell}}{\psi}\right)^{n-1} \psi_{\ell} \qquad (7)$$

The same may be done for ψ_r. The term between brackets in formula (7) is not subject to change in sign when changing the expression for the moisture stress from negative to positive. Only the first power of ψ_{ℓ} determines the sign of the right hand side of equation (6c). But instead of changing the sign of this side of the equation, we may also change the sign of E in the left hand part.

The transition to moisture content. The moisture stresses ψ and ψ_r are less convenient in research or practical application because the formula will be used to predict moisture quantities. The ψ_r will be used to link the groundwater flow to the flow through the plant and it will be eliminated in this process.

For ψ an expression may be used, which describes the desorption curve as (FONCK, 1962):

$$\frac{1}{\psi} = \frac{G' v^{a}}{(v_m - v)^{\ell}} \qquad (8a)$$

where G', p and q are parameters, v_m is the pore space and v the moisture content in volume per cent.

Often the interval in v which really matters, is rather small and in those cases in the denominator $\bar{v}$, the moisture content in the middle of that interval may be taken instead of v. This simplifies the formula to

$$\frac{1}{\psi} = \frac{G'}{(v_m - \bar{v})^{\ell}} v^{a} = G v^{a} \qquad (8b)$$

The quantity of moisture. Now the moisture content v may be expressed as the quantity of moisture I in the root zone, of which the thickness L is mentioned in formula (5). By inserting

$$v = I/L \qquad (9a)$$

we obtain:

$$\frac{1}{\psi} = G \frac{I^{a}}{L^{\ell}} \qquad (9b)$$

The resulting equation. By applying all these expressions in formula (6c) and lumping the constants of formulae (6d) and (9b) together to the new parameters $A = GA'$ and $m = (n-1)a$ we may write:

$$\psi_r^{m-1}\left\{\frac{A}{L^m} I^m - E\right\} = A \qquad (10)$$

In the next step a number of further constants will be brought into the formula. The way in which the constants of the separate relations make up the parameters of the ultimate relation will be discussed later.

Moisture movement in the plant

The movement of moisture through the plant may be considered as flow along a flow path made up from p consecutive lengths l_{si} each with separate values for conductivity k_i, area of flow F_{pi} and gradient $\frac{\psi_2 - \psi_1}{l_{si}}$.
We therefore may write:

$$\begin{aligned} \psi_2 - \psi_1 &= q\, l_{s1}/k_1 F_{p1} \\ \psi_3 - \psi_2 &= q\, l_{s2}/k_2 F_{p2} \\ \psi_4 - \psi_3 &= q\, l_{s3}/k_3 F_{p3} \\ \hline \psi_u - \psi_1 &= q\left(\frac{l_{s1}}{k_1 F_{p1}} + \frac{l_{s2}}{k_2 F_{p2}} + \ldots\ldots \frac{l_{su}}{k_m F_{pu}}\right) \end{aligned} \qquad (11.1)$$

For each part of the flow path, q may be considered to have the same value being the total amount of water extracted by the plant. The sum of terms of flow resistance $l_{si}/k_i F_{pi}$ may be lumped together in a conductivity constant $1/\alpha$. The pressure difference $\psi_u - \psi_1$ is the difference between the pressure in the atmosphere ψ_a and the pressure ψ_r at the root interface, already mentioned in the discussion on soil moisture movement. Therefore we may write:

$$\alpha(\psi_a - \psi_r) = q \qquad (11b)$$

From this equation ψ_r is used to eliminate the same value from the formula of soil moisture flow, see the discussion on the transition to moisture content. Further ψ_a will not be an observable value and has to be expressed in other measurable magnitudes. Finally the value of q will have to be expressed per unit area.

The evapotranspiration. In case the evapotranspiration should not be hampered in any way by an insufficient availability of the soil moisture, the pressure ψ_r at the root interface should be zero. In this case the evapotranspiration will be equal to q_o per plant or gE_o per unit area, with g a reduction constant to be discussed later.

Combining formula (11b) with the expression for q_o at zero value of ψ_r, or

$$\alpha \psi_a = q_o$$

we obtain

$$\psi_r = \frac{q_o - q}{\alpha} \tag{11c}$$

The crop and root density. The density of the crop may be related to the density of the root system as well as to the density of the stems, see formula (5).

