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The moisture consumption of plants described as a hydrological phenomenon

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Evapotranspiration is considered to depend on three factors: the capillary movement of water through the unsaturated soil to the root surface, the transmissibility of the stomata and the evaporative capacity of the atmosphere.

It has proved to be possible to evolve a quantitative description of the flow of moisture through the soil and the plant. This flow is a function of the availability of the soil moisture and the consumptive needs of the plant depending on the potential evaporation due to radiation. In the formula, parameters of the soil, the plant and the climate describe how evapotranspiration is determined by the co-operating factors. The elaboration which leads to the formula is given elsewhere (VISSER, 1962, 1963 a, b and c). Here we will deal particularly with the parameters depending on the properties of the plant

The flow equation

The formula uses as starting point a description of the extraction of moisture from a cylinder of soil around each root. The moisture flow converges to the soil-root interface. The flow into and through the plant may be considered as Poisseuille flow through a number of flow sections, each with a specific length l_p, a constant conductivity k_p and cross sectional area of flow F_p. To one of these sections, representing the stomata, special consideration will be given.

The influence of the soil moisture availability V_i, the evaporative capacity of the atmosphere E_o and the flow resistance in the stomata $\Delta s = l_s/k_s F_s$ is given by the formula:

$$g^{m-1}(E_o - E^*)^{m-1}\left(\sum_{i=1}^{u} A_i V_i - g E^*\right) = \sum_{i=1}^{u} A_i \left(\frac{h_p}{s+\Delta s}\right)^{m-1} \qquad (1)$$

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In fig. 1 the influence of g, E_o and V on the evapotranspiration E* as given by formula (1) is depicted.

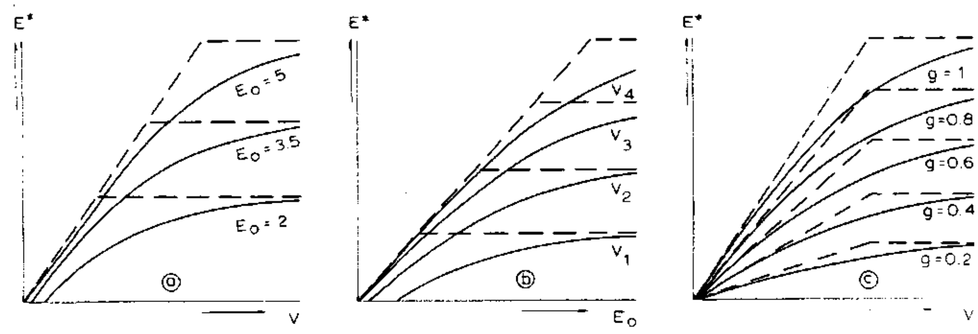

Fig. 1. Change in E_o - fig. a - and V - fig. b - have the effect of changing the horizontal asymptote of the curve. Change of g - fig. c - changes both asymptotes.

Meaning of the symbols

The parameters and constants appear in the formula as single values or lumped together, with the following meaning and composition:

E_o = evaporation of open water, for which pan values or calculated values according to Penman are used;

g = a reduction factor, allowing for 1) discrepancies between the values used and the real values of E_o, 2) for differences in climatological exposition of the site and 3) for differences in flow resistance in the plant;

E* = evapotranspiration only dependent from the soil moisture content and more specifically not influenced by the properties, accounted for by g. The real evapotranspiration E is equal to gE*;

V = availability level of soil moisture content according:

$$V = \frac{1}{\psi^{n-1}} = \left(\frac{G\, v^a}{(v_{max} - v)^b} \right)^{n-1} \qquad (2)$$

G, a and b are constants of the desorption curve; v_{max} the apparent pore space and v the soil moisture content. ψ stands for the soil moisture stress at a moisture content v. Generally n has the value 2 so that n-1 will be unity. The value of a is of the order of 3. The value of b may change from 0 to 10 or higher and is very variable;

A_i = availability factor for the i^{th} layer of the profile with:

$$A = \frac{0.3^{m} \cdot 4}{m-1} \frac{k_s}{r^{m}_{max}} \frac{L}{d^2\left\{\ln\left(\frac{d}{r_p}\right)^2 - 1\right\}} \tag{3}$$

Here L is the thickness of each layer, d the radius of the cylinder of moisture extraction around each root and r_p the average radius of the roots. All values may vary from layer to layer;

