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Soil moisture content and evapotranspiration

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A number of rules are used to determine the moisture content of the soil below which application of water is desirable, and the content above which the moisture is considered to be freely available. Field capacity and wilting point are the end marks on this measuring stick. There is not much scientific evidence that these moisture contents have the importance attributed to them.

By evolving a theory of moisture flow through the capillary zone a different concept is obtained. The proof of this elaboration is given elsewhere (VISSER, 1963a). The evapotranspiration is governed by a few constants, each made up of a number of well defined plant- and soil properties, which may be determined in the field as complexes or in the laboratory as soil parameters. An accurately weighing lysimeter was constructed to test the equation in detail (VISSER, 1962). The observations communicated here were made to study the water requirements of orchards.

The formula

The basic assumption is that evapotranspiration causes a vertical Poisseuille flow through the vessels of the plant and a horizontal capillary flow through the soil to the roots, which are acting as sinks. Simple mathematical reasoning leads^{to} the formula:

$$(g E_o - E)^{m-1} \left(\frac{C}{\psi^{m-1}} - E \right) = D \quad (1)$$

Changing from the moisture stress ψ to the moisture content v , and transforming the capillary permeability parameter k_c into the saturated permeability k_s is done according the following formulae (details to be published elsewhere):

$$\frac{1}{\psi} = g \frac{v^a}{(v_m - v)^2} \quad (2)$$

simplified: $\frac{1}{\psi} = g v^a \quad (3)$

$$k_c = \left(\frac{\psi_e}{\psi} \right)^m k_s \quad (4)$$



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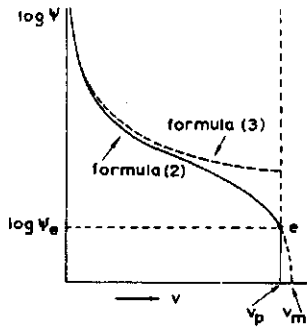


Fig. 1. The soil moisture depletion curve may be described over the lower range of moisture contents by the simplified formula (3). v_p is ^{the} real-, v_m the virtual pore space of formula (2), e the air entry point with tension ψ_e of formula (3)

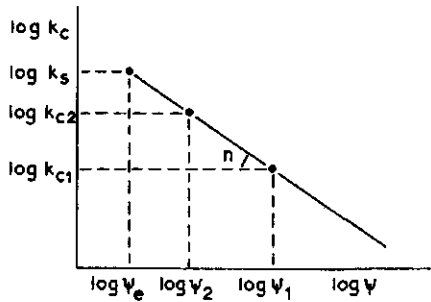


Fig. 2. The saturated conductivity k_s , combined with the moisture tension ψ_e at air entry point, is a point on the straight line relation between the log of the capillary conductivity k_c and the log of the matching moisture tension ψ , given by formula (4)

This leads to:

$$(g E_o - E)(A v^m - E) = B \quad (5)$$

The simplification of formula (2) to formula (3) consists of the assumption that in the lower range of moisture contents that is of importance for evaporation studies the denominator of formula (2) may be taken to be constant. The simplification of formula (1) to (5) is further based on the experience that in clay and loamy soils the exponent n in formula (4) may be taken equal to 2, so the exponent $n-1$ in the first term of formula (1) will vanish. For coarse soils the value of n may be higher than 2, but for non-scientific purposes the simplified formula still may give a good fit with the experimental data.

Meaning of the symbols

g, E_0 . A constant g allows for discrepancies between the real and the applied value of the evaporative capacity of the atmosphere E_0 . It may correct systematic deviations due to lateral inflow of heat, deviations of pan-readings, not closed canopies and so on. Value generally near unity.

