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Water economy of a fictive crop

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Abstract

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A computer program for simulation of the water economy of a fictive crop is described. Although all processes have been extremely simplified, the results agree, quantitatively, with what is known about the transpiration process. Changes in parameters and given curves make it possible for the influence of several external and internal factors to be estimated.

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Each analysis should be followed by a synthesis

Van Herk 1946

Introduction

The water economy of a fictive crop was simulated for a better understanding of the relation between actual evapotranspiration (AE), potential evaporation (PE) and moisture content of the soil (SM). Theoretically, actual evapotranspiration follows the Law of Limiting Factors (Blackman, 1905): on moist soil potential evaporation determines evapotranspiration, while with a soil moisture deficit the moisture imposes a limitation. Makkink & van Heemst (1965) established such a relation for a grass sward; Visser (1965) provided a mathematical background for the relation between these three factors. Holmes & Robertson (1963) gave the relation AE = f (PE, SM) for wheat grown in cylinders of soil; Denmead & Shaw (1962) did the same for maize grown in pots in the middle of a field of maize. With this relation in the form AE/PE = f(SM), Baier & Robertson (1966) and Baier (1969) calculated the trend of evapotranspiration throughout the growing season. Makkink & van Heemst (1970) applied the relation AE = f(PE, SM) in a continual calculation of the watertable and the components of the water balance of a cropped area for 2 years. This relation was established beforehand with a digital dynamic simulation of a fictive crop (corresponding to this study). The decision for this pure digital study was made to eliminate the disturbances of precipitation and crop growth on this relation.

Moreover, the weather could be standardized and the parameters changed separately and according to requirement. To keep the algorithm as simple as possible and so shorten the calculation time, the physical description of evaporation and water absorption from the soil was simplified. It is unlikely, that the effect of the simplification changed the results distinctly. In any case the results corrrespond qualitatively to the physiology of transpiration. Experimental testing of the results is impossible, since non-growing crops do not exist.

The technique of digital dynamic simulation is according to Forrester (1961, 1970, 1971).

The system

This study concerns a fictive green crop that covers the soil completely but does not grow. Its parameters are further defined. For simplicity the whole crop above and underground was considered as one compartment for water. Since conductivity within the plant is great compared to that between soil and plant (Allerup, 1961; Kramer, 1938) the crop was not divided into layers. Since precipitation (rainfall and dew) affects transpiration a compartment for adhering water was added, covering the crop on the outside. The soil is the third compartment and concerns the rooted layer to a depth above which a homogenous root system is assumed to have the same absorbing capacity as the actual root system. This depth is called the effective rooting depth.

The system is located between atmosphere and subsoil (Fig. 1). The water contents and transports have been indicated as follows (figures between brackets indicate the equations):

Contents (mm)

A	adhering water (1)
P	water content of the plant (2)
R	available water content of the effective root zone (3)

Transports (mm/h(ours))

ATA	precipitation rate (4)
AP	absorption from adhering water (10)

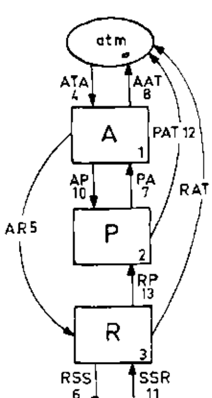

Fig. 1. Scheme of the system. Ellipses represent reservoirs with irrelevant contents; rectangles symbolize reservoirs with relevant contents and capacity. Arrows indicate transports of water. The figures refer to equations, letters are explained in the text. atm. = atmosphere.

Fig. 1. Skemo de la sistemo. Elipsoj reprezentas tenujojn kun nesciendaj enhavoj; rektanguloj simbolas tenujojn kun sciendaj enhavoj kaj kapacitoj. Sagoj indikas transportojn de akvo. La ciferoj montras al ekvacioj. atm = atmosfero, subsoil = subradikara grundo. A = tenujo de akvo adheranta al plantoj, P = tenujo de akvo en la plantoj, R = tenujo de sorbebla akvo en la efektiva radikara travolo de la grundo. AAT = evaporado, AP = sorbo de akvo el adheranta akvo, ATA = pluvo kaj roso, PA = gutado, PAT = transpirado, PER = perkolado, RP = sorbo de akvo el la tavolo en kiu estas la radikaro, SSR = kapilara transporto de akvo en la radikaran tavolon.

AR	throughfall adhering water (5)
RSS	water percolating to the subsoil (6)
AAT	evaporation rate of adhering water (8)
PAT	transpiration rate (12)
RAT	evaporation rate from soil (9)
PA	guttation rate (7)
RP	absorption rate from the root zone (13)
SSR	rate of capillary rise into the root zone (11)

Contents

According to Fig. 1 the equations for the water balance of the three compartments are as follows: they apply to one time-interval DT (in h):

$$A_t = A_{t-1} + DT \cdot (ATA + PA - AR - AP - AAT) \quad (1)$$

$$P_t = P_{t-1} + DT \cdot (AP + RP - DA - PAT) \quad (2)$$

$$R_t = R_{t-1} + DT \cdot (AR + SSR - RSS - RAT - RP) \quad (3)$$

For the whole system S(in mm) the three equations can be summed. In the equation the external transports (atmosphere and subsoil) remain:

$$S_t = S_{t-1} + DT \cdot (ATA - AAT - PAT - RAT + SSR - RSS) \quad (3a)$$

For each subsequent time-interval the equations are calculated, after which the values of the contents with index t − 1 are substituted by the values of the contents with index t. The rates are recalculated always. The contents at moment 0 are given.

Transports

In a sufficiently short time-interval (DT, h) the rates of transport can be considered independent of each other and are calculated accordingly.

Precipitation (ATA)

Precipitation includes rainfall rate (RF, mm/h) and dew rate (DW, mm/h):

$$ATA = RF + DW \quad (4)$$

Rainfall is given as a time series:

$$RF = INPOL(YRF, TIME) \quad (4a)$$

The INPOL function, interpolates anywhere between the series of data indicated by the first term in the brackets (Y axis of a graph), by means of the value of the second term mentioned. When one of the terminal values on the Y axis are exceeded, this value is used.

YRF is a series of values of RF on Y axis of Graph RF (TIME) and TIME is time.

In this study rainfall was put at 0. Dew equals the positive calculated value of the negative evaporation of the water adhering to the crop, condensation:

$$DW = -MIN(O., EA) \quad (4b)$$

in which EA is evaporation of the water adhering (mm/h) and MIN is the function,

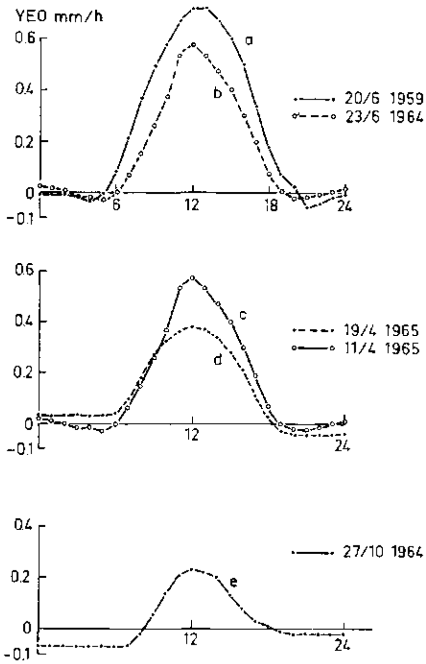

Fig. 2. Evaporation rate from a free water surface (EO, mm/h) in the course of 24 h on 5 different days.

Fig. 2. Evaporada rapideco el libera akvosurfaco (EO, mm/h) dum 24 horoj en 5 malsamaj tagoj (kurboj donitaj).

choosing the minimum value of the data or symbols between the brackets.

Evaporation of the adhering water is roughly calculated from the evaporation of a free water surface (EO, mm/h), by adding a multiplication factor (FEA, 1*), with which is estimated the effect of the roughness length, resistance and reflection coefficient of the crop.

$$EA = FEA \,.\, EO \tag{4c}$$

Evaporation of a free water surface is given as a time series:

$$EO = INPOL\,(YEO, TIME) \tag{4d}$$

YEO is a series values of EO on the Y axis of the graph in Fig. 2.

Throughfall of water on the crop to the root zone (AR)

We assume that water from a crop only starts dripping to the soil (TF, mm/h) when it is completely wet. We also assume that all the surplus drips to the soil in one time-interval DT. Since all the rates are expressed in mm/h, the throughfall quantity should be multiplied by 1/DT. Contents can only be used from the preceding moment of computation (t − 1). Thus, feedbacks are formed.

$$TF = (A_{t-1} - ACAP)/DT \tag{5a}$$

ACAP is the capacity of the compartment for adhering water (mm).

* 1 = No dimension.

The capacity of the adhering water is supposed to be a fraction (FACAP, 1) of the internal water capacity of the crop stand (PCAP, mm). This capacity and fraction are given.

$$ACAP = FACAP \,.\, PCAP \qquad (5b)$$

To prevent negative results when $A_{t-1} < ACAP$, a maximum function is used:

$$AR = MAX\,(O., TF) \qquad (5)$$

MAX is the function, choosing the maximum value of the quantities mentioned between brackets.

Percolation from the root zone to the subsoil (RSS)

This variable has been included to anable percolation of possible excess water (PER, mm/h), which occurs when field capacity is exceeded. Since this is water in excess of available water, field capacity has also to include available water (AFCAP, mm).

$$PER = (R_{t-1} - AFCAP)/DT \qquad (6a)$$

A negative value of percolation is prevented by

$$RSS = MAX\,(O., PER) \qquad (6)$$

The available field capacity AFCAP, is the difference between normal field capacity (FCAP, mm) and wilting capacity (WCAP, mm):

$$AFCAP = FCAP - WCAP \qquad (6b)$$

Both these capacities are inferred from the saturation capacity of the root zone (RCAP, mm), each by means of a certain factor (FFCAP, 1 and FWCAP, 1):

$$FCAP = FFCAP \,.\, RCAP \qquad (6c)$$
$$WCAP = FWCAP \,.\, RCAP \qquad (6d)$$

The saturation capacity is the product of the effective root depth (ERD, cm) and the specific water capacity of the soil (SSCAP, mm/cm):

$$RCAP = ERS \,.\, SSCAP \qquad (6e)$$

The effective root depth was defined on page 8. Its value is given as well as that of the specific water capacity of the soil.

