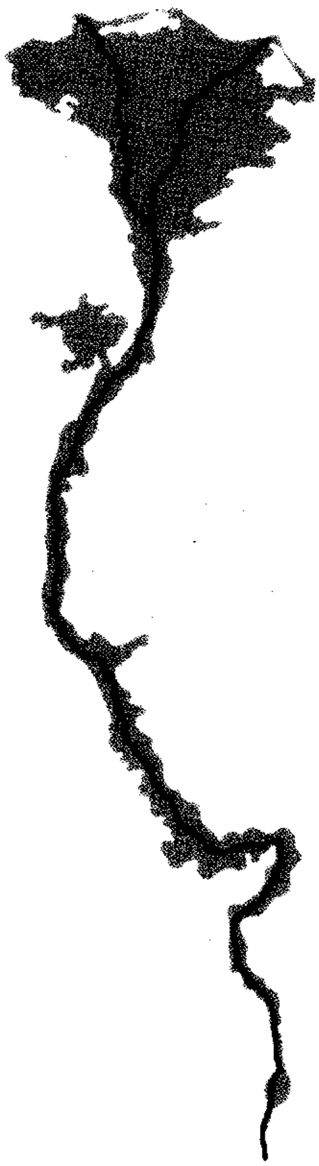
REUSE OF DRAINAGE WATER PROJECT

DRAINAGE
RESEARCH
INSTITUTE (DRI)
CAIRO
EGYPT



Reuse of Drainage Water Model, Calculation method of real evapotranspiration

M.A. Abdel Khalik, C.W.J. Roest and P.E. Rijtema

INSTITUTE FOR
LAND AND WATER
MANAGEMENT
RESEARCH (ICW)
WAGENINGEN
THE NETHERLANDS

5 SEP. 1986

ICW nota 1710 II
April 1986

REUSE OF DRAINAGE WATER PROJECT

Reuse of Drainage Water Model, Calculation method real evapotranspiration

M.A. Abdel Khalik, C.W.J. Roest and P.E. Rijtema

INSTITUTE FOR LAND AND WATER MANAGEMENT RESEARCH
P.O. BOX 35, 6700 AA WAGENINGEN, THE NETHERLANDS

DRAINAGE RESEARCH INSTITUTE
13 GIZEH STREET, GIZEH, CAIRO, EGYPT

C O N T E N T S

1. INTRODUCTION

The Reuse of Drainage Water Project is a research project financed by the Ministry of Irrigation in Egypt and the Ministry of Foreign Affairs in the Netherlands. The responsability for the implementation of this research has been delegated to the Drainage Research Institute (DRI) in Egypt and the Institute for Land and Water Management Research (ICW) in the Netherlands. The main objective of the project is to assist the Ministry of Irrigation in Egypt in the planning of future water management strategies incorporating reuse of drainage water practices. In order to achieve this main objective a comprehensive measurement programme has been initiated an a mathematical model is being formulated for the prediction of future effects of different water management strategies.

In the model approach the agricultural crop and its reaction to different water management practices is of prime importance. A separate model has been formulated to calculate the irrigation water distribution between the subarea's distinguished in the Nile Delta (RIJTEMA and BOELS, 1985). On subarea level a model has been formulated simulating the farmers behaviour with respect to priorities in irrigating the crops on his land and with respect to the (unofficial) reuse of drainage water if the irrigation water supply is insufficient.

For each identified subregion and for each crop present in this subregion the calculation of crop water use, drainage rate and soil salinity forms the core of the Reuse of Drainage Water Model. This part of the model can be subdivided into four related submodels: the calculation of the irrigation efficiency, the calculation of actual evapotranspiration, the calculation of drainage rates, and the calculation of soil and drainage water salinity. The irrigation efficiency submodel has been formulated and programmed (BOELS, 1986). On the calculation of drainage rate and salinity separate reports will be issued. In the present report the calculation of actual evapotranspiration will be treated.

The actual evapotranspiration is influenced by meteorological conditions, water management and soil and plant characteristics. Meteorological conditions do not differ much from year to year in Egypt (RIJTEMA and ABOU KHALED, 1975). For this reason use will be made of standardized meteorological data given by these authors. The soil characteristics influencing the evapotranspiration rate are the available moisture between field capacity and wilting point and the capillary characteristics of the soil. The crop influences evapotranspiration by the evaporative demand (crop height), the available water (rooting depth) and the plant stress conditions at which the stomata are closing. The influence of osmotic pressure in the soil due to salinity on the closure of stomata has also to be taken into account.

2. SOIL MOISTURE BALANCE

After irrigation of the soil a certain amount of soil moisture will be ultimately available for evapotranspiration. Upon depletion of this soil moisture capillary rise can positively contribute to this soil moisture reservoir. Because on the long term capillary rise may lower the watertable this phenomenon will only be considered under seepage conditions (i.e. with a stable watertable).

2.1. Calculation of available moisture

In the present model approach the total quantity of soil water present above drainage level after irrigation is considered present in three reservoirs:

- water stored in the drainable pore space; this water is available for drainage and for capillary rise;
- water stored below field capacity that will be available for evapotranspiration;
- water that is neither available for drainage nor for evapotranspiration.