$\psi, \psi_a, k_c, k_s, v_m, G, a, b, m$. The relation between the logarithms of the capillary conductivity k_c and the soil moisture stress appears in many cases to be described with sufficient accuracy by a straight line which relates the saturated conductivity k_s , at air entry point with tension ψ_e , with the capillary conductivity k_c and the corresponding moisture tension ψ . The line has an angle of inclination n . This relation only holds up to the value ψ_e , the air entry point, at which stress the soil changes from ^{unsaturated} saturated to ~~unsaturated~~ saturated and the conductivity is no longer a function of ψ . The capillary conductivity should be expressed in terms of the saturated permeability k_s at ψ_e . This is obviously described by formula (4). In formula (2), the formula for the desorption curve, v_m represents ~~the~~ maximum moisture content and is ^{nearly} equal to the pore space; G, a, b and m are constants.

$A = C Q R$ The value A is made up of three parts C, Q and R . C is a constant, Q is a soil influence and R is a root influence.

$C = 4/(n-1)$ The soil influence consists of the factor G from formula (3) as a simplification of the equation for the desorption curve (2). The values k_s, n and ψ_e were mentioned earlier

$Q = G L k_s \psi_e^m$

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

The root factor includes the thickness L of the root zone. The natural logarithm of $(d/r)^2$ contains the ratio of the radius d of the cylinder from which each root extracts water to the radius r of the root itself.

The value of B is made up from the hydrological factor A and the plant factor P .

$B = A P$ The value of A was discussed before. In B a plant factor is present, equal to the inverse of the sum of values $l_{si}/k_i F_{pi}$. This expresses the resistance of the water flowing through the successive length l_s of each part i of the flow path in the plant, where each part is described by its length l_{si} , its conductivity k_i and its area of flow F_{pi} . The density of the crop in the field h_p is given by the number of plants per

$P = \left(\frac{h_p}{\frac{l_{s1}}{k_1 F_{p1}} + \frac{l_{s2}}{k_2 F_{p2}} + \dots + \frac{l_{su}}{k_u F_{pu}}} \right)^{m-1}$

unit. This density is inserted to bring P on a scale of unit area.

The way in which, as discussed above, the climate-, soil-, root- and plant properties are grouped together in the parameters g , A , B and m of formula (5) follows from a mathematical elaboration. The soil properties may be determined from soil samples by determining the desorption- and the conductivity function. Climate-, root- and plant properties might also be approximated by direct determination. It is, however, easier to determine the combination constants A , B , g and m from field observations without much consideration for the splitting up of these constants in their details.

The graphical representation of the parameters

Assuming that the value of $p = 2$ and of $n = 3$, which gives in many cases a fair agreement between formula (5) and the observations, the data of E_r are plotted according this formula against the third power of v or against E_o . The formula gives a number of curves for each value of E_o or of v^m as depicted in fig. 3. These curves can be brought to coincidence by parallel shifting in the direction of the oblique asymptote. In this way the curves can be condensed to a single curve for the mean value of E_o . This curve has an oblique asymptote with an angle of inclination A or g and a vertical distance equal to \sqrt{B} between the curve and the point of intersection of the two asymptotes.

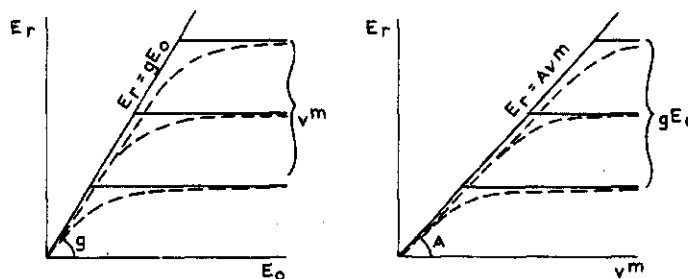


Fig. 3. Formula (5) may be depicted as given in this diagram with v^m or gE_o as third variable. The curves for different values of this variable may be unified by shifting them to coincidence along the oblique asymptote

Now this value of B is very small and may be taken zero. This means that approximately the actual evapotranspiration E may be calculated according formula (6a) or (6b), of which two the lower value holds. The two formulae are:

$$E = Av^m \quad (6a) \quad \text{and} \quad E = gE_o \quad (6b)$$

It should be remembered that at high values of v the simplified formula (3) may no longer hold and formula (2) should be used.