Guttation (PA)

We assume that the guttation drops fall on the leaves. They are formed when the internal water capacity of the plant is exceeded:

$$PA = MAX\,(O., (P_{t-1} - PCAP)/DT) \qquad (7)$$

Evaporation from the adhering water (AAT)

The rate at which the adhering water evaporates equals that of the unlimited evaporation rate (UEA, mm/h) or equals the rate at which the compartment is exhausted completely in time-interval DT (EEA, mm/h). The smaller of the two values is correct:

$$AAT = MIN\,(UEA, EEA) \qquad (8)$$

Because the negative evaporation is accounted for as dew, it should be eliminated:

$$UEA = MAX\ (O., EA) \tag{8a}$$

For EA see Eqn (4c). The exhaustion rate of the compartment for adhering water is:

$$EEA = MAX\ (O., A_{t-1}/DT) \tag{8b}$$

Evaporation from the soil (RAT)

For simplicity we assume that no more than a small fraction (FEOS, 1) of the positive evaporation of a free water surface can evaporate from a saturated soil under a crop, though no radiation reaches the soil through the closed crop canopy. When the soil is not saturated, we assume that evaporation is limited in proportion to its water content (RWCR, 1).

$$RAT = FEOS \, . \, RWCR \, . \, MAX\ (O., EA) \tag{9}$$
$$RWCR = (R_{t-1} + WCAP)/RCAP \tag{9a}$$

For WCAP see Eqn (6d) and for RCAP see Eqn (6e).

Absorption of water from the adhering water (AP)

We assume that when there is a water shortage in the leaves, they can absorb water from the adhering water. This amount is limited either by the amount of adhering water, or by the water deficit in the plants. We assume the transport takes place within the time interval DT.

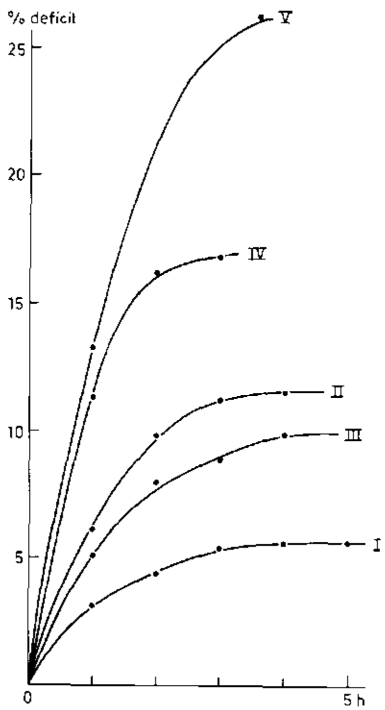

Fig. 3. Trend in water absorption of leaves of *Onosma Visianii* first dried to 5 different water deficits and then immersed to maximum capacity. Absorbed water given in percentages of the fresh weight before drying (according to table 20 of Krause, 1935).

$$AP = MIN\ (EEA, RDP) \tag{10}$$

For EEA see (8b). RDP is the refilling rate of deficits in plants (mm/h).

The rate of this absorption is assumed to be proportional to the water deficit in the plants. This corresponds with the experiments of Krause (1935) and of Diachun & Valleau (1939). The constant was taken from Krause, after re-arranging her data on Onosma Visianii (Figs. 3 and 4). The value of the constant is of the same magnitude for a number of plant species.

$$RDP = FABA\ .\ MAX\ (O., (PCAP - P_{t-1})) \tag{10a}$$

FABA is a factor for absorption from adhering water (1/h) (FABA = 0.80 according to Krause, 1935).

Capillary rise from the subsoil (SSR)

This quantity was included for completeness. It can be put at 0, at a constant value, or increased according to a given function of the relative water deficit in the root zone with respect to field capacity (RWDFC, 1). In the last case:

$$SSR = INPOL\ (YCR, RWDFC) \tag{11}$$

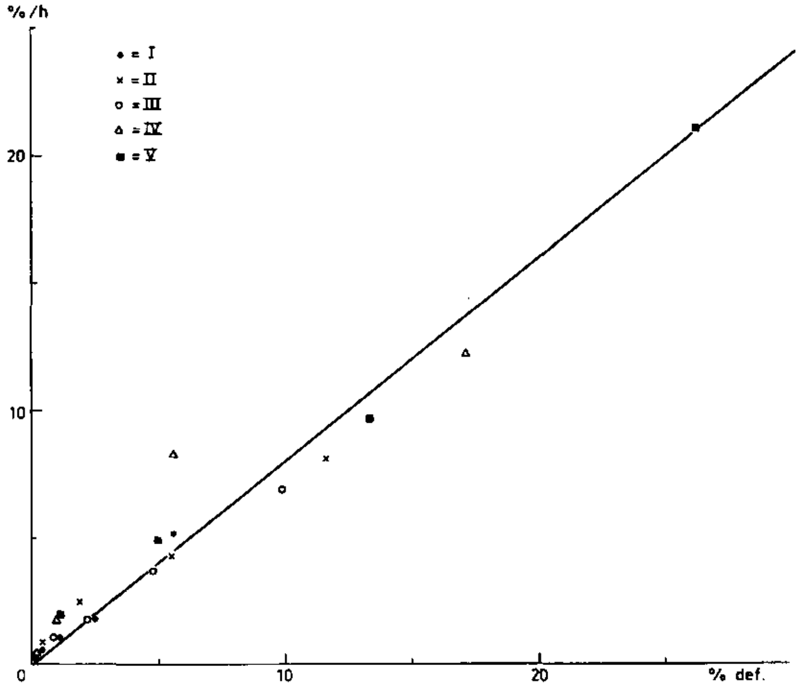

Fig. 4. Absorption rate in percentages of the relative water content per hour as a function of the relative water deficit itself. The same data of Fig. 2.I–V, the 5 absorptions with the different deficits at the start of Fig. 3.

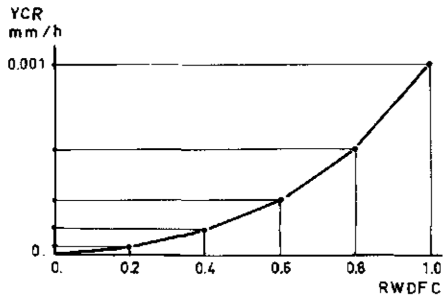

Fig. 5. Rate of capillary rise (CR) plotted on Y axis as a function of the relative water deficit in relation to field capacity (RWDFC).

Fig. 5. Rapideco de kapilara transporto (CR, mm/h) metita sur la Y-ordinato kiel funkcio de la relativa akvomanko rilate al la kampokapacito (RWDFC).

YCR series of data for the rate of capillary rise on Y axis of Graph CR (RWDFC) (Fig. 5).

$$RWDFC = (FCAP - WCAP - R_{t-1})/FCAP \qquad (11a)$$

For FCAP see (6c) and for WCAP see (6d).

Transpiration (PAT)

Transpiration is the evaporation from the leaves, after the adhering water has evporated:

$$PAT = MAX\,(O., (TRP - AAT)) \qquad (12)$$

TRP is the transpiration from externally dry leaves (mm/h), for AAT see (8).

Using AAT in a transport equation means that the rate of PAT is dependent on AAT (cf Transports p. 9), but since calculation of the transports occurs in the same order as the transports themselves, this treatment is justified.

TRP consists of two components: cuticular (CUTR, mm/h) and stomatal (STTR, mm/h) transpiration:

$$TRP = CUTR + STTR \qquad (12a)$$

Since Thallophytes without stomata desiccate exponentially with time (Stocker, 1956), we may assume that cuticular transpiration is proportional to the relative water content of the plant (RWCP, 1):

$$CUTR = RWCP\,.\,PCUTR \qquad (12b)$$

PCUTR is potential CUTR (mm/h).

The relative water content in the plants is:

$$RWCP = P_{t-1}/PCAP \qquad (12c)$$

For PCAP see (5b).

Potential cuticular transpiration equals potential transpiration (PTR, mm/h) minus the potential stomatal transpiration (PSTTR, mm/h). The last transpiration is set at a given fraction (FPSTTR, 1) of potential transpiration:

$$PSTTR = FPSTTR\,.\,PTR \qquad (12d)$$
$$PCUTR = (1 - FPSTTR)\,.\,PTR \qquad (12e)$$

Potential transpiration is set at a given fraction (FPTR, 1) of the positive evaporation of the externally wet crop:

$$PTR = FPTR . MAX (O., EA) \tag{12f}$$

The actual stomatal transpiration is the result of two limiting influences on the potential: relative water content in the plant and the light intensity on and in the vegetation. Each of these influences is indicated by a factor between 0 and 1:

$$STTR = FRWCP . FLI . PSTTR \tag{12g}$$

in which FRWCP is a factor for relative water content in plant (1) and FLI is a factor for light intensity (1).

The limitation by water content is expressed by a factor between 0 and 1 (FRWCP, 1), with which the closing interval of the stomata can be placed within a certain interval of relative water content. In this way one can express that in a number of plant species the stomata are maximally open when the leaf is not completely saturated (Stålfelt, 1929; Makkink & van Heemst, 1972) (Fig. 6a):

$$FRWCP = INPOL (YFRWCP, RWCP) \tag{12h}$$

in which YFRWCP is a series of values of FRWCP on Y axis of a Graph (Fig. 6a), for RWCP see (12c).

At a certain light intensity the stomata of a few leaves are still quite open. When these leaves are at the top side of the vegetation, the value of the limiting factor FLI for the entire vegetation is much smaller than 1. A considerably higher light intensity is then required to open a maximum number of stomata in the vegetation. The value of FLI is 1 then. When no light falls on the crop, the value of FLI is 0. For simplicity, instead of light intensities we apply the corresponding values of EO. To account for there being an evaporation exchange component in EO, the estimated EO interval of the light effect begins at a certain value above 0.

$$FLI = INPOL (YFLI, MAX (O., EO)) \tag{12i}$$

in which YFLI are values of FLI on the Y axis of the graph in Fig 7.