A number of h_p plants per unit area means that the relation holds

$$E = h_p q \quad \text{or} \quad q = \frac{E}{h_p} \qquad \text{and} \quad q_o = \frac{gE_o}{h_p} \quad \text{or} \quad \psi_r = \frac{gE_o - E}{h_p \alpha} \tag{12}$$

The formula for evapotranspiration

By inserting the expression for ψ_r from formula (12) in formula (10), the equation for evapotranspiration is solved. The result is, expressed in moisture contents:

$$(gE_o - E)^{n-1}(Av^m - E) = B$$

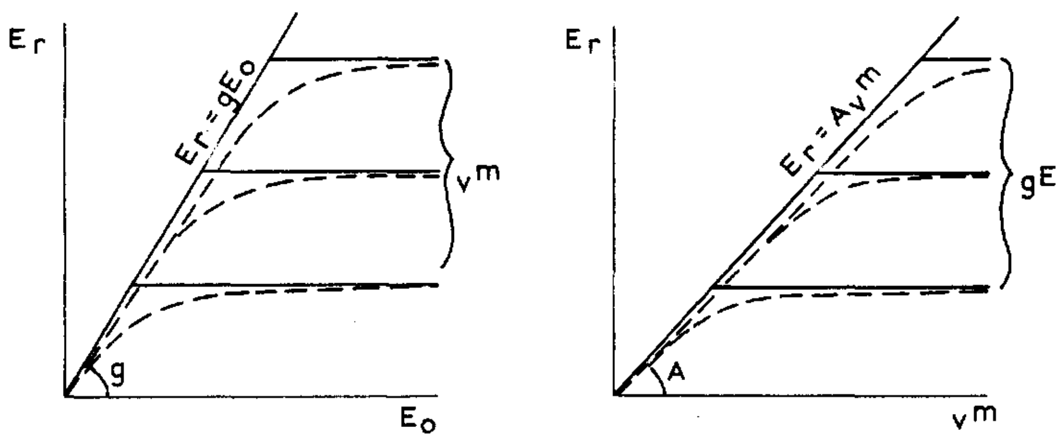

Fig. 3. The expression, given as formula (13), describes a three dimensional relation. Depicted is the projection resp. on the E_r - E_o plane and on the E_r - v^m plane. The asymptotes in these diagrams are the projections of asymptotical planes

Expressed in quantities I of moisture in a layer L:

$$\left(g E_o - E\right)^{n-1}\left(A \frac{I^m}{L^m} - E\right) = B \tag{13}$$

In this expression B consists of constants from the two equations mentioned (fig. 3).

In this equation five parameters are present, namely g, m, n, A and B. By collecting the constants, the way in which the parameters are built up may be shown and their meaning discussed.

g is a reduction factor with which the calculated or observed evaporation has to be multiplied to obtain the real evaporation of a crop with zero water tension at the root interface. This factor contains therefore a reduction factor to obtain potential evapotranspiration, it embraces the influence of exposition, of inflow of lateral heat and of insufficient closure of the canopy.

n is the slope of the line giving the relation between the logarithms of the capillary conductivity and the moisture stress according formula ([illegible]), assuming that this relation is linear for logarithmic scales. An average value of 2 is a good first guess.

m is obtained by multiplying (n-1) and a. Here a is the exponent of formula (8a), assuming that the logarithms of ψ and v are linearly related over the relevant interval of v. The slope of this line equal to a. A value of 3 is generally a good first estimate.

A is built up of a constant, a capillarity description Q and a flow equation R (see formula 6d).

$$A = C\,Q\,R \qquad C = 4(n-1)$$

$$Q = \mathcal{G}\,\psi_e^{n}\,\delta L$$

$$R = \frac{1}{d^2\left\{\ln\left(\frac{d}{r}\right)^2 - 1\right\}} \tag{14}$$

The A value is clearly an availability factor and $A I^m$ the availability function.