In the complete soil profile, untill drainage depth the moisture present below wilting point is considered unavailable for evapotranspiration. In the soil layer between the rootzone and drainage depth an additional quantity of 50% of the moisture between field capacity and wilting point is considered unavailable (Fig. 1). Based on this assumptions the content of this reservoir can be calculated:

$$M_u = \frac{1}{2}(d_w+d_d)\ \theta_{wp} + \frac{1}{2}(d_d-d_w)\ \theta_{fc} \tag{1}$$

where: M_u = moisture in the soil profile above drainage depth not available for evapotranspiration (m)

d_w = thickness effective root zone (m)

d_d = drainage depth below soil surface (m)

θ_{wp} = moisture fraction at wilting point ($m^3.m^{-3}$)

θ_{fc} = moisture fraction at field capacity ($m^3.m^{-3}$)

The water in the soil profile available above field capacity (i.e. below the watertable) is considered to be available for capillary rise and drainage:

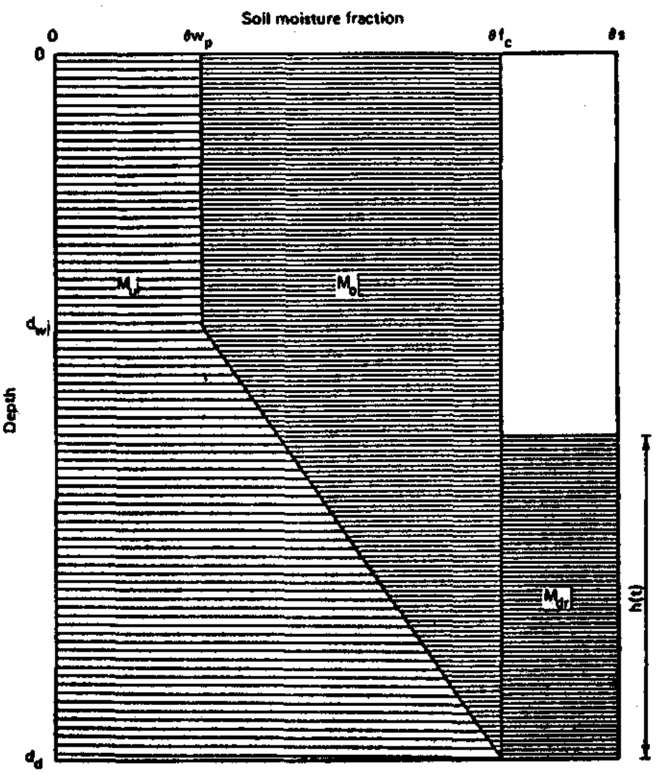


Fig. 1. Definition of unavailable moisture, M_u available moisture, M_o and drainable moisture, M_{dr}

$$M_{dr} = \mu h(t) \qquad h(t) > 0 \tag{2}$$

where: M_{dr} = moisture in the soil profile above drainage depth available for capillary rise or drainage (m)

μ = $\theta_s - \theta_{fc}$ = drainable porosity ($m^3.m^{-3}$)

θ_s = moisture fraction at saturation ($m^3.m^{-3}$)

$h(t)$ = phreatic waterlevel above drain depth (m)

Given the total moisture deficit and the phreatic waterlevel the moisture available for evapotranspiration can be calculated as the difference:

$$M(t) = M_s - M_d - \mu h(t) - M_u \tag{3}$$

where: $M(t)$ = moisture available for evapotranspiration (m)

M_s = moisture above drain depth at saturation (m)

= $d_d\theta_s$

M_d = total moisture deficit (m)

The maximum value for M(t) is reached when the moisture fraction above drain depth is completely at or above field capacity:

$$M_o = \frac{1}{2}(d_d+d_w)(\theta_{fc}-\theta_{wp}) \tag{4}$$

where: M_o = maximum available moisture for evapotranspiration at field capacity (m)

2.2. Mass balance equation

Immediately after irrigation the moisture available for evapotranspiration is known. Based on the two flux components influencing this available moisture in the period following irrigation, the evapotranspiration flux and the capillary flux the mass balance can be formulated:

$$\frac{dM(t)}{dt} = - E_r + f_c \qquad \text{with} \qquad M(t) = M(t_o) \qquad \text{if} \qquad t = t_o \tag{5}$$

Where: E_r = actual evapotranspiration rate at time t ($m.day^{-1}$)

f_c = capillary flux at time t ($m.day^{-1}$)

Depending on the occurrence of crop stress conditions the actual evapotranspiration may be equal to the atmospheric demand, or be reduced due to closure of the stomata in the plant leafs. Considering a fraction of the maximum available water M_o to be available under crop stress conditions only, (RIJTEMA and ABOUKHALED, 1975; RIJTEMA, 1981; 1982) the actual evapotranspiration rate can be approached:

$$E_r = E_{max} \qquad M(t) > aM_o \tag{6a}$$

$$E_r = \frac{M(t)}{aM_o} E_{max} \qquad M(t) \leqq aM_o$$

where: a = fraction of the maximum available soil water that is still available for evapotranspiration when reduction starts

E_{max} = maximum evaporative demand ($m.day^{-1}$)

The fraction a is depending, amongst others, on the leaf water potential at which the stomata start to close, the resistance of the plant for water transport from the soil to the leafs, the soil suction characteristics, the osmotic pressure in the soil water solution due to salinity, and on the maximum evaporative demand. The maximum evaporative demand is determined by meteorological factors and the crop stage of development (crop height and fractional soil cover).

Depending on leakage or seepage conditions and the soil moisture suction in the plant root zone the capillary flux will be assumed absent, equal to the seepage flux or between zero and seepage flux:

$$f_c = 0 \qquad \text{if } f_s \leqq 0 \tag{7a}$$

$$f_c = f_{max}\left(1 - \frac{M(t)}{M_o}\right) \qquad \text{if } M(t) > M_c \quad \text{and} \quad f_s > 0 \tag{7b}$$

$$f_c = f_s \qquad \text{if } M(t) \leqq M_c \quad \text{and} \quad f_s > 0 \tag{7c}$$

where: f_s = seepage flux when the phreatic water level is in equilibrium at drain depth ($m.day^{-1}$)

f_{max} = maximum possible capillary flux ($m.day^{-1}$)

M_c = available moisture at the moment that the seepage flux becomes limiting for the capillary flux ($m.day^{-1}$)

The boundary value for the available moisture M_c can be found by considering equation (7b) equal to the seepage flux f_s:

$$M_c = M_o \frac{f_{max} - f_s}{f_{max}} \tag{8}$$

The theoretical maximum capillary flux f_{max} can be calculated assuming the soil root zone at wilting point. This quantity depends on the distance between root zone and phreatic waterlevel and on the soil characteristics.