$\frac{k_s}{r_{max}^n}$ = measure for the unsaturated permeability, derived from the relation:

$$\frac{k_c}{k_s} = \left(\frac{r_{max}}{r_c}\right)^m \tag{4}$$

This relation between the capillary conductivity k_c, the saturated conductivity k_s, the maximum pore size r_{max}, the size of the largest pore r_c containing moisture and an exponent n describes the change in capillary conductivity with changing moisture content and changing size of the largest water filled pore. The value of k_c vanishes by elimination, the r_c is substituted by the value of the availability level V;

h_p = number of plants per unit area;

s,Δs = the flow resistance in the plant according the Darcy formula for moisture flow

$$S = \sum_{j=1}^{p-1} \frac{l_{pj}}{k_{pj} F_{pj}}$$

$$\Delta S = \frac{l_s}{k_s F_s} \tag{5}$$

In this formula l stands for the length of the section of the flow path, k for the conductivity and F for the cross sectional area of the j^{th} section or for the s^{th} section, the section of the stomata. For s the sum of the flow resistance is taken, with the exception of the flow resistance Δ s of the stomata.

All units should be expressed in a consistent system, especially the formula (7), obtained by integration.

The influence of the plant parameters

The plant influences the magnitude of the evapotranspiration by the size and distribution of its root system, represented by d and r_p of the parameter A, by the transmissibility k_sF_s of the stomata contained in the parameter Δs and by the value of g.

The stomata

The closing of the stomata is described by a zero value of the transmissibility k_sF_s in formula (5) and therefore by an infinite value of Δs. This makes the right hand side of equation (1) equal to zero. This means that also the left hand side of equation (1) becomes zero. This requires alternatively:

a) $\sum_{i=1}^{u} A_i V_i - gE^* = 0$

b) $E_o - E^* = 0$

c) $g = 0$

Alternative a) and b) mean that as a consequence of the closing of the stomata the observations should shift from the curve to the two asymptotes of the curve. This shift from the curve to the asymptote, however, is not likely to depict the result of closing of the stomata correctly, for it means an increase in evapotranspiration (fig. 2).

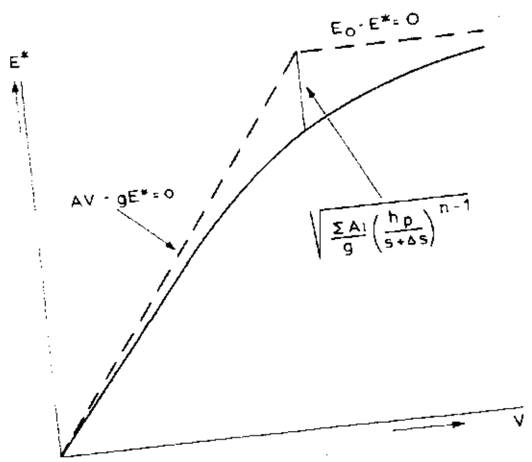

Fig. 2. An infinite value of Δs, describing closed stomata, with constant value of g, makes the right hand side of formula (1), depicted by the vertical distance between the point of intersection of the asymptotes and the curve, equal to zero. The value of g cannot be constant, for it would mean an increase in evapotranspiration. A decrease in transmissibility k_sF_s can only mean a decrease in g and with $E = gE^*$ a decrease in E

The only sensible solution is that a decrease in the transmissibility $k_s F_s$ means a decrease in the value of g and because of the relation $E = gE^*$, a decrease in the real evapotranspiration E.

Now by decreasing value of the availability $\sum$ AV, the stomata will close more and more and the successive evapotranspiration values will shift to curves with decreasing value of g (fig. 3a). Up to now, not much of such curving to the right of the lower end of the experimental curves has been observed (fig. 3b).

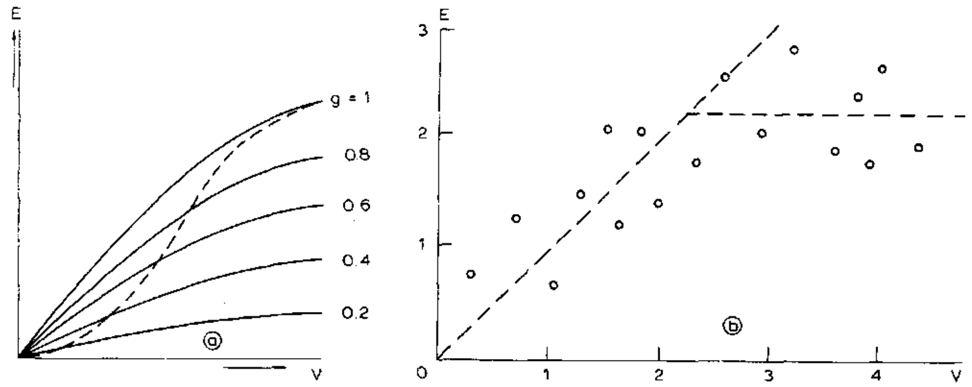

Fig. 3. In case the stomata would have an active influence on evapotranspiration, superimposed on the influence of the moisture content of the soil, this would mean that experimental curves would be found, shifting from a higher value of g to lower ones. The s-shaped dotted curve of fig. 3a might be expected. Not much evidence for such influence can be obtained, however, from experimental data (fig. 3b)