B is found by multiplication of the availability factor A by P, a plant factor, which in turn consists of a crop density value h_p according to formula (12) and a flow resistance factor α.

$$B = A\,P \qquad P = (\alpha h_p)^{m-1}$$
$$\alpha = 1/\sum_{i=1}^{u} (l_{si}/k_i F_{pi}) \tag{15}$$

The value $P = (\alpha h_p)^{m-1}$ is a definition of the uptake ability of the crop, which increases by an increasing number of plants h_p, by an increase in permeability k_i and in area of the vessels F_{pi}. On the other hand P decreases by increase of the length of the flow path $\sum l_{si}$ through the plant.

The formula defines the process of moisture flow in the most functional way as:

$$(gE_o - E)^{m-1}\left(\frac{I^m}{L^m} - \frac{E}{A}\right) = P \tag{16}$$

where the parameter for availability A and that for plant ability for uptake P are separated.

The equation is depicted by curves for different values of gE_o as given in fig. 2, the well-known reaction of the evapotranspiration on the soil moisture content (MAKKINK and VAN HEEMST, 1962; HALLAIRE, 1961).

Influence of moisture variations with depth

The formula for the influence of the moisture content on evapotranspiration was evolved on the assumption of extraction of the moisture from a layer of L units depth and uniform moisture content.

The availability factor. The solution for p layers with different moisture contents may be derived from formula (6c). We may write:

$$E = (E_1 + E_2 + \ldots E_p) = \frac{A_1 + A_2 + \ldots A_p}{\psi_r^{m-1}} - \left(\frac{A_1}{\psi_{s1}^{m-1}} + \frac{A_2}{\psi_{s2}^{m-1}} + \ldots \frac{A_p}{\psi_{sp}^{m-1}}\right) \tag{17}$$

The formula expresses that the evapotranspiration is equal to the sum of moisture extractions from the successive layers. An assumption is made that the tension at the root interface in the successive layers will not vary to a great extent and may be taken equal for all layers. This assumption depends on the experience that B is of very small importance for the moisture extraction, meaning that α is not of much consequence, apparently due to a transport capacity of the plant that is far larger than the usual transporting capacity of the soil. The tension in the root zone will be held constant by internal moisture transport through the plant from the part of the root with low surface tension to the part with high tension.

From formula (17) we derive:

$$\psi_r^{m-1}\left\{\left(\frac{A_1}{\psi_{s1}^{m-1}}+\frac{A_2}{\psi_{s2}^{m-1}}+\dots\dots\frac{A_p}{\psi_{sp}^{m-1}}\right)-E\right\}=\left(A_1+A_2+\dots\dots A_p\right) \quad (18$$

The uptake ability factor. In P the value of h_p - see formulae (5a) and (15) - is constant for the successive layers because the number of plants is the same irrespective of the layer of extraction. The value of α, (see formula (11), varies because from the lower parts of the flow path upward the quantity of flow q will change in the direction of higher layers.

When the extraction of the w successive layers is given by q_1, q_2 ...... q_w and the total extraction by q, formula (11a) may be rendered into

$$\psi_u-\psi_r=q\sum_1^u\left(\frac{l_{si}}{k_i F_{pi}}\right)-\sum_1^w\left(\frac{(q-q_j)\,l_{sj}}{k_j F_{pj}}\right) \quad (19)$$

which means that in the first term the amount of flow is considered constant over the whole of the flow path, but in the second term the quantity $q - q_j$, the excess of what really is extracted from the successive lower layers of the soil, is subtracted again.

The difference between a homogeneous and a varying moisture content of successive layers is, that α will decrease with an amount $\Delta\alpha$ equal to

$$\Delta\alpha=\frac{1}{q}\sum_1^w\left\{\frac{(q-q_j)\,l_{sj}}{k_j F_{pj}}\right\} \quad (20)$$

Now the experience is that the value of P is of little importance for the evapotranspiration so that this correction $\Delta\alpha$ of α may be ignored, or may be incorporated in a slightly lower value of α.

The resulting formula. The values, derived for A and B, mean that the equation describing evapotranspiration from a non-homogeneous moisture profile is given by the formula

$$(gE_o - E)^{n-1}\left\{\sum_1^n (A_i v_i^m) - E\right\} = P\sum_1^n (A_i) \tag{21}$$

If the parameters A are known, the evapotranspiration E and the extraction E_i per unit area from each layer, and therefore the remaining amount of moisture v_i may be calculated, as will be discussed under the rate of extraction.