By defining the seepage flux equal to zero under leakage conditions equation (7a) becomes identical to equation (7c) and for the soil moisture balance equation by combination of equation (5), (6) and (7) four solutions are found:

1. Maximum evapotranspiration and capillary flux limited by the seepage flux:

$$\frac{dM(t)}{dt} = f_s - E_{max} \tag{9a}$$

2. Reduced evapotranspiration and capillary flux limited by the seepage flux:

$$\frac{dM(t)}{dt} = f_s - \frac{E_{max}}{aM_o} M(t) \tag{9b}$$

3. Maximum evapotranspiration and capillary flux limited by the available moisture for evapotranspiration:

$$\frac{dM(t)}{dt} = f_{max} - E_{max} - \frac{f_{max}}{M_o} M(t) \tag{9c}$$

4. Reduced evapotranspiration and capillary flux limited by the available moisture for evapotranspiration:

$$\frac{dM(t)}{dt} = f_{max} - \frac{1}{M_o}(\frac{E_{max}}{a} + f_{max})\ M(t) \tag{9d}$$

Depending on the sequence of boundary conditions and on the actual value of the moisture content these equations are valid in different combinations. In Table (1) a summary of the different boundary conditions and the applicability of the equations is given. Also included is a code under the heading 'type'. This code is used to facilitate the programming of equation (9)

Table 1. Validity of the different soil moisture balance equation

General conditions	Condition for M(t)	Equation	Type
$M_c \leq aM_o < M_o$	$aM_o < M(t) \leq M_o$	3	3
	$M_c < M(t) \leq aM_o$	4	
	$M(t) \leq M_c$	2	
$M_c \leq M_o \leq aM_o$	$M_c < M(t) \leq M_o$	4	4
	$M(t) \leq M_c$	2	
$aM_o \leq M_c < M_o$	$M_c < M(t) \leq M_o$	3	2
	$aM_o < M(t) \leq M_c$	1	
	$M(t) \leq aM_o$	2	
$aM_o < M_o \leq M_c$	$aM_o < M(t) \leq M_o$	1	1
	$M(t) \leq aM_o$	2	
$M_o \leq M_c$ and $M_o \leq aM_o$	-	2	5

2.3. Moisture balance algorithm

The equation given in Table 1 can be written in a generalized form:

$$\frac{dM(t)}{dt} = B - AM(t) \tag{10}$$

where: A = constant with dimension (day^{-1})

B = constant with dimension ($m.day^{-1}$)

The general solution of equation (9) is:

$$M(t) = \frac{B}{A} + (M(t_o) - \frac{B}{A})\ e^{-At} \qquad \text{if} \quad A \neq 0 \tag{11}$$

$$M(t) = M(t_o) + Bt \qquad \text{if} \quad A = 0 \tag{11b}$$

For the calculations of the soil moisture balance it will be necessary to determine which equation has to be used (which A and B constant). Based on the general conditions for the boundary values as characterized by the code given under 'type' the appropriate set of equations can be chosen (see Table 1). Based on the initial conditions for M(t) with respect to M_o, aM_o and M_c the appropriate equation is selected. Next, it will be necessary to determine for which part of the calculation time step this equation will be valid. The time required to reach the lower boundary value for M(t) can be calculated by introducing this boundary value into equation (11) and solving for time:

$$T = \frac{1}{A} \ln\left\{\frac{AM(t_o)-B}{AM_b-B}\right\} \qquad \text{if } A \neq 0 \text{ and } B \neq 0 \tag{12a}$$

$$T = \frac{M_b - M(t_o)}{B} \qquad \text{if } A = 0 \text{ and } B \neq 0 \tag{12b}$$

$$T = \infty \qquad \text{if } A = 0 \text{ and } B = 0 \tag{12c}$$

where: T = duration of validity of the current equation (days)

M_b = lower boundary value for M(t) (m)

This algorithm is illustrated in Fig. (2).

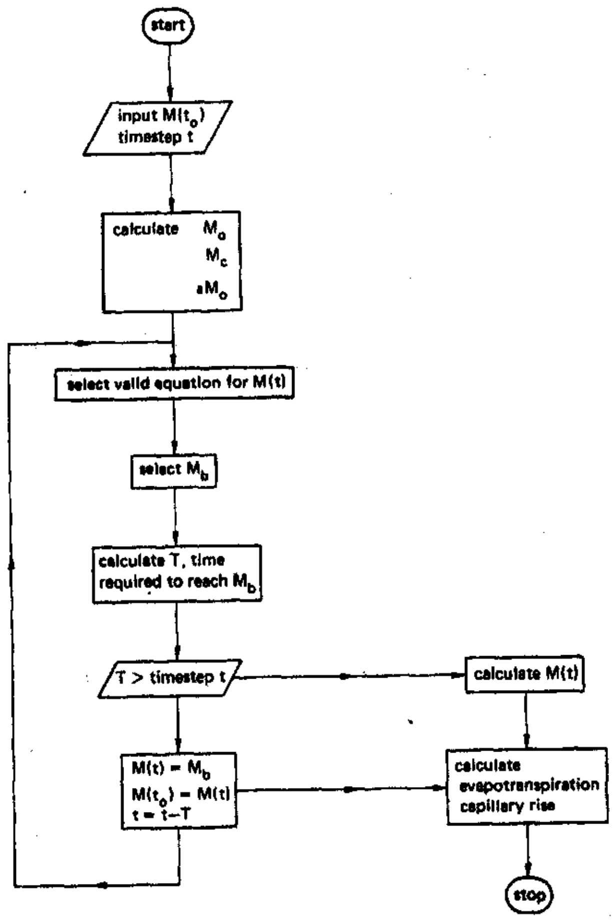


Fig. 2. Algorithm for the soil moisture balance

2.4. Atmospheric evaporative demand

In a previous study RIJTEMA and ABOUKHALED (1975) distinguished three climatological zones in the Nile Delta in Egypt: Coastal region, Centre Delta region and Desert Delta region. On the basis of standardized meteorological data for these regions they calculated mean monthly atmospheric evaporative demands related to crop height and fraction soil cover.