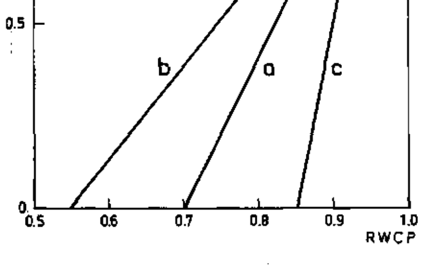

Fig. 6. Factor for the rate of transpiration in relation to the width of the stomata (FRWCP) on the Y axis as a function of the relative water content in the plant (RWCP). Curve a used as a standard, curves b and c as variants.

Fig. 6. Koeficiento por la rapideco de transpirado en rilato al la larĝeco de la stoma aperturo (FRWCP) metita sur la Y-ordinato kiel funkcio de la relativa akvoenhavo en la plantoj (RWCP). Kurbo a estas uzita kiel normo, kurboj b kaj c kiel variaĵoj.

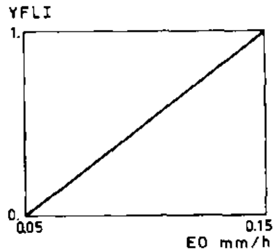

Fig. 7. Factor for the effect of the closing of the stomata in the crop (FLI) caused by low light intensities on Y axis as a function of light intensity, represented by the evaporation rate from a free water surface (EO).

Pisek & Winkler (1953) found that an increasing light intensity below a certain value hampered the closing of the stomata due to a certain moisture deficit in the leaves. This interaction has not been included in the algorithm as a function of the factors FRWCP and FLI.

Absorption of water from the root zone (RP)

Since absorption of water from the root zone is complicated by the variable resistances of roots and soil, the process is simplified to the utmost. We assume that absorption in most crops at optimum soil moisture status can guarantee potential transpiration at midday on a radiant summer day. We also assume that absorption can be limited by a decreasing water content in the soil and increased by an increasing water deficit in the plant. For each of these two effects a factor is included. However, there is another variable causing absorption, even if there is no water deficit in the plant: root pressure. This causes guttation. We set it at an estimated value enabling a weak flow of water and express it in mm/h. The variable is placed in the formula in such a way that it is independent of the water deficit in the plant, but dependent on that in the soil:

$$RP = (ABC \,.\, FAP + RPR) \,.\, FAR \qquad (13)$$

in which ABC is the absorption constant (mm/h), FAP is a factor absorption due to water deficit in the plant (1), RP is the root pressure (mm/h) and FAR is a factor for absorption due to water content in the root zone (1).

The absorption factor increasing with the water deficit in the plant is given as a function with a corresponding trend to diffusion pressure deficit (DPD) as a function of the relative water deficit in the plant (RWDP, 1) (Weatherley & Slatyer, 1957; Shepherd, 1964):

$$FAP = INPOL\ (YFAP, RWDP) \qquad (13a)$$
$$RWDP = 1. - RWCP \qquad (13b)$$

in which YFAP are values of FAP on the Y axis of Fig. 8a, for RWCP see (12c).

The absorption factor decreasing with the water deficit in the soil is also given as a function. This corresponds with the curves obtained in drying a thin layer of material (Sprenger, 1958) or soil (Lemon, 1956). With dense rooting the soil may be seen as a thin layer of material exposed to suction. Drying was, however, related to the available water in the root zone and in such a way that it is not limited at field capacity, but to a maximum at wilting capacity.

$$FAR = INPOL\ (YFAR, RAWCR) \qquad (13c)$$

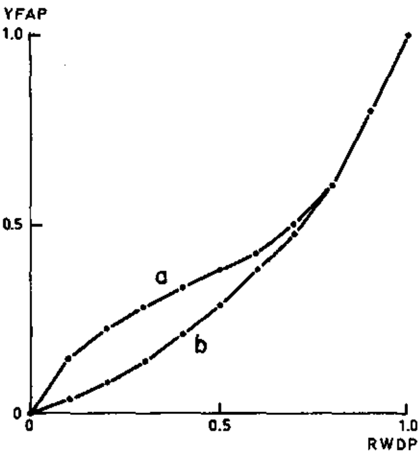

Fig. 8. Factor for the absorption of water from the soil (FAP) caused by a water deficit in the plant (Y axis) as a function of the relative water deficit in the plants (RWDP). Curve a used as a standard, curve b as a variant.

Fig. 8. Koeficiento por la sorbado de akvo el la grundo (FAP) kaûzita de akvomanko en la plantaro (Y-akso) kiel funkcio de la relativa akvomanko en la plantoj (RWDP). Kurbo a uzita kiel normo, kurbo b kiel variaĵo.

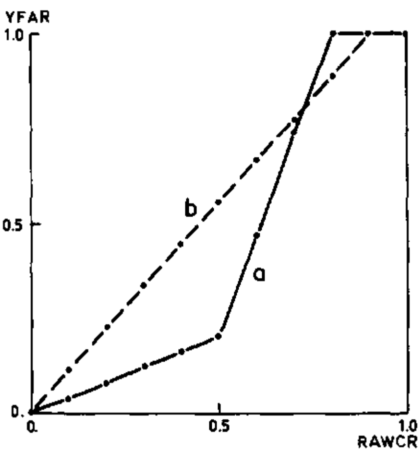

Fig. 9. Factor for the absorption rate (FAR) of water from the rootzone as a function of the relative available water content in a thin layer of rootzone (RAWCR). Curve a used as a standard for a sandy soil, curve b for a clay soil.

Fig. 9. Koeficiento por la sorborapideco (FAR) de akvo el la radikara tavolo kiel funkcio de la relativa sorbebla akvoenhavo en maldika tavolo da grundo (RAWCR). Kurbo a uzita kiel normo por sabla grundo, kurbo b por argila grundo.

in which YFAF are values of FAG on Y axis of Fig. 9a., RAWCR is the relative available water content in the root zone (1).

This content is calculated as follows:

$$RAWCR = R_{t-1}/ARCAP \qquad (13d)$$

in which ARCAP is the available capacity of the root zone.

$$ARCAP = RCAP - WCAP \qquad (13e)$$

For RCAP see (6e) and for WCAP see (6d).

The value of the absorption constant ABC is once calculated in Eqn (13) as follows. A transpiration maximum TRMAX has to be guaranteed. ABC then follows from Eqn (13) by substituting TRMAX for RP. Guaranteed maximum values should also be included for the quantities FAR and FAP;

$$ABC = ((TRMAX/FARM) - RPR)/FARM \tag{13f}$$

The value of TRMAX corresponds with the maximum value of EO (see (4d) on a cloudless summer day (EOMAX, mm/h):

$$TRMAX = EOMAX \, . \, FEA \, . \, FPTR \tag{13g}$$

(see (4c) and (12f)).

FARM is derived from:

$$FARM = INPOL\,(YFAR, RAWCRL) \tag{13h}$$

in which RAWCRL is the lowest value of RAWCR assuming the stomata still to be wide open; this value may possibly be lower than that of the available field capacity and has to be estimated.

The value of FAPM is found from Fig. 6, in which the value of RWDP must be inserted for the stomata being opened at a maximum (RWDPO, 1). According to Fig. 6 this is a value of 1. − RWCPO = 0.05.

$$FAPM = INPOL\,(YFAP, RWDPO) \tag{13i}$$

It was considered whether absorption from the soil could not be better calculated as the smaller of two alternatives; one is the absorption rate only limited by the roots; the other that only limited by the soil. It was found that this method gave improbable results, because transpiration decreased too rapidly after a few days.

Results

The results have been obtained by subsequent runs of the whole algorithm each with a different input of a set of values for the parameters or curves of crop, soil and weather. From the subsequent output data different graphs have been drawn. A number of actual days provided the data for drying periods, each of which was assumed to be a repetition of the same daily weather.

Results of a grass crop on a sandy soil during a period of identical sunny summer days

As initial values of the compartment contents were used: $A_{t=0} = 0.$, $P_{t=0} = PCAP$ and $R_{t=0} = AFCAP$

PCAP see (1.5) and below, AFCAP see (6b).

Concerning the atmosphere the following data were inserted:

YRF	= 0., 0., ... 0. see (4a)
YEO	see Fig. 2 and (4e)

For the plant stand were inserted:

YCR	see Fig. 5 and (11)
YFRWCP	see Fig. 6, curve a and (12h)
YFLI	see Fig. 7 and (12i)
YFAP	see Fig. 8 and (13a)
FEA	= 1.25 see (4c)
FACAP	= 0.4 see (5b)
PCAP	= 1.6 see (5b), (7) and (10a)
ERD	= 25 see (6e)
FEOS	= 0.05 see (9)
FABA	= 0.40 see (10a) (the value of *Onosma visianii* was halved)
FPSTTR	= 0.85 see (12d) and (12e)
FPTR	= 0.65 see (12f)

For soil the following data were inserted:

YFAR	see Fig. 9 curve a and (13c)
FFCAP	= 0.86 see (6c)
FWCAP	= 0.285 see (6d)
SSCAP	= 3.5 see (6e)
RAWCRO	= 0.80 see (13h) and Fig. 9
EOMAX	= 0.72 see (13g) and Fig. 2
RWDPO	= 0.05 see (13i) and Fig. 8

Fig. 10. Trend in a number of quantities during a series of 24 hours for a grass crop on a sandy soil during a period of identical sunny summer days (1, 3, 5 etc.). Left: the potential evapotranspiration (. . . .) and the actual transpiration (——), the absorption from the soil (– – –) and guttation (– · –); right: the relative water content in the plants (——) and the relative available water content in the root zone (– · –).