Moisture characteristics for practical use

Formula (21) defines a number of practical characteristics, which may be used for assessment of the moment to supply irrigation water, of the amount of water to be supplied and of the rate of moisture depletion to be expected.

Three simplifications of the formula are usually made. The value of n is generally set at 2. The expression (8a) for the soil moisture depletion curve is simplified to formula (8b). The value of B is small and of little importance to the value of E calculated. Therefore B is assumed to be zero, which splits the formula into two parts:

$$E = gE_o$$
$$E = A_1 v_1^m + A_2 v_2^m + \ldots\ldots A_p v_p^m \tag{22}$$

The error is largest at the point of intersection of the two asymptotes, given by formula (22) and has a value equal to $\sqrt{B}$ which may amount to 5% of gE_o.

The simplification into formula (8b) is at higher values of v no longer admissable and deserves closest attention.

The point of zero moisture flow. By taking E equal to zero in formula (21) the moisture content at zero flow is found to be

$$A_1 v_1^m + \ldots\ldots\ldots A_p v_p^m = \frac{(A_1 + \ldots\ldots A_p)P}{gE_o} \tag{23}$$

It should be remembered that this point of zero flow is not the same as wilting point which has a physiological but not a well-defined physical meaning.

The lower limit of potential evapotranspiration. The point of intersection of the two asymptotes of formula (22) describes the lowest moisture content at which the plant evaporates at potential rate gE_o. This occurs at:

$$A_1 v_1^m + \ldots\ldots A_p v_p^m = g E_o \tag{24}$$

It should be born in mind that this point is not equal to field capacity which is not considered to be dependent on E_o.

The moisture content at a constant ratio of real to potential evapotranspiration

A reduction of a percentage f of the potential evaporation gE_o will occur at a certain distribution of the soil moisture over the profile, given by:

$$A_1 v_1^m + \ldots\ldots A_p v_p^m = f g E_o \tag{25}$$

The value of f determines the number of midday hours during which the evaporative capacity of the atmosphere surpasses the amount of moisture that the plant can extract from the profile. It determines the number of hours of hampered assimilation and may serve as an agricultural characteristic of the need for water suppletion. At deeper layers, the value of A may decrease considerably and the matching moisture content may transgress the range where the simplification of formula (8b) is still acceptable, while in higher layers no need to use formula (8a) may exist.

The depth of extraction. The extent of the daily extraction is calculated in a separate way for moisture distributions which in formula (25) yield a f-value equal respectively below unity. For the drier soils with f below unity, each layer supplies its share to the evapotranspiration E according to its availability function equal to

$$E_1 = A_1 v_1^m \qquad E_p = A_p v_p^m \tag{26}$$

For the wetter soils with f equal to unity each layer supplies water according the fraction that its own availability is from the total availability

$$E_1 = \frac{A_1 v_1^m}{A_1 v_1^m + \ldots\ldots A_p v_p^m} g E_o \qquad E_m = \frac{A_p v_p^m}{A_1 v_1^m + \ldots\ldots A_p v_p^m} g E_o \tag{27}$$

The rate of extraction below the limit of potential evaporation. The rate at which a certain quantity of soil moisture is taken up by the crop is constant for the wetter soils, and is gradually reducing with time for the drier soils. The extraction in the upper layers is, however, more rapid than in the deeper layers.

The rate of extraction for the drier soils is found by an integration using the expression:

$$E_i = -\frac{dI_i}{dt} = A_i \left(\frac{I_i}{L}\right)^m$$

$$t = \frac{1}{m-1} \frac{L^m}{A} \left\{ \frac{1}{I_{it}^{\,m-1}} - \frac{1}{I_{io}^{\,m-1}} \right\} \tag{28}$$

Here I_{io} is the moisture content in the i^{th} layer at the beginning of the period of depletion at a time t = 0. At time t the moisture content has decreased to I_{it}. To calculate the matching evapotranspiration E for each layer, I_{it} has to be solved and inserted in formula (22).