For the model calculations it is convenient to have these data available on decade basis. The results of calculations with the same standardized data, but on decade basis are presented in Table 2 for

Table 2. Mean atmospheric evaporative demand and open water evaporation E_o Coastal region in $mm.day^{-1}$

Decade	Crop height (m)										
	0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	E_o
1	1.10	2.29	2.90	3.21	3.45	3.67	3.85	4.03	4.16	4.25	1.66
2	1.30	2.45	3.08	3.39	3.65	3.87	4.06	4.25	4.37	4.47	1.78
3	1.44	2.63	3.28	3.60	3.86	4.08	4.28	4.48	4.61	4.70	2.06
4	1.62	2.89	3.57	3.91	4.19	4.43	4.63	4.84	4.97	5.08	2.29
5	1.82	3.14	3.86	4.23	4.52	4.77	4.99	5.21	5.35	5.46	2.37
6	2.09	3.40	4.14	4.51	4.80	5.06	5.28	5.50	5.65	5.76	2.87
7	2.41	3.82	4.63	5.03	5.35	5.64	5.88	6.12	6.28	6.40	3.23
8	2.76	4.27	5.12	5.55	5.89	6.19	6.44	6.70	6.87	7.00	3.56
9	3.12	4.57	5.42	5.85	6.19	6.49	6.75	7.00	7.17	7.30	3.95
10	3.41	4.80	5.63	6.04	6.38	6.67	6.92	7.17	7.33	7.46	4.32
11	3.75	5.10	5.93	6.34	6.68	6.97	7.21	7.46	7.63	7.75	4.61
12	4.18	5.46	6.30	6.72	7.05	7.35	7.60	7.85	8.02	8.14	5.11
13	4.56	5.71	6.51	6.91	7.23	7.51	7.75	7.99	8.15	8.28	5.54
14	4.94	5.96	6.75	7.14	7.46	7.73	7.97	8.20	8.36	8.48	6.11
15	5.28	6.23	6.98	7.36	7.66	7.93	8.15	8.38	8.53	8.64	6.29
16	5.55	6.46	7.20	7.57	7.87	8.13	8.35	8.58	8.73	8.84	6.60
17	5.81	6.64	7.36	7.71	8.00	8.25	8.47	8.69	8.83	8.94	7.04
18	6.01	6.89	7.61	7.97	8.26	8.51	8.73	8.95	9.09	9.20	7.09
19	6.23	7.10	7.82	8.19	8.48	8.73	8.95	9.17	9.31	9.42	7.37
20	6.32	7.21	7.94	8.30	8.59	8.84	9.06	9.28	9.42	9.53	7.64
21	6.23	7.10	7.81	8.16	8.45	8.69	8.91	9.12	9.26	9.37	7.37
22	6.00	6.84	7.52	7.86	8.13	8.37	8.57	8.78	8.91	9.01	7.08
23	5.74	6.61	7.29	7.64	7.91	8.15	8.35	8.56	8.70	8.80	6.89
24	5.43	6.39	7.09	7.44	7.72	7.96	8.17	8.38	8.52	8.62	6.67
25	5.10	6.17	6.92	7.30	7.60	7.87	8.09	8.32	8.47	8.58	6.06
26	4.70	5.82	6.60	7.00	7.31	7.58	7.82	8.05	8.21	8.33	5.74
27	4.26	5.32	6.07	6.45	6.75	7.02	7.25	7.47	7.62	7.74	5.12
28	3.77	4.73	5.42	5.77	6.05	6.29	6.50	6.70	6.84	6.95	4.60
29	3.19	4.13	4.77	5.09	5.35	5.57	5.76	5.95	6.08	6.18	4.07
30	2.83	3.80	4.45	4.78	5.04	5.26	5.46	5.65	5.78	5.88	3.54
31	2.42	3.33	3.95	4.27	4.52	4.74	4.93	5.12	5.24	5.34	3.01
32	1.86	2.77	3.33	3.61	3.84	4.03	4.20	4.37	4.48	4.56	2.24
33	1.42	2.44	3.00	3.28	3.51	3.70	3.87	4.04	4.15	4.23	2.19
34	1.14	2.16	2.72	3.01	3.23	3.43	3.60	3.77	3.88	3.97	1.90
35	1.01	2.08	2.67	2.96	3.19	3.40	3.57	3.75	3.87	3.95	1.47
36	1.06	2.23	2.85	3.16	3.41	3.62	3.81	3.99	4.12	4.21	1.53

the Coastal region, Table 3 for the Central Delta region and Table 4 for the Desert Delta region.

The reduction factor of the evaporative demand for incomplete soil cover by the crop is given in Table 5 (RIJTEMA and ABOUKHALED, 1975).

Table 3. Mean atmospheric evaporative demand and open water evaporation E_o Central Delta region in mm.day^{-1}