An autonomous influence of the stomata was not to be expected. The stomata regulate the loss of water to a value as nearly equal to the uptake of water by the roots as is possible. Thereby the turgor of the plant is maintained to the utmost. The explanation of the activity of the stomata cannot be found in the stomata or the plant, but in the moisture situation in the soil. The influence of the stomata therefore does not constitute an independent variable in the formula for the evapotranspiration.

The root system

The significance of the size and distribution of the root system is described by the availability factors A_i for the successive layers of the profile.

From formulae (1) and (2) may be deduced that the ratio A_i/A_j between the availability factors of two layers may be computed from the soil moisture contents of these layers by solving the differential equation:

$$\int_{v_1}^{v_t} \frac{1}{A_i}\left(\frac{(v_{max}-v_i)^b}{G\,v_i^{a}}\right)^{n-1} dv_i = \int_{v_1}^{v_t} \frac{1}{A_j}\left(\frac{(v_{max}-v_j)^b}{G\,v_j^{a}}\right)^{n-1} dv_j \qquad (6)$$

The constants G, a, b and n follow - see formulae (2) and (4) - from soil tests. We assume a = 3, b = 1 and n = 2, whilst G cancels out, taking the case that the soil profile is homogeneous. Integration and rearrangement leads to the formula:

$$\alpha_{ij} = \frac{A_j}{A_i} = \frac{\left(\frac{1}{v_{1i}}-\frac{1}{v_{ti}}\right)\left(\frac{1}{v_{1i}}+\frac{1}{v_{ti}}-\frac{2}{v_{max}}\right)}{\left(\frac{1}{v_{1j}}-\frac{1}{v_{tj}}\right)\left(\frac{1}{v_{1j}}+\frac{1}{v_{tj}}-\frac{2}{v_{max}}\right)} \qquad (7)$$

For other values of a, b and n the solution will differ. As i^{th} layer is taken the layer with the most reliable observations of moisture extraction. As soil sampling data two or more successive data should be taken, without rain or other moisture supply in the interval.

When the values of α_{ij} are known, the value of $A_{1 \ldots u}$ are found as $A\alpha_{i,\,1\ldots u}$ by calculating the values of $\sum \alpha V$ and $\sum \alpha$. A follows from:

$$A = \frac{E}{\sum_{j=1}^{u} \alpha_{ij} V_j - \frac{\sum_{j=1}^{u} \alpha_{ij} P}{g E_0 - E}} \simeq \frac{E}{\sum_{j=1}^{u} \alpha_{ij} V_j} \qquad (8)$$

Here F stands for $(h_p/s + \Delta s)^{n-1}$ but this value is small and may be neglected so that the second term of the denominator may be omitted. Observations with small values of gE_0 - E and an increasing magnitude of the second term have slight indicative value for the computation of A and may be left out.

Example

An example of calculation is given for a homogeneous soil, with a recently sown grass sod. The frequency of observation of the soil moisture content in layers of 20 cm was once in a fortnight. The moisture content should be expressed in a per unit scale.

The results for α_{1j} in table 1 clearly show how quickly the capacity α_{ij} of the plant to extract water diminishes with increasing depth. This decrease is sufficiently close to a geometrical series with an argument of 0.225. This means that in this case the availability factor of the next deeper layer of 20 cm is 22.5% of the factor of the higher layer (fig. 4).