The rate of extraction above the limit of potential evaporation. The extraction of moisture from wetter soils is more complicated, due to the fact that the depletion of the successive layers are mutually dependent. The rate of extraction will be given for a two-layer profile. The expression to be integrated is given by formula (27) with $E_1 = -dI_1/dt$ and $E_2 = -dI_2/dt$.
We may write:

$$\frac{A_1 I_1^m + A_2 I_2^m}{A_1 I_1^m}\, dI_1 = \frac{A_1 I_1^m + A_2 I_2^m}{A_2 I_2^m}\, dI_2 = -g E_o\, dt \tag{29}$$

The first two terms may be integrated to find the expression for the relation between I_1 and I_2, which reads:

$$\frac{1}{A_1 I_{1t}^{\,m-1}} = \frac{1}{A_2 I_{2t}^{\,m-1}} - \gamma$$

$$\gamma = \frac{1}{A_1 I_{01}^{\,m-1}} - \frac{1}{A_2 I_{20}^{\,m-1}} \tag{30}$$

Here I_{10} is the moisture present in the first layer at t = 0, I_{2t} is the moisture left in the second layer at a time t. The value of the integration constant γ depends on the moisture content at the start.

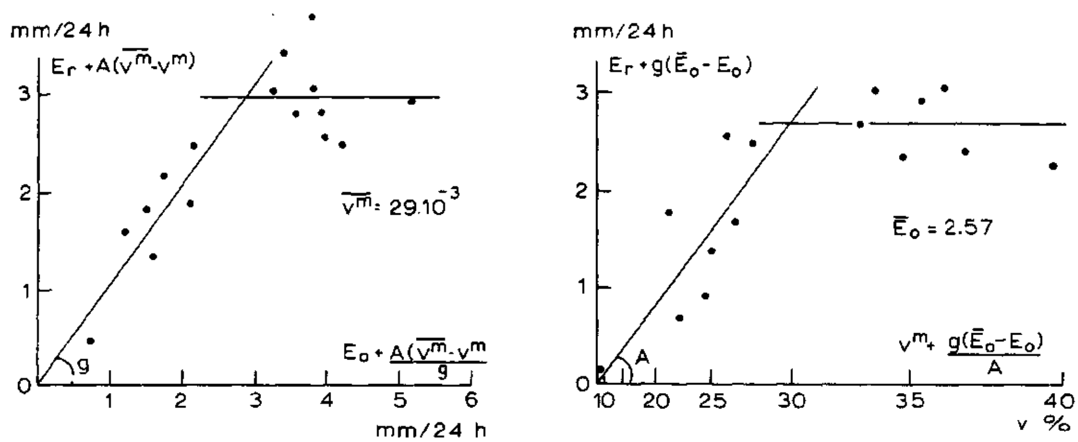

Fig. 14. Result of the field investigations with a neutron probe into the evapotranspiration of an orchard on river levee loam, after correcting for differences in v^m (left hand figure) and E_o (right hand figure).

m = 3.04 A = 120 g = 1.04

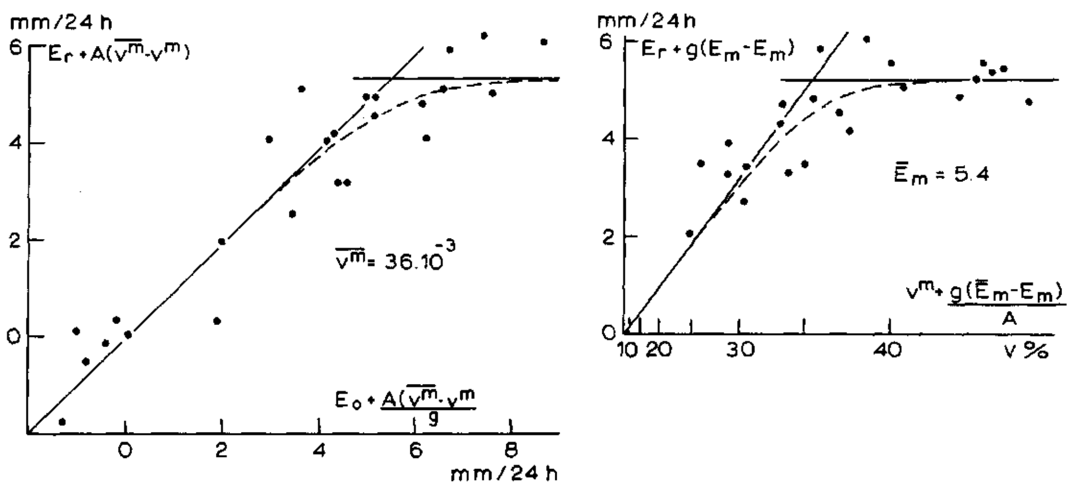

Fig. 15. Result of lysimeter investigations into evapotranspiration for a grass sod on sandy soil, after correcting for differences in v^m (left hand figure) and E_o (right hand figure).