Decade	Crop height (cm)										
	0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.90	0.90	E_o
1	.89	1.58	1.95	2.15	2.30	2.44	2.56	2.68	2.75	2.81	1.21
2	.95	1.43	1.75	1.91	2.04	2.16	2.25	2.35	2.41	2.46	1.35
3	1.13	1.77	2,16	2,36	2,52	2.66	2.78	2.90	2.98	3.04	1.69
4	1.38	2.32	2.86	3.13	3.34	3.53	3.69	3.85	3.96	4.04	1.97
5	1.62	2.72	3.34	3.66	3.91	4.13	4.31	4.50	4.63	4.72	2.14
6	1.85	3.02	3.68	4.01	4.28	4.51	4.70	4.90	5.03	5.13	2.61
7	2.17	3.32	3.98	4.31	4.57	4.80	5.00	5.20	5.33	5.43	2.98
8	2.54	3.71	4.41	4.76	5.03	5.28	5.49	5.69	5.83	5.94	3.25
9	2.96	4.22	4.99	5.38	5.68	5.95	6.18	6.41	6.57	6.68	3.82
10	3.37	4.89	5.80	6.25	6.62	6.93	7.21	7.48	7.66	7.80	4.40
11	3.73	5.46	6.46	6.97	7.37	7.72	8.02	8.32	8.52	8.68	5.13
12	4.09	6.10	7.23	7.80	8.26	8.66	9.00	9.34	9.57	9.74	5.21
13	4.48	6.62	7.83	8.43	8.92	9.34	9.71	10.07	10.31	10.49	5.63
14	4.82	6.81	8.00	8.59	9.07	9.48	9.84	10.20	10.44	10.62	6.09
15	5.21	7.06	8.19	8.76	9.21	9.61	9.95	10.29	10.52	10.69	6.46
16	5.63	7.37	8.48	9.04	9.49	9.88	10.21	10.54	10.77	10.93	6.96
17	5.91	7.56	8.63	9.16	9.59	9.96	10.28	10.60	10.82	10.98	7.59
18	5.95	7.19	8.09	8.53	8.89	9.21	9.47	9.74	9.92	10.06	7.23
19	5.84	6.54	7.18	7.50	7.75	7.98	8.17	8.36	8.49	8.58	6.99
20	5.80	6.30	6.84	7.11	7.33	7.52	7.68	7.84	7.95	8.03	6.91
21	5.73	6.03	6.50	6.74	6.93	7.10	7.24	7.38	7.48	7.55	6.68
22	5.57	5.74	6.16	6.37	6.54	6.69	6.81	6.94	7.02	7.09	6.50
23	5.32	5.50	5.88	6.08	6.23	6.37	6.48	6.60	6.68	6.74	6.48
24	5.04	5.27	5.68	5.89	6.06	6.21	6.33	6.46	6.54	6.60	5.98
25	4.69	4.99	5.44	5.67	5.85	6.01	6.14	6.28	6.37	6.44	5.48
26	4.23	4.71	5.21	5.45	5.65	5.82	5.97	6.12	6.22	6.29	5.21
27	3.84	4.29	4.79	5.05	5.25	5.43	5.58	5.73	5.83	5.91	4.64
28	3.40	3.99	4.52	4.79	5.01	5.19	5.36	5.52	5.62	5.71	4.16
29	3.03	3.63	4.16	4.42	4.64	4.82	4.98	5.14	5.24	5.32	3.70
30	2.60	3.26	3.78	4.05	4.25	4.44	4.59	4.75	4.86	4.93	3.21
31	2.14	2.83	3.32	3.56	3.76	3.93	4.08	4.23	4.32	4.40	2.72
32	1.69	2.38	2.85	3.08	3.27	3.43	3.58	3.72	3.81	3.88	2.04
33	1.27	2.14	2.63	2.87	3.07	3.24	3.39	3.53	3.63	3.70	1.96
34	.98	1.87	2.36	2.60	2.80	2.97	3.11	3.26	3.36	3.43	1.52
35	.84	1.70	2.19	2.43	2.63	2.80	2.94	3.09	3.18	3.26	1.37
36	.87	1.64	2.08	2.31	2.49	2.64	2.78	2.91	3.00	3.07	1.31

This reduction factor has been formulated in such a way that for the fraction without plantcover the evaporation of medium dry bare soils is calculated. For the rice crop the above procedure is not correct. In this case the maximum evaporative demand has to be calculated as the weighted average of crop transpiration and open water evaporation:

Table 4. Mean atmospheric evaporative demand and open water evaporation E_o Desert Delta region in $mm.day^{-1}$

Decade	Crop height (m)										
	0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	E_o
1	1.17	2.67	3.45	3.84	4.15	4.43	4.66	4.89	5.05	5.17	1.66
2	1.28	2.78	3.57	3.96	4.27	4.55	4.78	5.02	5.18	5.30	1.90
3	1.43	3.00	3.81	4.22	4.55	4.84	5.08	5.33	5.49	5.61	2.20
4	1.65	3.38	4.28	4.73	5.09	5.41	5.68	5.95	6.13	6.26	2.47
5	1.95	3.94	4.98	5.50	5.91	6.28	6.59	6.90	7.11	7.26	2.57
6	2.25	4.39	5.50	6.06	6.51	6.90	7.23	7.56	7.79	7.95	3.21
7	2.65	4.98	6.19	6.79	7.27	7.69	8.06	8.42	8.66	8.84	3.67
8	3.10	5.52	6.79	7.43	7.93	8.38	8.76	9.14	9.39	9.58	4.17
9	3.42	6.02	7.35	8.01	8.54	9.01	9.41	9.80	10.07	10.27	4.55
10	3.70	6.44	7.83	8.52	9.08	9.57	9.98	10.40	10.68	10.89	4.98
11	3.97	6.84	8.29	9.02	9.61	10.12	10.55	10.99	11.28	11.50	5.34
12	4.32	7.45	9.03	9.82	10.45	11.00	11.48	11.95	12.27	12.50	5.88
13	4.74	7.97	9.64	10.47	11.13	11.72	12.22	12.71	13.05	13.30	6.35
14	5.28	8.51	10.25	11.12	11.82	12.43	12.95	13.47	13.82	14.08	6.97
15	5.71	8.86	10.59	11.46	12.15	12.76	13.28	13.80	14.15	14.41	7.17
16	6.03	9.20	10.93	11.80	12.49	13.10	13.62	14.14	14.48	14.74	7.52
17	6.23	9.35	11.04	11.89	12.57	13.16	13.67	14.17	14.51	14.77	8.07
18	6.30	9.01	10.50	11.25	11.85	12.37	12.82	13.27	13.57	13.79	7.97
19	6.33	8.49	9.77	10.41	10.92	11.36	11.74	12.13	12.38	12.57	7.83
20	6.35	8.11	9.25	9.82	10.28	10.67	11.02	11.36	11.58	11.76	7.64
21	6.21	7.88	8.97	9.51	9.95	10.33	10.66	10.99	11.20	11.37	7.51
22	5.97	7.55	8.57	9.07	9.48	9.84	10.14	10.45	10.65	10.80	7.15
23	5.69	7.11	8.05	8.53	8.90	9.24	9.52	9.80	9.99	10.13	7.07
24	5.35	6.71	7.62	8.07	8.43	8.75	9.02	9.30	9.48	9.61	6.48
25	5.04	6.39	7.30	7.76	8.12	8.44	8.71	8.99	9.17	9.31	5.95
26	4.58	5.98	6.88	7.33	7.69	8.00	8.27	8.54	8.72	8.86	5.75
27	4.05	5.48	6.34	6.77	7.12	7.42	7.68	7.94	8.11	8.24	5.19
28	3.64	4.92	5.73	6.13	6.45	6.73	6.98	7.22	7.38	7.50	4.55
29	3.27	4.36	5.10	5.48	5.78	6.04	6.26	6.49	6.64	6.75	4.01
30	2.79	3.67	4.30	4.62	4.87	5.10	5.29	5.48	5.61	5.70	3.47
31	2.27	2.90	3.41	3.66	3.86	4.04	4.19	4.34	4.44	4.52	2.92
32	1.78	2.64	3.17	3.43	3.64	3.83	3.99	4.15	4.25	4.33	2.16
33	1.35	2.44	3.01	3.29	3.52	3.72	3.89	4.05	4.17	4.25	2.06
34	1.03	2.49	3.16	3.50	3.77	4.01	4.21	4.41	4.54	4.64	1.95
35	1.05	2.62	3.39	3.78	4.09	4.36	4.59	4.82	4.97	5.09	1.65
36	1.10	2.57	3.34	3.72	4.03	4.30	4.53	4.76	4.91	5.02	1.59