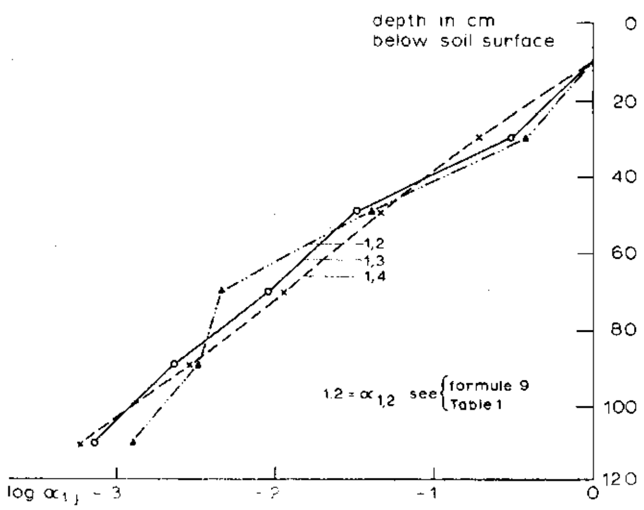

Fig. 4. The log of α_{1j} for a homogeneous soil and the three consecutive sampling data of table 1 show a linear relation with the depth below soil surface, which proves tha the moisture extraction capacity of the root system decrease according to a geometrical series

The ratio of the α-values to each other is proportional to the number of roots n per unit area according:

$$\alpha_{1j} = \frac{n_j}{n_1} \left(\frac{\dfrac{4}{\ln \pi r^2 n_1} - 1}{\dfrac{4}{\ln \pi r^2 n_j} - 1} \right) \qquad (9)$$

as comparison with formula (3) may show. This relation enables one to compute activity constants for unit length or unit weight of the plant roots in relation to depth.

There is in fig. 4 some scatter in the results for successive layers or sampling data. This may be due to errors in the moisture determination - here neutron probe readings - as well as to capillary movement between

Table 1

Date		26/5	12/6	[illegible]	[illegible]	26/5	12/6	27/6	[illegible]
			V_1				$1/V_1$		
[illegible] time		1	2	3	4	1	2	3	4
Layer	1	0.210	0.180	[illegible]	0.095	4.76	5.56	[illegible]	10.53
	2	0.270	0.240	[illegible]	0.170	3.70	4.17	5.26	[illegible]
	3	0.425	0.390	0.340	[illegible]	[illegible]	2.56	[illegible]	[illegible]
	4	0.470	0.455	[illegible]	0.320	2.13	2.20	[illegible]	[illegible]
	5	[illegible]	0.465	[illegible]	0.410	[illegible]	[illegible]	[illegible]	2.44
	6	0.465	0.460	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

	$\left(\frac{1}{V_t} - \frac{1}{V_1}\right) = g$			$\left(\frac{1}{V_t} + \frac{1}{V_1} - 4\right) = h$		
	2 - 1	3 - 1	4 - 1	2 + 1	3 + 1	4 + 1
1	[illegible]	[illegible]	5.77	6.32	[illegible]	11.39
2	0.47	[illegible]	[illegible]	[illegible]	[illegible]	5.58
3	[illegible]	[illegible]	[illegible]	[illegible]	1.25	[illegible]
4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	[illegible]	[illegible]	0.10	[illegible]	0.35	0.40

	$g\,h$			$\alpha_{1j} = \frac{(gh)_j}{(gh)_1}$		
	2,1	3,1	4,1	2,1	3,1	4,1
1	5.056	24,758	65.143	1.0000	1.0000	1.0000
2	[illegible]	[illegible]	12.164	0.3598	0.3125	0.1867
3	0.191	0.761	2.768	[illegible]	[illegible]	0.0425
4	0.023	[illegible]	1.260	0.0045	0.0094	0.0193
5	0.016	0.056	0.187	0.0032	0.0023	[illegible]
6	0.006	0.018	0.040	[illegible]	0.0007	[illegible]

soil layers without the plant as mediator. It also may be due to an increase or decrease with time in the number of active roots, or to penetration of the roots to deeper layers. Work is in progress to get to a better understanding of the extractive capacity of the plant and of the errors involved in the determination of this plant property.

Summary

The way in which real evapotranspiration depends on the evaporative capacity of the atmosphere, the soil moisture content and the density and distribution of the root system, can be described by an equation based on the formula of Darcy.

The extractive capacity of the root system decreases rapidly with increasing depth. In a homogeneous soil this decrease may be described by a geometrical series.

Up to now no autonomous effect of the stomata could be shown. They apparently only regulate the evapotranspiration to be as equal to the uptake of water as possible. The explanation of the regulative activity of the stomata has to be found in the changing moisture situation in the soil and the evaporative capacity of the atmosphere. The stomatal aperture is no free variable in the process and in the given formula.

This formula enables one to elucidate the influence of environmental factors on evapotranspiration and the influence of moisture extraction by the plant on the shape of the moisture profile. It is also possible to calculate a number of evaporation parameters, which consist of soil, plant and site constants with a definite physical meaning. The plant activity constants, often not so easy to determine, may be computed by inserting the soil constants in the complex evaporation parameters.

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