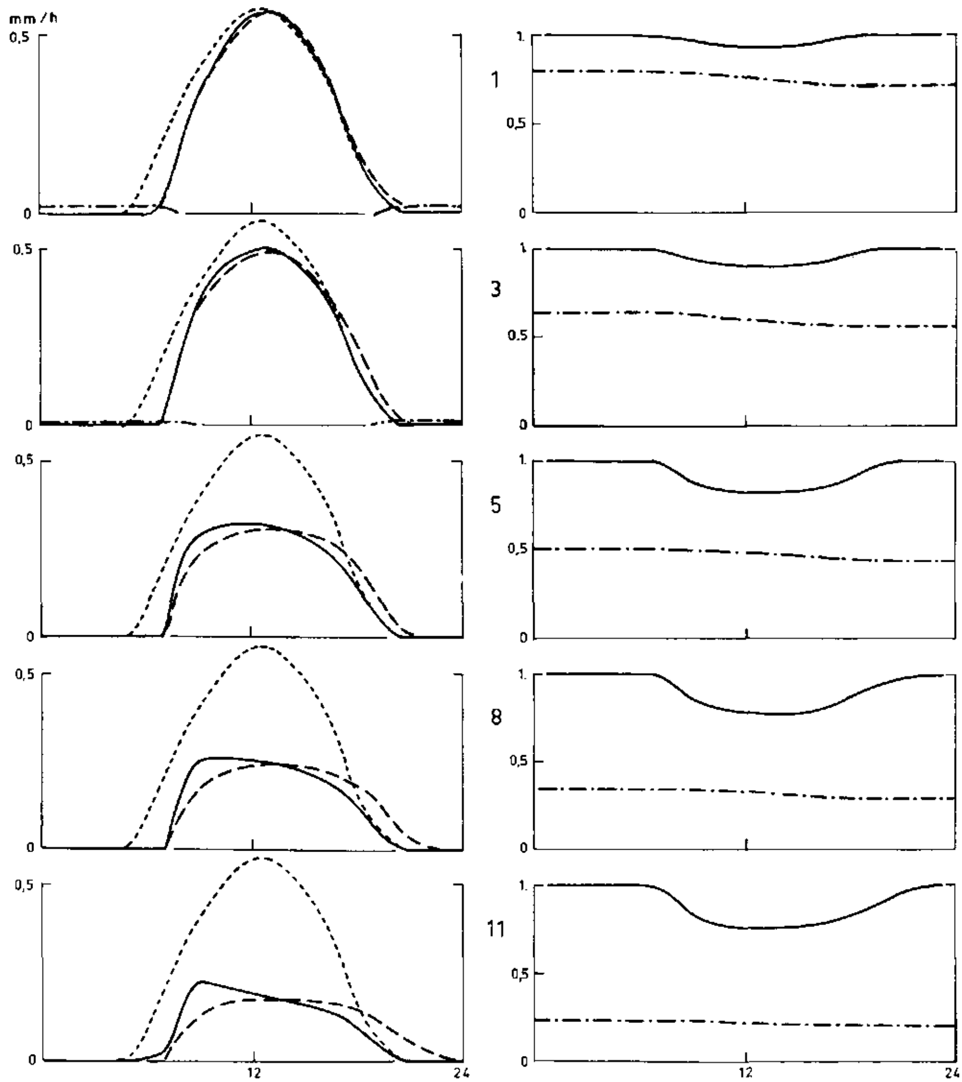

Fig. 10. Irado de kelkaj grandoj dum serio de 24 horoj pri gresplantaro sur sabla grundo dum periodo de identaj sunaj somertagoj (1, 3, 5 ktp.). Maldekstre: la potenciala evapotranspirado (. . . .) kaj la efektiva transpirado (—), la sorbado el la grundo (– – –) kaj la gutado (–· –·); dekstre: la relativa akvoenhavo de la plantoj (—) kaj la relativa sorbebla akvoenhavo de la radikara tavolo (– –).

Fig. 10. Continued.

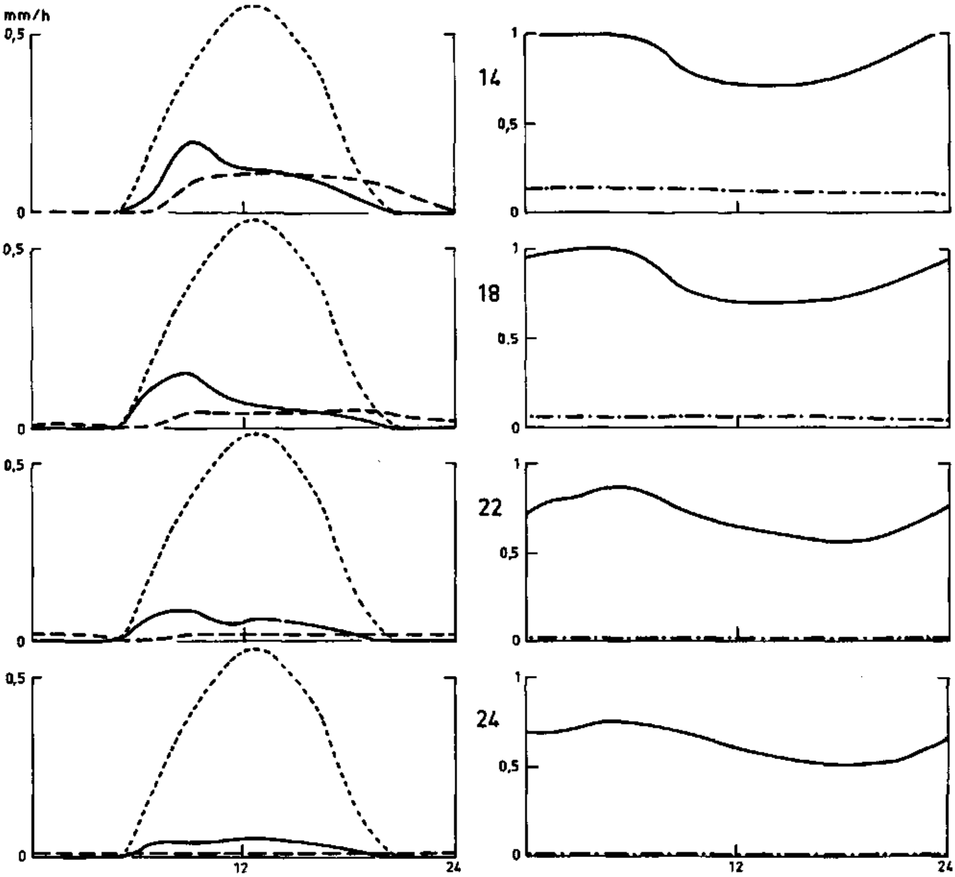

Fig. 10. Kontinuita

Water economy during the day

In Fig. 10 the trend in the potential and actual transpiration has been depicted in a number of 24-h periods. Absorption from the soil and guttation have also been indicated. It can be seen that transpiration in the morning hours is suppressed by evaporation of dew and guttation water. During day time absorption keeps pace with transpiration, continues during the night and then produces guttation. From the second day transpiration decreases and absorption lags behind. From the 5th day there is no longer guttation; transpiration is clearly asymmetrical in favour of the morning hours. From the 9th day transpiration starts earlier, because evaporation from the wet crop decreases since the leaves start to absorb the adhering water already in the evening. On the 16th day there is again distinct absorption from the soil during the morning hours which is caused by the deficit in the plant that was formed the previous day. On the 23rd and 24th day absorption from the soil is constant throughout the 24-h period. On the 25th day the calculation is stopped as directed, because the available soil water has decreased below 1%.

The relative water content in crop and soil has also been depicted; in the soil it decreases continually, somewhat more rapidly in daytime than at night. During the day a deficit is formed in the plant. It increases every day, but is completely compensated for during the night. From the 10th day the moment of complete compensation of the deficit in the plant is retarded. On the 19th day for the first time turgescence is not completely recovered. On the last day the maximum of the relative water content is only at 0.76 (at 05h00) and the minimum at 0.51 (at 17h00).

Water economy during a drought period

The trend of some quantities throughout a period of drought shows (Fig. 11) that during the first 6 days absorption is greater than transpiration, because a part of absorption is guttated by root pressure. Afterwards absorption is continuously below transpiration. Evaporation from the adhering water first increases, since dew formation of the first evening is not included, t_0 standing for midnight. After the second day evaporation starts to decrease until the 20th day. From the 7th day there is some absorption by the leaves from adhering water. The amount increases gradually as the deficit in the plant increases

Fig. 11. Trend in a number of quantities during the drying period. Above: transpiration, absorption from the soil, evaporation and absorption from adhering water, guttation; below: relative water content of plants at 05h00 and 17h00, and relative available moisture content of root zone at 05h00.

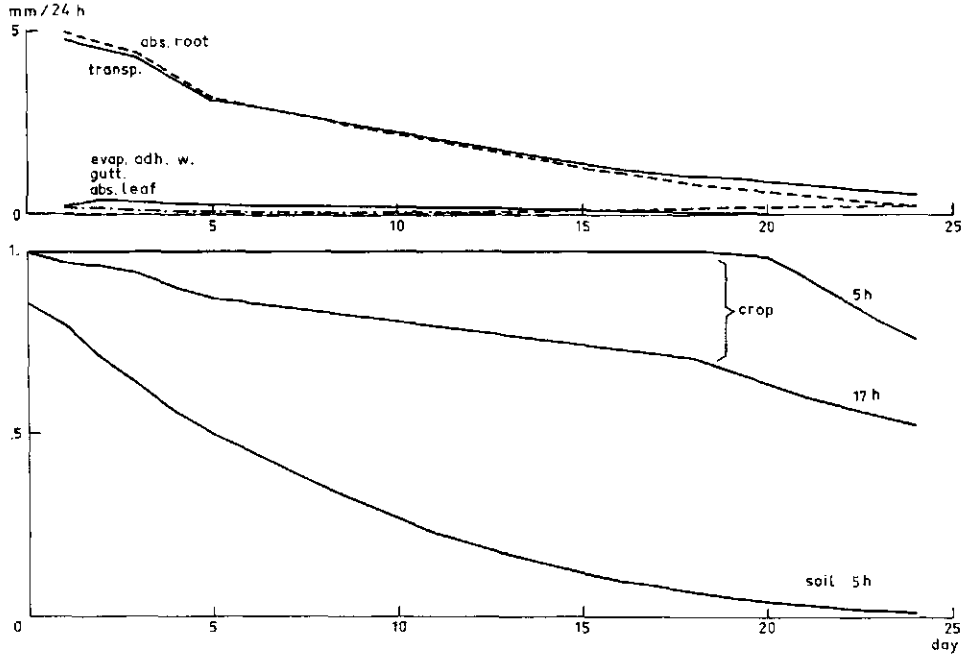

Fig. 11. Irado de kelkaj grandoj dum la sekiga periodo. Supre: transpirado, sorbado el la grundo, evaporado kaj sorbado el adheranta akvo, gutado; malsupre: relativa akvoenhavo en la plantoj je horo 5.00 kaj 17.00, kaj la relativa akvoenhavo de la radikara tavolo je horo 5.00.

until it attains its maximum on the 20th day when condensation is completely absorbed by the leaf. Including the 14th day there still is a measurable guttation total of 0.01 mm per 24 h, amounts hardly worth mentioning as hourly values.