Experimental results

On six fields, three orchards and three grasslands, moisture content determinations were made with a neutron probe at regular intervals. Corrections for eventual moisture loss to deeper layers were made. The differences in moisture content of the upper 50 cm layer, divided by the length of the time interval, provided the mean daily evapotranspiration. This value, together with the moisture content and with the potential evapotranspiration according to an evaporation pan, provided the following data for the constants. See also fig. 4.

Crop and soil		g	m	A	$A^{1/m}$	$B \cdot 10^{-3}$
Orchard						
river levee soil	1	1.08	3.00	88	4.45	50
	2	0.90	2.90	88	4.69	26
	3	1.04	3.04	120	4.83	25
Grasslands						
river wash clay		0.90	2.75	47	4.07	50
dune sand		1.00	3.75	158	3.85	30
humiferous sand		1.20	3.00	115	4.86	25

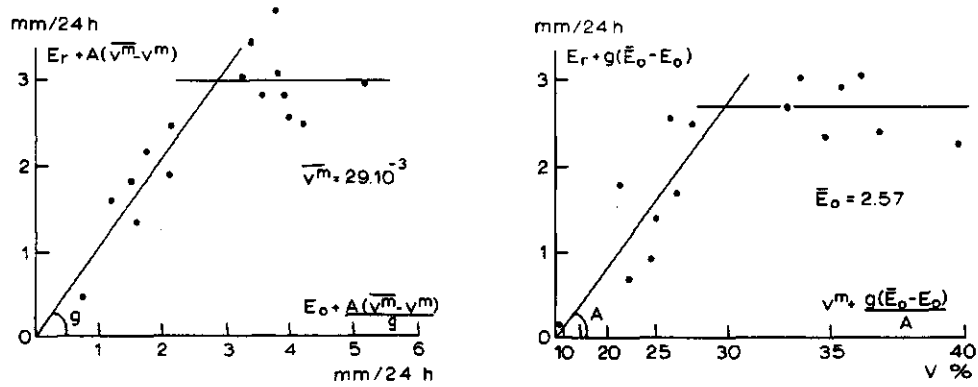


Fig. 4. Example of the diagrams used to determine the values of the parameters of formula (5) for an orchard on river levee loam

The data show that a low value of A is partly compensated by a high value of m . This has as consequence that $A^{1/m}$ is a more constant parameter and a better yardstick to compare soil- and root properties with respect to moisture flow.

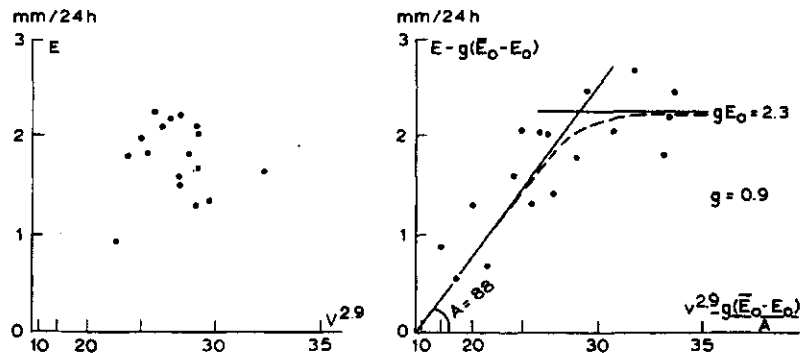


Fig. 5. Only correlation of the evapotranspiration with both E_0 and v can explain which of these factors acted as limiting factor for the value of E . Left, not corrected, right with correction for differences in E_0

A graphical representation in fig. 5, with and without correction on variations in gE_o , but in both cases plotted against v^m , gives an insight in the limited value of the soil moisture content alone as an indication of the magnitude of evapotranspiration. Considering that v^m is linearly related to the inverse values of the soil moisture stresses, the same holds for the moisture stress. The meaning of a moisture content with respect to evapotranspiration depends on the evaporative capacity of the atmosphere.