$$E_{max} = s_c E_t + (1-s_c)\, E_o \qquad (13)$$

where: s_c = soil cover fraction

E_t = crop transpiration ($m.day^{-1}$)

E_o = open water evaporation ($m.day^{-1}$)

Table 5. Reduction factor of evaporative demand for soil cover percentage

Soil cover percentage	Coastal region		Central Delta region		Desert Delta region	
	winter	summer	winter	summer	winter	summer
0	0.27	0.32	0.28	0.38	0.25	0.29
10	0.34	0.40	0.35	0.47	0.32	0.38
20	0.41	0.47	0.43	0.54	0.39	0.45
30	0.49	0.55	0.50	0.62	0.47	0.52
40	0.57	0.63	0.58	0.69	0.55	0.61
50	0.67	0.72	0.66	0.78	0.65	0.70
60	0.78	0.82	0.78	0.86	0.76	0.80
70	0.86	0.89	0.87	0.91	0.85	0.88
80	0.94	0.95	0.94	0.96	0.93	0.94
90	1.00	1.00	1.00	1.00	1.00	1.00
100	1.00	1.00	1.00	1.00	1.00	1.00

2.5. Capillary rise

The capillary flux depends on the depth to the phreatic level and on the soil moisture suction in the rootzone. Assuming the maximum flux to occur when the soil moisture fraction on the rootzone is at wilting point; this will mean in practice a phreatic waterlevel at drain depth, or very close to it. The relation between capillary flux and distance to waterlevel has been reported by RIJTEMA (1969) for a number of standard soils. In Fig. (3) some of these relations are presented.

These type of curves can be approached by one or more exponential functions:

$$f_{max} = \sum_{n=1}^{3} a_n e^{-b_n Z} \tag{14}$$

where: a_n and b_n = curve fitting coefficients

$Z = d_d - 0.5\, d_w$ = distance between the centre of the rootzone and drain depth (m)

The coefficients a and b are presented in Table (6) where also the soil moisture fractions at saturation, field capacity (1 m suction) and wilting point have been included.

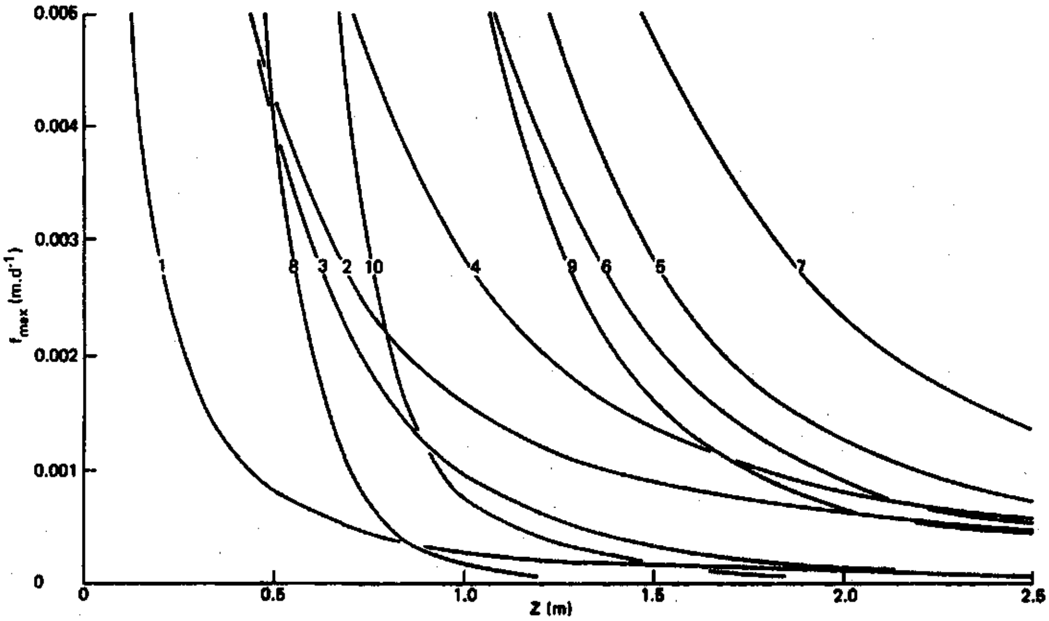


Fig. 3. Relation between maximum capillary flux f_{max} (m.day^{-1}) and distance to groundwater table Z (m) assuming a soil moisture suction of 160 m for a number of standard soils (data from RIJTEMA, 1969)

1 - basin clay	6 - loam
2 - silty clay	7 - silt loam
3 - clay loam	8 - sandy loam
4 - silty clay loam	9 - loamy fine sand
5 - sandy clay loam	10 - medium fine sand