The discrepancy between the relative water content in the crop at 05h00 and at 17h00 increases rapidly in the first 5 days, and afterwards less rapidly parallel with the intensity of transpiration. This break after the 5th day can be explained by the break in the moisture supply by the soil, which at a relative available content of 0.5 is much limited (Fig. 9, Curve a). From the beginning the water deficit in the plant continues to increase between 05h00 and 17h00, until it starts decreasing again from the 18th day. This almost corresponds with the time that the relative content of 0.7 is attained in the plant. With this content the stomata are completely closed (Fig. 6, Curve a). This closing does not have a retarding effect on the rate of drying.

From the second day the moisture content in the soil decreases gradually with a dimishing rate to the prescribed limit.

Fig. 12. Evapotranspiration rate per 24 h as a function of the relative available moisture content of rootzone (θ_r) at 13h00 for 5 periods each of identical days of different type. The curves are drawn through dots, one for each day, but only those mentioned in the legend, are depicted. a. for a grass crop on a sandy soil, b. for a grain crop on the same soil. The signs on the curves indicate the end of the day concerned.

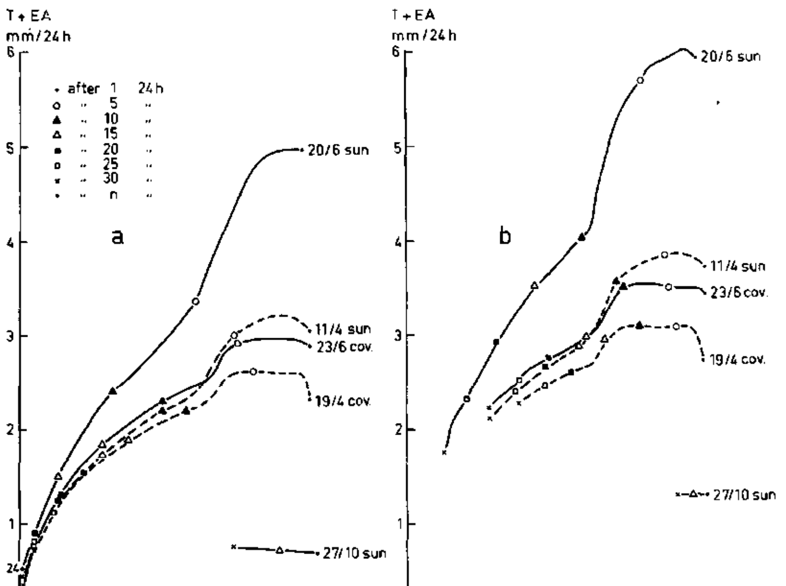

Fig. 12. La rapideco de la evapotranspirado en 24 h kiel funkcio de la relativa sorbebla akvoen havo de la radikara tavolo (θ_r) je horo 13.00 por 5 periodoj de identaj tagoj de malsama tipo. La kurboj estas desegnitaj tra punktoj, unu por ĉiu tago, sed nur tiuj menciitaj en la klarigo estas prezentitaj. a pri gresplantaro sur sabla grundo, b pri grenplantaro sur la sama grundo. La signoj sur la kurbo indikas la finon de la koncerna tago.

The trend in transpiration or total evapotranspiration of the crop as a function of the available water content in the soil (Fig. 12a, curve 20/6, sun) shows that soon (within the first 24 hours) and near the available field capacity transpiration starts to decrease with the drying of the soil. This decrease is not even, but is reduced when a content of 0.5 is attained (compare Fig. 9, Curve a). The decrease takes place less and less rapidly (see numbering of the days).

Daily evapotranspiration as a function of soil water content and weather

For periods with identical days of a varying level of potential evaporation, the trend in the daily actual evapotranspiration was calculated, and considered as dependent on the relative available water content of the root zone at 13h00. This calculation was done for a series of drying periods of identical days; extremely dry, sunny midsummer days (EO = 6.03 mm, 20/6 1959), cloudy summer days (EO = 3.56 mm, 23/6 1964), sunny spring days (EO = 3.63 mm, 11/4 1965), cloudy spring days (EO = 2.94 mm, 19/4 1965) and sunny autumn days (EO = 0.62 mm, 27/10 1964). In the nights there was a considerable fall of dew: 0.16 mm (20/6), 0.13 mm (23/6), 0.12 mm (11/4), 0.23 mm (19/4) and 0.69 mm (27/10).

Drying has been calculated for two crops on the same soil, which may be considered sandy (Fig. 12). The crops might be called a grass crop (Fig. 12a) and a cereal crop (Fig. 12b). They only differ in the factor for the ratio of potential evaporation of a wet crop to that of a free water surface (FEA): grass, 1.25; cereal crop 1.50; for the capacity of adhering water (FACAP): grass 0.4 mm; cereal crop 0.2 mm; for the capacity of internal water (PCAP): grass 1.6 mm; cereal crop 2.5 mm and for effective root depth (ERD): grass 25 cm; cereal crop 60 cm. All the other quantities are the same for both crops, including the constant for the guaranteed absorption rate from the soil (ABC): 10 mm/h. This means with regard to the difference in effective root depth that the root density of the grass crop was in fact assumed to be greater than of the cereal crop.

The lines in the figures indicate tne trend in the daily evapotranspiration (sum of evaporation of adhering dew and transpiration) as a function of the available soil water. The lines begin at the end of the first day; the relative available water content of the soil at the beginning is 0.80. With some curves the rate of evapotranspiration on the second day is somewhat higher than that on the first day, because on the first day only dew could evaporate that fell between 0h00 and sunrise, whereas on the second day dew could evaporate which fell throughout the preceding evening. A maximum in transpiration caused by the wider opening of the stomata in the interval of a relative water content in the plants from 1.0 to 0.95 is not expressed in the daily observations, possibly because it was concealed by evaporation.

All curves show a slight break which is a reflection of that in the drying curve of sandy soil (Fig. 9). The sandy soil is emptied more by the grass in the drying period than by the cereal crop because there is a smaller amount of water available at less deep rooting. In a period of days with lower evaporation and heavy dew fall (27/10), water is used up only for a small part. On sunny summer days it is exhausted to 1% by grass in 24 days and by a cereal crop to only 10% in in 30 days.

The curves almost meet when the soil is not quite exhausted. They can also intersect, as those in 11/4 and 23/6. The trend in evaporation differs considerably on both days, although dew is almost the same in these periods (0.12 and 0.13 mm/24 h, respectively). Therefore it cannot be foretold in which periods transpiration is no longer concealed by evaporation, nor on which day its limitation due to closing of the stomata becomes important.

The level of the highest evapotranspiration being higher for a cereal crop than for grass is due to the higher value of factor FEA for a cereal crop.

If dew fall is omitted and evaporation from the crop is therefore absent transpiration starts earlier in the day and so the daily sum always lies between that of evapotranspiration and the share of transpiration at dew fall (Fig. 13a). Increased transpiration due to wider opening of the stomata can neither be observed now, which is proved by the case that dew fall has been omitted.

Effect of various quantities and functions on the water economy

To test the importance of various quantities and functions on water depletion a cereal crop on sandy soil on a cloudless day was chosen. Since only near sunrise and sunset is the light weak enough to drop below the limit value at which the closing of the stomata starts, changing this limit value (from EOP 0.15 to 0.25 mm h^{-1}) has no demonstrable effect. This has not been examined for a sunny autumn day. As already mentioned, in this algorithm the light dependence of the value of the relative water content in the plant at which the stomata close completely is not taken into account, i.e. that at higher light intensity the stomata close only completely at a lower water content (Pisek & Winkler, 1953).

The influence of absorption of water by the leaves from adhering water is small. The value of factor FABA was put at 0.40 (for a plant with the highest value Krause (1935) found 0.80), when this value is put at 0, Fig. 13 shows that neither evapotranspiration nor transpiration are demonstrably affected. Apparently, it is unimportant whether the plant takes up water from adhering water or a little later from the soil. The effect is only noticeable to some extent with continual drying out (available relative water content in the soil 0.25). Some more water is left on the leaf then for evaporation, which decreases the transpiration share in evapotranspiration somewhat. This means that, since the plant does not take up this water from adhering water, it is absorbed from the soil: the lines end at somewhat lower relative moisture content.

The effect of root pressure is also small (Fig. 13c). So long as the relative water content of the soil is still rather high (over 0.5), root pressure gives guttation and this increases evaporation somewhat, thus decreasing the transpiration share.

The activity of the stomata has a considerable effect. As a standard it was assumed that the stomata closed completely at a relative water content of 0.7 in the plant, and examples were studied in which this value was put at 0.55 and at 0.85 (Fig. 6, curves b and c). The result shows that at the lower closing value transpiration continues at a higher level and leads to greater exhaustion of the soil (Fig. 14a). The higher closing value, on the other hand, suppresses transpiration and leaves somewhat more water in the soil.

Much more important for the water economy is, however, the relation between the suction of the plant and its relative water content. A decrease in suction at low water deficits in the plant with respect to the standard curve (Fig. 8, curves a and b) considerably decreases transpiration over a wide interval in the water content of the soil. Correspondingly more water is left in the soil (Fig. 14b). Especially in the second part of the drying

Fig. 13. Evapotranspiration rates as a function of the relative available moisture content of root zone with a grain crop on a sandy soil, a. evapotranspiration with dew (above), transpiration share alone with dew (below), transpiration without dew (middle), b. evapotranspiration with (——) and without (– – –) absorption from dew (above), transpiration share alone with (——) and without (– – –) absorption from dew (below), c. evapotranspiration with (——) and without (– – –) root pressure (above), transpiration share alone with (———) and without (– – –) root pressure (below).