m = 3 A = 110 g = 1.07

Eliminating I_2 from the first term of formula (29) with formula (30) and combining with the third term gives the formula to be integrated, reading:

$$\left\{1+\left(\frac{A_1}{A_2}\right)^{\frac{1}{m-1}}\frac{1}{\left(1-\gamma A_1 I_1^{\,m-1}\right)^{m/m-1}}\right\}dI_1=-g\,E_o\,dt$$

The solution of this integral is:

$$g\,E_o t = I_{10}\left\{1+\frac{1}{\left\{\frac{A_2}{A_1}\left(1-\gamma A_1 I_{10}^{\,m-1}\right)\right\}^{1/m-1}}\right\}-I_{1t}\left\{1+\frac{1}{\left\{\frac{A_2}{A_1}\left(1-\gamma A_1 I_{1t}^{\,m-1}\right)\right\}^{1/m-1}}\right\} \quad (31)$$

The matching value of I_{2t} is found with formula (30). In the formulae (28) and (31), no allowance is made for capillary redistribution of moisture between the layers. For high moisture contents and large gradients between layers, formula (31) may give devergences between the actual and the calculated moisture profile.

Experimental results

The experiments were concentrated on the determination of the moisture requirements of orchards. The moisture content was measured with neutron probes, the evaporation determined as moisture loss during two successive moisture content determinations after correcting for subsoil run-off. Due to the wet climate the moisture content in the successive layers were highly correlated so no influence of separate layers could be detected.

In fig. 4 the result of the experiment in one of the orchards is given, in which the influence of differences in E_o are eliminated. The limited accuracy of the determination of the evapotranspiration, as a difference between the quantities of water in the whole soil profile at successive moments, accounts for the scatter of the observations.

A comparison of some results from orchards and grasslands does not show much of an influence of the crop on the moisture constants, as might be expected from the small influence of the plant factor P. Influence of the soil is large and the size of the root surface may also be important, but the latter could not be determined in the orchards. Variations in uptake ability will depend more on the soil than on properties of special crops.

The values found for the constants were for one of the orchards:

$$g = 1.08 \qquad m = 3.00 \qquad A = 88 \qquad B = 50.10^{-3}$$

Here E is expressed in mm per day and v in parts per unit. For a value of gE_o equal to 3 mm this means that:

zero moisture flow occurs according formula (23) at:		v = 8.3%	
lower limit of potential evapotranspiration, formula (24) at		v = 32.4%	
extraction rate from 32.4% downward, formula (28)			
	during 10 days	v = 27.7%	E = 1.87 mm/day
	during 50 days	v = 19.2%	E = 0.62 mm/day
	during 100 days	v = 14.9%	E = 0.29 mm/day

This soil may supply moisture for a very long time, but after a month the evapotranspiration is reduced to 1 mm, after 100 days to 0.3 mm.

It will be clear that such a reduction of the moisture uptake in an upper layer will induce extraction from deeper layers. The time interval is in this case, for the sake of showing the applicability of formula (28), extrapolated beyond the range of the data studied.

Summary

The moisture requirements of crops follow from hydrological, plant physiological, soil scientific and climatological reasoning. These influences can partly be determined by assessing the moisture content of the soil and the potential evaporation. A further group of factors, as moisture retaining capacity and permeability of the soil may, but generally will not, be determined. A third group dealing with root density, is not easily determined and is accounted for by determination of constants in which several influences are lumped together. The specific plant properties have only a minor in-

fluence on the moisture requirement and may be neglected. Formulae are given to determine the relation between the soil moisture content and the actual evapotranspiration, the moisture content at which potential or zero evapotranspiration occurs, to determine the moisture extraction for successive layers and the rate of extraction for rainless periods of prolonged duration.

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