Table 6. Coefficients for the calculation of f_{max} (m.day^{-1}) and the soil moisture characteristics of 10 standard soils

Soil type	Code	a_1	b_1	a_2	b_2	a_3	b_3	θ_s	θ_{fc}	θ_{wp}
basin clay	1	0.000589	0.840	0.00227	3.52	0.00656	9.04	0.540	0.519	0.321
silty clay	2	0.000951	0.392	0.00406	1.70	0.0138	4.29	0.507	0.463	0.257
clay loam	3	0.00640	0.203	0.0201	5.00	-	-	0.445	0.406	0.242
silty clay loam	4	0.00155	0.444	0.0188	2.33	-	-	0.475	0.372	0.185
sandy clay loam	5	0.00163	0.432	0.0856	2.50	-	-	0.432	0.338	0.180
loam	6	0.00495	0.900	0.164	3.67	-	-	0.503	0.420	0.098
silt loam	7	0.00495	0.600	0.0802	2.28	-	-	0.509	0.461	0.092
sandy loam	8	0.00663	0.611	0.692	12.90	-	-	0.465	0.260	0.061
loamy fine sand	9	0.00122	0.540	0.0995	3.00	-	-	0.439	0.179	0.060
medium fine sand	10	0.00448	2.140	1.19	8.63	-	-	0.350	0.155	0.023

3. CALCULATION OF READILY AVAILABLE SOIL MOISTURE; a-FACTOR

3.1. Theoretical approach

For the calculation of the soil and crop factor a (eq. 6b) the approach given by RIJTEMA and ABOUKHALED (1975) has been extended with the osmotic suction in the soil solution due to dissolved salts. Including these osmotic effects the relation between leaf water suction, transpiration and soil physical conditions can be given:

$$\Psi_\ell = E(r_{pl} + \frac{b}{k}) + \Psi_s + \Psi_{osm} \tag{15}$$

where: Ψ_ℓ = leaf water suction (bar)
E = evapotranspiration ($mm.day^{-1}$)
r_{pl} = crop resistance for water flow from root surface to the substomatal cavities ($bar.day.mm^{-1}$)
b = geometry and activity factor of the root system (bar)
Ψ_s = mean soil water suction in the rootzone (bar)
k = capillary conductivity at soil water suction Ψ_s ($mm.day^{-1}$)
Ψ_{osm} = mean osmotic suction in the rootzone at soil water suction Ψ_s (bar)

Assuming a linear increase of the osmotic suction with the decrease of the soil moisture fraction and taking the osmotic suction at field capacity as a reference the relation between Ψ_{osm} and the available moisture fraction at any time can be given as:

$$\Psi_{osm} = \frac{\theta_{ma} + \theta_{wp}}{\theta_a + \theta_{wp}} \Psi_o \tag{16}$$

where: Ψ_o = osmotic suction at field capacity (bar)
θ_a = available moisture fraction ($m^3.m^{-3}$)
θ_{ma} = maximum available moisture fraction ($m^3.m^{-3}$)

The crop resistance for water flow increases with the depletion of available soil moisture. Assuming a minimum value of 0.5 bar $day.mm^{-1}$ at field capacity and a maximum value of 3.60 at wilting point the following relationship is assumed:

$$r_{pl} = 0.613 \ln(\Psi_s) + 1.493 \tag{17}$$

Using the empirical relationships given by RIJTEMA and ABOUKHALED (1975) for Ψ_s, k and b and introducing the relations for Ψ_{osm} and r_{pl} in the general equation (15) the following relation between E and θ_a can be derived:

$$\Psi_\ell = E(3.60-0.613\ \alpha\theta_a + \frac{0.1275}{d_w a'}\ e^{-1.4\ \alpha\theta_a}) + 16\ e^{-\alpha\theta_a} + \Psi_o \frac{\theta_{fc}}{\theta_a + \theta_{wp}} \tag{18}$$

where: α = constant

d_w = effective rootzone depth (mm)

a' = constant ($mm.day^{-1}$)

Based on a classification of standard soils in three groups: fine textured, medium textured and coarse textured soils the constants and the average value for θ_a and θ_{wp} are given in Table (7).

Equation (18) can be used to calculate the critical available moisture fraction Θ_c at which the stomata start to close by substituting the critical leaf water potential Ψ_c for Ψ_ℓ and the maximum evaporative demand E_{max} for the transpiration rate E. Due to the complex nature of equation (18) the solution has to be found by trial and error. Once the value of $\theta_a (= \theta_c)$ for which the Right Hand Side of eq. (18) equals the Left Hand Side has been found, the a-factor can be calculated:

$$a = \frac{\theta_c}{\theta_{ma}} \tag{19a}$$

where θ_c = available moisture at which reduction starts

Table 7. Soil parameters for the calculations with equation (18)

Soil type	α	a'	θ_{wp}	θ_{ma}
fine textured	22.55	0.000462	0.200	0.225
medium textured	33.67	0.000264	0.100	0.150
coarse textured	74.45	0.000132	0.025	0.067

With extremely high maximum evaporative demands and/or with high osmotic pressures the possibility exists that evapotranspiration reduction starts already at field capacity. In this case equation (18) has no solution for a value of $\theta_c \leq \theta_{ma}$ and a different approach has to be followed. By introduction of the critical leaf water potential Ψ_c for Ψ_ℓ and the maximum available water θ_{ma} for θ_a the maximum attainable transpiration E_c can be calculated with equation (18). Assuming a linear reduction in transpiration for moisture fractions below field capacity the a-factor can be formulated in this case as:

$$a = \frac{E_{max}}{E_c} \qquad (19b)$$

where: E_c = maximum attainable evapotranspiration rate at field capacity ($mm.day^{-1}$)

These calculations have been performed for the three main soil groups (fine textured, medium textured and coarse textured) for different critical leaf water potentials (Ψ_c = 13 eg. cotton; Ψ_o = 10 eg wheat; Ψ_c = 7 eg sunflower; Ψ_c = 4 eg potatoes, tomatoes) and for different osmotic potentials ranging from 0 to 5.5 bar. The results that do not differ much between the main soil groups are presented in Tables 8, 9 and 10.