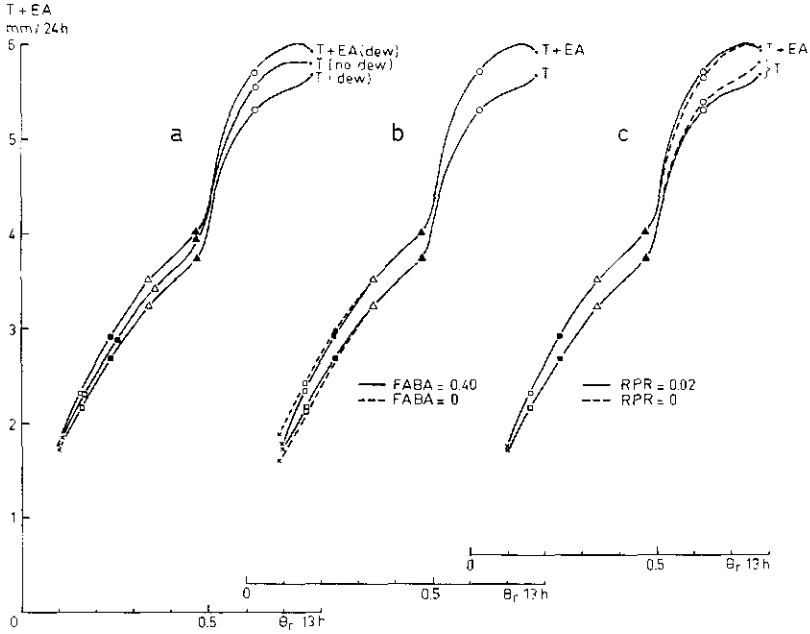

Fig. 13. Rapidecoj de evapotranspirado kiel funkcio de la relativa akvoenhavo de la radikara tavolo pri greno sur sabla grundo, a evapotranspirado post rosado (supre), transpirada partopreno post rosado (malsupre), transpirado sen rosado (mezo); b evapotranspirado kun (—) kaj sen (– – –) sorbado el la roso (supre), transpirada partopreno sola kun (—) kaj sen (– – –) sorbado el roso (malsupre), c evapotranspirado kun (—) kaj sen (– – –) radikara premo (supre), transpirada partopreno sola kun (—) kaj sen (– – –) radikara premo (malsupre).

period transpiration is low.

When the absorption constant, guaranteeing a certain maximum (ABC), is halved, an important decrease in absorption results. Comparison should be carried out in an example with the corresponding suction line. The level of the depletion line becomes lower, even though its level is not halved. The explanation is that the constant includes root effectivity, viz. mainly root length and root density, respectively. The effective rooting depth is included in the amount of soil water.

Finally, the drying curves for grass and a cereal crop on clay soil were compared during a drought period of sunny summer days and one of cloudy summer days (20/6, 23/6, respectively). Since the line inserted for soil type (Fig. 9, line b) does not show a break, the drying curves are smooth (Fig. 15). On both types of day, evapotranspiration of the cereal

Fig. 14. As Fig. 13. a. Stomata closed at a relative water content lower than 0.55, 0.70 and 0.85 (curves of Fig. 6), b. standard DPD-curve (absorption constant: 10 mm/h)(above), variant of DPD-curve (Fig. 8b) (the same absorption constant) (middle), variant of DPD-curve, halved absorption constant: 5 mm/h (below).

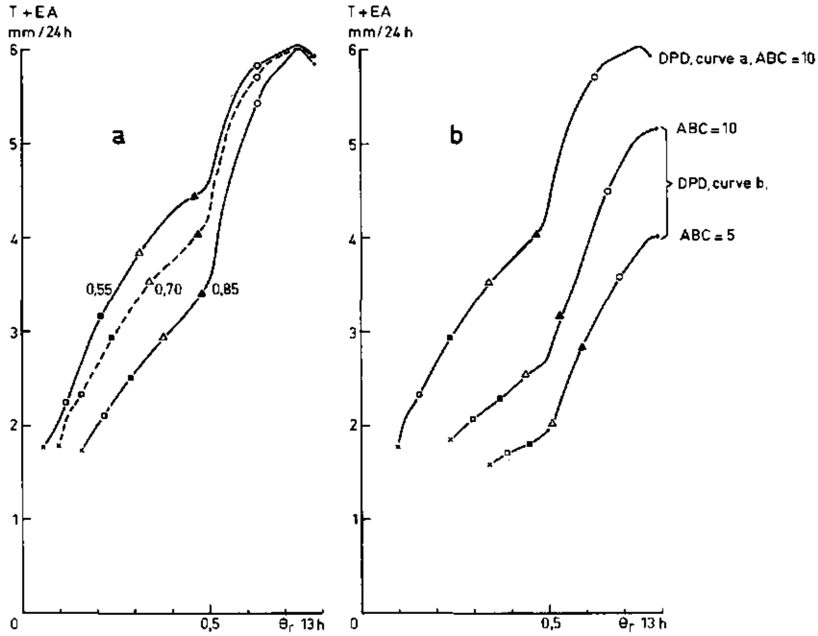

Fig. 14. Kiel figuro 13. a stomoj fermitaj ĉe relativa akvoenhavo sub 0,55, 0,70 kaj, 0,85 (kurboj de fig. 6), b norma DPD-kurbo (sorbada konstanto 10 mm/h)(supre), variaĵo de DPD-kurbo (fig. 8b)(la sama sorbada konstanto)(mezo), variaĵo de DPD-kurbo kaj sorbada konstanto je duonigita valoro 5 mm/h (malsupre).

crop is higher than that of grass due to canopy development (FEA). Limitation of transpiration sets in much earlier for grass and the soil is also exhausted sooner than for a cereal crop, due to the lower effective rooting depth (ERD). The absorption constant is the same in all four cases, viz. 10 mm/24 h.

Some amplifications to the algorithm

The algorithm can be more detailed and enlarged at will. Four examples are given here:

Interaction between the water-content in the leaves and light

The opening of the stomata is affected by the relative water content in the leaf and light. Both effects are independently accounted for in the algorithm in Eqn (12g). However, there is an interaction between these two factors (Makkink & van Heemst, 1972). When these are to be included Eqn (12g) should be replaced by:

$$STTR = FRWCLI \,.\, PSTTR \qquad (12j)$$

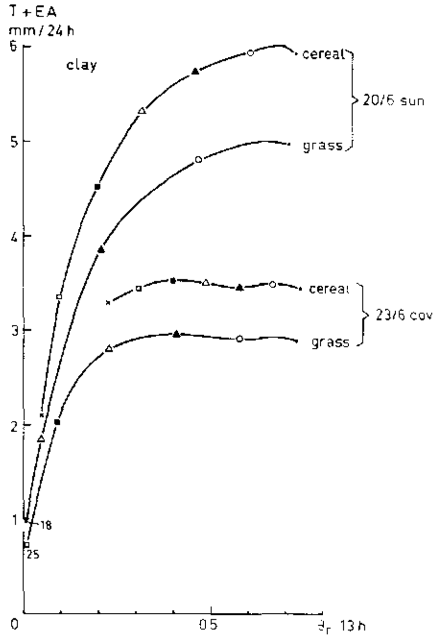

Fig. 15. Evapotranspiration rate as a function of the relative available moisture content of the root zone in a clay soil. 1 and 2 (above) on sunny summer days, 3 and 4 (below) on cloudy summer days. 1 and 3 for a grain crop, 2 and 4 for a grass crop.

Fig. 15. Rapideco de evapotranspirado kiel funkcio de la relativa sorbebla akvoenhavo de la radikara tavolo en argila grundo. 1 kaj 2 (supre) en sunaj somertagoj, 3 kaj 4 (malsupre) en nubaj somertagoj. 1 kaj 3 pri greno, 2 kaj 4 pri greso.

in which FRWCLI is the factor for relative water content and light intensity.

This factor is obtained from a number matrice consisting of, e.g. 5 rows of numbers for FRWCP as a function of the relative water content of the plant (RWCP), holding for 5 increasing light intensities. First interpolation takes place in each row to obtain for each of the 5 light intensities the value of FRWCP as a function of the relative water content in the plant. Then, in this vector of 5 values is interpolated by means of light intensity to obtain FRWCP.

With this sophistication light intensity cannot be substituted by evaporation intensity. The trend in light intensity during daytime should then be inserted too.

No run was carried out. It was mentioned, however, because it may be important in studying the effect of an interaction pattern changed in the direction of the water-content axis or in that of the light-intensity axis, or in both directions. It remains to be seen, however, whether there is any sense in applying these details without taking into account at the same time the extinction of light in the crop. This can be done by dividing the crop into layers. This introduced the problem whether the potential evapotranspiration per crop layer should be estimated with a number of factors or should be calculated by applying the evaporation formula per layer. This considerable amplification was not applied.

Effect of continuing drying on the suction in the plant

Measurements of DPD in the leaf blades and petioles of Trifolium repens showed that DPD increases at a certain relative water content with the duration of the drought (Shepherd, 1964). The increase in DPD between 8 and 72 h after beginning of the drought can be calculated from Fig. 4 of Shepherd (1964) (assuming that this rate is constant). The

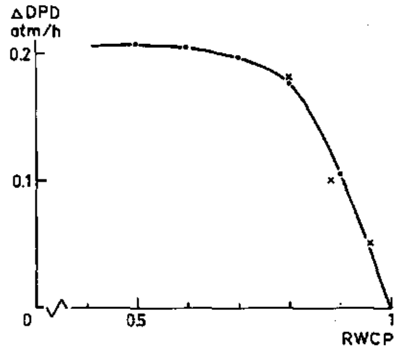

Fig. 16. Average increases of suction force (DPD) in atm/h^{-1} in a drying period between 8 and 72 h after severing the leaves and petioles of white clover, as a function of their relative water content (calculated from Shepherd, 1964). The three crosses concern data on pepper (Gardner & Nieman, 1964).

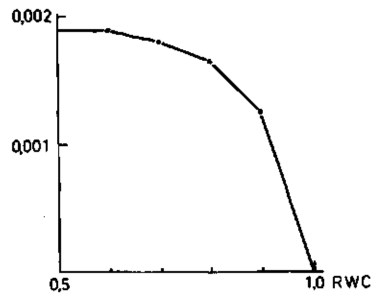

Fig. 17. Relative representation of the curve of Fig. 16 (see text).

rate is found to increase with the decrease in the relative water content of the leaves (Fig. 16).