The limit of availability of soil moisture

The moisture content at which a crop is no longer provided sufficiently with readily available moisture, may be defined by the percentage of the potential evaporation, that the actual evapotranspiration is able to attain. Apparently it would be correct reasoning to deduce the limit of ready availability from the number of hours of daylight during which the plant cannot take up CO_2 because, due to insufficient supply of moisture the stomata are closed. This number of hours, $a+b$, expressed as a percentage of the total number of hours of assimilation t might serve as a functional expression of the availability of the soil moisture and the still acceptable lowest limit of the moisture content (fig. 6). Our formula cannot yet serve as such an expression, because at very short time intervals the moisture relation is essentially non-steady. The formula assumes, however, steady flow. It will, however, be easy to visualize what the ultimate aim of the hydrological approach should be.

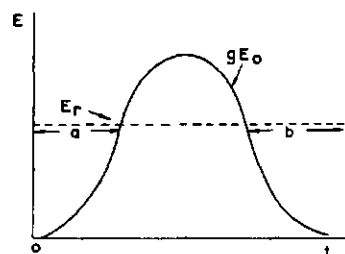


Fig. 6. The best expression for the level of availability of soil moisture will be the percentage of daylight hours, $a+b$, during which the evapotranspiration E_r , only dependent on the soil moisture content, surpasses the potential evaporation gE_o . The latter only depends on the climatological situation

Using the formula for this non-steady state problem, it may be expected that the values calculated are too high for the moisture contents and too low for the moisture stresses. The results when calculating according to the formula show, however, how the moisture status at which a certain per unit reduction α of evapotranspiration and assimilation may be expected, varies with the evaporative capacity of the atmosphere.

E_0	Moisture content at limit of ready moisture availability					
	1	2	3	4	5	6
$\alpha = 1.0$	26.4	29.7	33.1	36.1	38.8	41.1
0.8	22.3	26.8	30.3	33.3	35.8	38.0
0.6	20.0	24.2	27.5	30.2	32.5	34.5
0.4	17.5	21.3	24.0	26.4	28.4	30.1
	Log moisture stress at limit of ready moisture availability					
$\alpha = 1.0$	3.9	3.6	3.2	2.8	2.4	1.5
0.8	4.2	3.85	3.5	3.2	2.9	2.6
0.6	4.5	4.1	3.8	3.5	3.3	3.05
0.4	4.75	4.3	4.1	3.9	3.7	3.5

The value of $\alpha = 0.8$ means that $E = 0.8 E_0$. The table shows that at low values of E_0 the evapotranspiration is unhampered, even at fairly high moisture stresses, but at high values of E_0 the soil only seldom will contain enough moisture to supply the plant with all the water that might be transpired, if transpiration only depended on the climate.

The concept of availability of moisture between pF 2.7 and 4.2 holds somewhere between a potential evaporation of 3 to 5 mm. This concept, however, has only a remote bearing on the actual flow process and allows insufficiently for the influences of soil-, root-, plant- and crop parameters.

Summary

The moisture content at which the evapotranspiration decreases with a certain percentage - be it high or low - depends on the evaporative capacity of the atmosphere. At high potential evaporation, the moisture content above which evapotranspiration is unhampered will be considerably higher than at low potential evaporation. The amount of available moisture has therefore a variable lower limit. A theory of moisture transport through the soil and the plant has been evolved (VISSER, 1963b), and agrees well with data determined in the field. This theory seems to be a better guide in determining the date of application of irrigation water than the concept working with field capacity and wilting point.

The constants for capillary-, root- and plant properties together with the constants for crop density- and climatological properties are discussed. The way in which these constants should be combined to obtain the evaporation parameters is stated.

Literature

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