From Gardner & Nieman's Graph 1 (1964) based on observations of peppers, the daily increase in DPD could also be inferred. With the average DPD curve for leaf blades and petioles of White clover (Shepherd, 1964), these values could be related to the relative water contents. It was found that the rate with which DPD-increase (atm h^{-1}) for peppers corresponds with that for white clover (Fig. 16). Since the DPD-curve in our algorithm was represented relatively, the DPD-increase curve is also relative (at RWCP = 0.5 is FAP = 0.38 = 40 atm, and so its increase rate FAPIR at a maximum is 0.38 . 0.2/40 = 0.0019) (Fig. 17).

Based on these data the algorithm should be extended by replacing quantity FAP in Eqn (13) by the cumulative factor FAPC. Eqn (13a) now reads:

$$\text{FAPC} = \text{INPOL (YFAP, RWDP)} + \text{FAPI}_{t-1} \quad (13j)$$

$$\text{FAPI} = \text{FAPI}_{t-1} + \text{DT. FAPIR} \quad (13k)$$

$$\text{FAPTS} = \text{INPOL (YFAPTR, RWCP)} \quad (13b)$$

in which, FAPC is a factor for absorption due to water deficit in plant cumulative (1), FAPI FAP-increase (1), FAPIR increase rate of FAP (1/h), YFAPIR values on Y axis of FAPIR and RWCP relative water content in plant (1).

In this detailed model it was assumed that after recovery of the maximum turgescence at the end of the night the effect of drought has not diasppeared.

For grass on clay it was found for sunny summer days that evapotranspiration in-

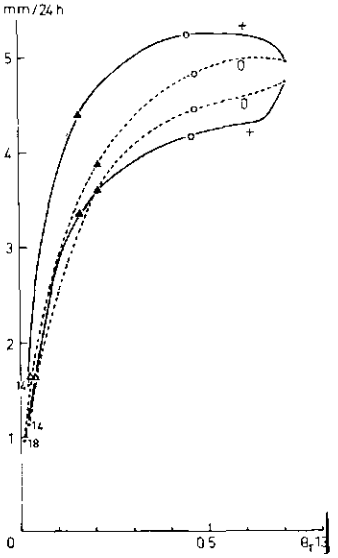

Fig. 18. Evapotranspiration of grass on clay soil in a period of bright summer days with (+) or without (0) increase of suction of the plant. The two lower lines concern the share of transpiration.

Fig. 18. Evapotranspirado de greso sur argila grundo en periodo de brilaj somertagoj kun (+) aû sen (0) pliiĝo de la sûco en la plantoj. La du pli malsupraj kurboj koncernas la partoprenon de la transpirado.

creases considerably at once, due to the increasing suction, in which especially evaporation of the adhering water increases, since guttation forms more water on the crop. The transpiration part is proportionally decreased and the result is that the soil is exhausted earlier (Fig. 18).

Effect of root distribution

In this algorithm root distribution was assumed to be uniform. When this is not so the rooted soil should be divided into layers, e.g. in 5 layers. For each layer a content equation should be composed, in which the transports between the layers are accounted for.

Absorption of the first layer is now:

$$R1P = FRD1 \, . \, (ABC \, . \, FAP + RPR) \, . \, FAR1 \tag{13m}$$

FRD1 Factor root distribution layer 1, 1

$$FAR1 = INPOL\,(YFAG, RAWCR1) \tag{13n}$$

$$RAWCR1 = R1_{t-1}/(ARCAP \, . \, FRD1) \tag{13o}$$

For the other layers corresponding equations hold. Moreover:

$$RP = R1P + R2P + R3P + R4P + R5P \tag{13p}$$

At regularly decreasing rooting the factors FRD1 to FRD5 are:

0.333, 0.266, 0.200, 0.134 and 0.067, resp. (sum 1.000).

For a cereal crop (FEA = 1.50) on sandy soil the regular decreasing rooting (at equal root depth ERD and absorption factor ABC) was found to decrease evapotranspiration to a less extent than one expects (Fig. 19). Perhaps the result looks somewhat too

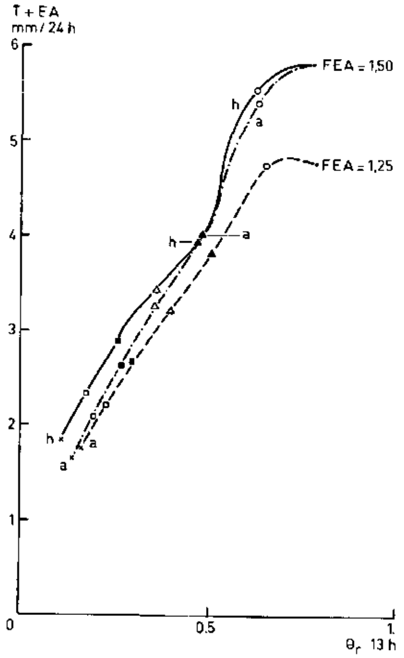

Fig. 19. Transpiration of a grain crop on sandy soil in a period of bright summer days (evaporation from interception water eliminated) with a homogeneously distributed root system (h) and a regulàrly diminishing root system (a). The latter with a higher and lower crop.

Fig. 19. Transpirado de greno sur sabla grundo en periodo de brilaj somertagoj (la evaporado el la adheranta akvo estas eliminita) kun homogene distribuita, radikaro (h) kaj kun regule maldensiĝanta radikaro (a). La lasta pri pli alta kaj pri pli malalta plantaro.

favourable, because it was assumed that the soil coat round the roots was a thin layer, which here probably is not so in the deeper soil layers.

For comparison the result is shown for a cereal crop which is much lower (FEA = 1.25) with decreasing rooting. The lower evaporation level due to a lower zero plane displacement and roughness length (included in FEA), results in about the same degree of depletion of the soil after 30 days with about the same evapotranspiration rate in the end as of the higher cereal crop.

Discussion

The algorithm evidently reflects well the water economy of a fictive crop qualitatively, without attempts being made to attain this result by adjustment of the parameters. Only approximate functions for complicated physical relations have been inserted. Thus the separate functions for the radiation and evaporation share of the transpiration have been avoided, as well as a function including the moisture gradients and resistances in the soil round the roots. From the models most acceptable one was chosen (see Eqn (13)). To apply climatological and micro-climatological interpretations (Penman & Long, 1960; Rijtema, 1965; Tanner, 1968) the crop would have to be divided into a number of layers and for the application of soil physics (Gardner, 1964; 1968) rooted soil would have to be divided in a number of layers, either parallel to the surface or concentrically round the roots. Apparently, it is possible to do without these divisions, which greatly shortens the calculation time, the actual situation being acceptably approximated. The use of a drought characteristic (FAB = f (RAWCR)) seems to be reasonably accurate. The nature of this relation is clearly expressed in the absorption trend of the soil (Fig. 9 Curve a and Fig. 13).

The lag of the absorption behind transpiration (Fig. 10) is attained without a retardation parameter, but only because the compartment for internal water of the plants acts as a buffer between atmosphere and soil (cf. Kramer, 1948). Important for evapotranspiration are canopy size (in FEA), root depth (ERD), root density (in ABC) and the DPD-curve with its possible changes affected by drought. Compared to this, activity of the stomata, root pressure and absorption by the leaves are of less importance.

It was found that actual evapotranspiration (AE) as a function of the potential (EP) and the water content in the soil (SM) (Fig. 12a,b and 15) cannot be indicated as the quotient AE/EP as a function of SM, as Baier & Robertson (1966) and Baier (1968) did: viz. this relation shows increasing convexity with increasing potential evapotranspiration. AE = F (EP, SM) should be applied for each day, e.g by inserting a three dimensional array. However, it is possible to proceed from a uniform AE-curve, using a parameter on the X axis that is dependent on the potential evapotranspiration and the available water content in the soil (Makkink & van Heemst, in preparation).

If the algorithm is to be used for a growing crop, the following constants should be included as a time series: PCAP cf. Eqn (1.5), ERD (6e), YFLI (12i), EOMAX (13g), FEOS (9), ABC (13f) and FEA (4c).

Moreover, by including a series of variable weather types, possibly with rain, the calculated results could be tested with actual observations in a field crop.

Summary

A digital dynamical simulation was performed for a better understanding of the relationship of the actual evapotranspiration as a function of potential evapotranspiration and soil moisture content of the soil. A fictive crop was chosen to avoid interference of rainfall and growth. The system (Fig. 1) and the equations for the rates of water transports were kept very simple to limit computor time. Analytical equations were replaced by estimated ones and by curves. A list of symbols is given at the end. Input relationships and parameters are given in the chapter Results and Fig. 2, 5, 9 and 17. Hourly rates of transpiration, absorption from soil, guttation and relative water content of plant and relative available water content of soil (root zone) throughout each day of a drying period of identical days are in agreement with our knowledge of plant physiology (Fig. 10). Corresponding daily rates are presented, Fig. 11.

For 5 day types, 2 soil types (sandy soil and clay soil) and 2 types of crops (grass, grain crop) runs were performed. Evapotranspiration as a function of potential evapotranspiration and relative available soil moisture content is presented in Fig. 12. The effect of dew (Fig. 13 and 18), the quantity of crop mass (in FEA, Fig. 19), root capacity and absorption constant (ABC, Fig. 14), the drying curve of the soil (Fig. 12 and 15) and the DPD-characteristics of crops (Fig. 14) are important factors. Root pressure (RPR Fig. 13), the factor of absorption by the leaves from interception water (FABA, Fig. 13) and stomata characteristics (Fig. 14), are less important. Cumulation of DPD as a function of continuous drying is demonstrated in Fig. 18; the influence of root distribution (homogeneous or gradually diminishing) does not seem very important (Fig. 19).

Resumo

La akvomastrumado de fiktiva plantaro.

Ni faris algoritmon por digita dinamika simulado de la akvomastrumado de fiktiva plantaro por pli bone kompreni la influojn de la potenciala evapotranspirado kaj la akvoenhavo de la grundo al la reala evapotranspirado. Ni elektis fiktivan plantaron por eviti la influojn de pluvo kaj kreskado. Ni tenis la sistemon (fig. 1) kaj la ekvaciojn por la rapidecoj de la akvotransportoj tre simplaj por mallongigi la komputeradan tempon. Analitikajn ekvaciojn ni anstataŭigis per supozitaj kaj per kurboj. La simbolaro (en la angla) troviĝas je la fino de ĉi tiu artikolo. La enigitaj rilatoj kaj parametroj estas donitaj en la ĉapitro "Results" kaj en la figuroj 2, 5, 9 kaj 17. Horaj rapidecoj de transpirado, sorbado el la grundo, gutado kaj la relativa akvoenhavo de la plantoj kaj la relativa sorbebla akvoenhavo de la grundo (en la tavolo de la radikaro) dum ĉiu tago de sekiga periodo el identaj tagoj konformas al la plantfiziologia scio (fig. 10). La korespondaj tagaj sumoj kaj enhavoj estas prezentitaj en figuro 11.

Pri 5 tipoj de tagoj, 2 tipoj de grundo kaj 2 tipoj de plantaroj (greso, greno) ni faris komputerajn iradojn.

La reala evapotranspirado kiel funkcio de potenciala evapotranspirado kaj relativa sorbebla akvoenhavo de la grundo estas prezentita en figuro 12. La roso (fig. 13 kaj 18), la kvanto de la plantaramaso (reprezentita de FEA fig. 19), la kapacito de la radikaro kaj la sorbokonstanto (ABC, fig. 14), la kurbo pri la sekiĝo de la grundo (fig. 12 kaj 15) kaj la DPD-rilatoj de la plantoj (fig. 14) estas la pli gravaj faktoroj. La radikopremo (RPR fig. 13), la koeficiento pri sorbado per la folioj el adheranta akvo (FABA, fig. 13) kaj la stomaj karakteroj (fig. 14) estas la malpli gravaj faktoroj. Kumulado de DPD kiel funkcio de daŭra sekiĝado estas montrita en figuro 18; la influo de la radikodistribuo (homogena aŭ malpliiĝanta kun la profundeco) impresas ne tre gravaj (fig. 19).

Symbols*

A	content water adhering to crop, mm
AAT	evaporation rate of adhering water, mm/h
ABC	absorption rate constant, mm/h
ACAP	capacity of A, mm
AFCAP	available field capacity, mm
AP	absorption rate of adhering water into plant, mm/h
AR	throughfall rate through crop, mm/h
ARCAP	available water capacity of root zone, mm
ATA	precipitation rate, mm/h
CUTR	cuticular transpiration rate, mm/h
DT	time element of computation cycle, h
DW	dew rate, mm/h
EA	evaporation rate of adhering water, mm/h
EEA	exhausting evaporation rate of adhering water, mm/h
EO	evaporation rate of free water surface, E_0, mm/h
EOMAX	maximum evaporation rate of free water to be warranted, mm/h
ERD	effective root depth, cm
FABA	factor absorption from adhering water, 1/h
FACAP	factor for ACAP, 1
FAP	factor for absorption due to water deficit in plants, 1
FAPC	FAP including cumulation of DPD, 1
FAPM	value of FAP enabling TRMAX, 1
FAPI	cumulated increment of FAP, 1
FAPIR	increase rate of FAP, 1/h
FAR	factor for absorption due to water content in root zone, 1
FARM	value of FAR enabling TRMAX, 1
FCAP	field capacity, mm
FEA	factor for EA, allowing for canopy development, 1
FEOS	fraction of EO evaporating from wet soil surface under crop, 1
FFCAP	factor for field capacity, 1
FLI	factor for light intensity, 1
FPTR	factor for PTR, allowing for material of leaves, 1
FPSTTR	factor for potential stomatal transpiration, 1
FRD	factor root share in layer, 1
FRWCLI	factor for relative water content of plant and light intensity in crop, 1

* 1 = No dimension.

FRWCP	factor for relative water content plant, 1
FWCAP	factor for wilting apacity, 1
INPOL	interpolation from graph
MAX	function choosing maximum value
MIN	function choosing minimum value
P	water content of plant, mm
PA	guttation rate, mm/h
PAT	transpiration rate, mm/h
PCAP	water capacity of plants, mm
PCUTR	potential cuticular transpiration rate, mm/h
PER	percolation rate, mm/h
PSTTR	potential stomatal transpiration rate, mm/h
PTR	potential transpiration rate, mm/h
R	available water content of effective root zone, mm
RAT	soil evaporation rate, mm/h
RCAP	capacity root zone, mm
RAWCR	relative available water content of root zone, 1
RAWCRL	lowest value of RAWCR at which stomata are still wide open, 1
RDP	refilling rate of deficit in plants, mm/h
RF	rainfall rate, mm/h
RP	absorption rate from the root zone, mm/h
R1 P . . . R5P	absorption from rootzone layer 1 . . . 5, mm/h
RPR	root pressure as a rate, mm/h
RSS	percolation rate out of root zone, mm/h
RWCP	relative water content in plant, 1
RWCR	relative water content root zone, 1
RWDFC	relative water deficit in comparance with field capacity, 1
RWDP	relative water deficit plants, 1
RWDPO	value of RWDP at which stomata are maximally open, 1
S	water content of system, mm
SSCAP	specific water capacity, mm/cm
SSR	rate of capillary rise into root zone, mm/h
STTR	stomatal transpiration rate, mm/h
TF	throughfall rate, mm/h
TIME	time, h
TRMAX	maximal warranted transpiration rate, mm/h
TRP	transpiration rate, mm/h
UEA	unlimited evaporation rate, mm/h
WCAP	wilting capacity, mm
YCR	values of capillary rise on Y axis
YEO	values of EO on Y axis
YFAR	values of FAR on Y axis
YFAP	values of FAP on Y axis
YFLI	values of FLI on Y axis
YFRWCP	values of RWCP on Y axis
YRF	values of RF on Y axis

References

Allerup, S., 1961. Stem cutting and water movement in young barley plants. Physiologia Pl. 14: 632–637.

Baier, W. & G. W. Robertson, 1966. A new versatile soil moisture budget. Can. J. Pl. Sci. 46: 299–315.

Baier, W., 1969. Concepts of soil moisture availability and their effect on soil moisture estimates from a meteorological budget. Agric. Met. 6: 165–178.

Blackman, F. F., 1905. Optima and limiting factors. Ann. Bot. 19: 281.

Denmead, O. T. & R. H. Shaw, 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 54: 385–390.

Diachun, S. & W. D. Valleau, 1939. Relation of stomatal opening to water soaking of tobacco leaves. Am. J. Bot. 26: 347–355.

Forrester, J. W., 1961. Industrial dynamics. Massachusetts, New-York, London, 464 pp.

Forrester, J. W., 1970. Urban dynamics. Massachusetts, New-York, London, 285 pp.

Forrester, J. W., 1971. World dynamics. Massachusetts, New-York, London, 142 pp.

Gardner, W. R., 1964. Relation of root distribution to water uptake and availability. Agron. J. 56: 41–45.

Gardner, W. R. & R. H. Nieman, 1964. Lower limit of water availability to plants. Science, N.Y. 143: 1460–1462.

Gardner, W. R., 1968. Availability and measurement of soil water. In: T. T. Kozlowski: Water deficits and plant growth I: 107–135.

Herk, A. W. H. van, 1946. Het totaliteitsprobleem in de plantefysiologie. Inaugural lecture, Amsterdam.

Holmes, R. M. & G. W. Robertson, 1963. Application of the relationship between actual and potential evapotranspiration in dry land agriculture. Trans. Am. Soc. agric. Engrs 6: 65–67.

Kramer, P. J., 1938: Root resistance as a cause of the absorption lag. Am. J. Bot. 25: 110–113.

Krause, H., 1935. Beiträge zur Kenntnis der Wasseraufnahme durch oberirdische Pflanzenorgane. Öst. bot. Z. 84: 241–270.

Lemon, E. R., 1956. The potentialities for decreasing soil moisture evaporation loss. Proc. Soil Sci. Soc. Am. 20: 120–125.

Makkink, G. F. & H. D. J. van Heemst, 1956. The actual evapotranspiration as a function of the potential evapotranspiration and the soil moisture tension. Neth. J. agric. Sci. 4: 67–76.

Makkink, G. F. & H. D. J. van Heemst, 1970. Berekening van de waterbalans van een perceel volgens de methode der dynamische digitale imitatie. Hydrologisch onderzoek in het Leerinkbeekgebied. Tweede interimrapport Comm. ter bestudering van de waterbehoefte van de Gelderse Landbouwgronden. Arnhem 1970: 195–208. Summary: 327.

Makkink, G. F. & H. D. J. van Heemst, 1972. De weerstand van bladeren als functie van hun watergehalte en het licht. Versl. landbouwk. Onderz. 774, 23 pp.

Makkink, G. F. & H. D. J. van Heemst. Simulation of the terms of the water balance in a soil. Simulation Monographs (in preparation).

Penman, H. L. & I. F. Long, 1960. Weather in wheat: an essay in micrometeorology. Q. Jl.R. met Soc. 86: 16–50.

Pisek, A. & E. Winkler, 1953. Die Schliessbewegung der Stomata bei ökologisch verschiedenen Pflanzentypen in Abhängigkeit von Wassersättigungszustand der Blätter und vom Licht. Planta 42: 253–278.

Rijtema, P. E., 1965. An analysis of actual evapotranspiration. Versl. landbouwk. Onderz. 659, 107 pp.

Shepherd, W., 1964. Diffusion pressure deficit and turgidity relationships of detached leaves of *Trifolium repens* L. Aust. J. agric. Res. 15: 746–751.

Sprenger, J. J. I., 1958. Kunstmatig drogen in de landbouw. 's-Gravenhage 1958, 289 pp.

Stålfelt, M. G., 1929. Die Abhängigkeit der Spaltöffnungsreaktionen von der Wasserbilanz. Planta 8: 287–340.

Stocker, O., 1956. Die Transpiration der Thallophyten. Handbuch der Pflanzenphysiologie III: 312–323.

Tanner, C. B., 1968. Evaporation of water from plants and soil. In: T. T. Kozlowski: Water deficits and plant growth I: 73–106.

Visser, W. C., 1965. The moisture consumption of plants described as a hydrological phenomenon. Proc. Symp. Wat. Stress Pl. Prague 1963: 257–267.

Weatherley, P. E. & R. O. Slatyer, 1957. Relationship between relative turgidity and diffusion pressure deficit in leaves. Nature. Lond. 179: 1085–1086.