Table 8. The fraction of soil water available under plants stress conditions, a-factor, in relation to osmotic pressure, evaporative demand and critical leaf water suction Ψ_c for fine textured soils

E_{max} mm/day	Osmotic pressure											
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
Ψ_c = 13												
1	.101	.120	.139	.160	.182	.205	.230	.256	.283	.313	.344	.378
2	.172	.194	.217	.242	.268	.295	.324	.355	.387	.421	.456	.492
3	.253	.279	.306	.335	.364	.395	.427	.460	.493	.528	.562	.597
4	.344	.373	.402	.432	.463	.494	.526	.558	.589	.621	.653	.684
5	.437	.466	.495	.525	.554	.583	.612	.640	.669	.697	.725	.752
6	.523	.550	.577	.604	.630	.656	.682	.707	.732	.757	.781	.804
7	.597	.622	.646	.669	.693	.716	.738	.760	.782	.804	.825	.846
8	.659	.680	.702	.723	.743	.764	.784	.803	.823	.842	.860	.879
9	.709	.729	.748	.766	.785	.803	.821	.838	.856	.873	.889	.906
10	.751	.769	.786	.803	.819	.835	.851	.867	.883	.898	.913	.928
11	.787	.802	.818	.833	.848	.862	.877	.891	.906	.920	.933	.947
12	.816	.831	.845	.858	.872	.886	.899	.912	.925	.938	.950	.963
13	.842	.855	.868	.880	.893	.905	.918	.930	.942	.953	.965	.977
14	.864	.876	.888	.899	.911	.922	.934	.945	.956	.967	.978	.989
15	.883	.894	.905	.916	.927	.937	.948	.958	.969	.979	.989	.999
Ψ_c = 10												
1	.168	.192	.217	.245	.275	.307	.341	.379	.419	.462	.508	.558
2	.258	.288	.319	.353	.389	.427	.467	.508	.552	.596	.642	.688
3	.364	.398	.433	.470	.508	.547	.586	.626	.666	.706	.745	.784
4	.473	.508	.543	.579	.614	.649	.684	.719	.752	.786	.819	.851
5	.572	.604	.636	.667	.698	.728	.758	.787	.816	.844	.872	.899
6	.654	.682	.709	.736	.763	.789	.814	.839	.864	.888	.911	.935
7	.718	.742	.766	.790	.812	.835	.857	.879	.900	.921	.942	.962
8	.769	.790	.811	.832	.852	.871	.891	.910	.929	.947	.965	.983
9	.810	.829	.847	.865	.883	.901	.918	.935	.952	.968	.984	1.002
10	.843	.860	.877	.893	.909	.925	.940	.955	.971	.985	1.000	1.114
11	.871	.886	.901	.916	.930	.945	.959	.973	.986	1.000	1.100	1.225
12	.894	.908	.922	.935	.948	.961	.974	.987	1.000	1.089	1.200	1.336
13	.914	.927	.939	.952	.964	.976	.988	.999	1.080	1.180	1.300	1.448
14	.931	.943	.954	.966	.977	.988	.999	1.072	1.163	1.270	1.400	1.559
15	.946	.957	.968	.978	.989	.999	1.065	1.149	1.246	1.361	1.500	1.671
Ψ_c = 7												
1	.265	.299	.338	.380	.426	.478	.533	.594	.659	.727	.798	.869
2	.391	.435	.481	.530	.581	.634	.689	.743	.798	.852	.905	.957
3	.528	.572	.618	.663	.709	.753	.798	.841	.884	.925	.966	1.050
4	.645	.684	.723	.761	.798	.834	.870	.904	.938	.972	1.032	1.400
5	.733	.766	.798	.829	.860	.890	.919	.947	.975	1.021	1.290	1.750
6	.798	.825	.852	.878	.904	.929	.954	.978	1.014	1.225	1.548	2.100
7	.846	.870	.893	.915	.938	.959	.980	1.009	1.183	1.429	1.805	2.450
8	.884	.904	.924	.944	.963	.982	1.005	1.153	1.352	1.633	2.063	2.800
9	.913	.931	.949	.966	.984	1.002	1.131	1.297	1.521	1.838	2.321	3.150
10	.937	.953	.969	.985	1.000	1.114	1.257	1.441	1.690	2.042	2.579	3.500
11	.957	.971	.986	1.000	1.100	1.225	1.382	1.585	1.859	2.246	2.837	3.851
12	.973	.986	1.000	1.089	1.200	1.336	1.508	1.730	2.028	2.450	3.095	4.201
13	.987	.999	1.080	1.180	1.300	1.448	1.633	1.874	2.197	2.654	3.353	4.551
14	.999	1.072	1.163	1.270	1.400	1.559	1.759	2.018	2.366	2.859	3.611	4.901
15	1.065	1.149	1.246	1.361	1.500	1.671	1.885	2.162	2.535	3.063	3.869	5.251
Ψ_c = 4												
1	.437	.500	.572	.652	.739	.831	.924	1.225				
2	.624	.689	.755	.821	.886	.949	1.089	2.451				
3	.765	.816	.866	.914	.961	1.050	1.634	3.676				
4	.853	.893	.931	.968	1.032	1.400	2.178	4.902				
5	.911	.942	.973	1.021	1.290	1.750	2.723	6.127				
6	.950	.976	1.014	1.225	1.548	2.100	3.267	7.353				
7	.979	1.009	1.183	1.429	1.805	2.450	3.812	8.578				
8	1.005	1.153	1.352	1.633	2.063	2.800	4.356	9.804				
9	1.131	1.297	1.521	1.838	2.321	3.150	4.901	11.029				
10	1.257	1.441	1.690	2.042	2.579	3.500	5.446	12.255				
11	1.382	1.585	1.859	2.246	2.837	3.851	5.990	13.480				
12	1.508	1.730	2.028	2.450	3.095	4.201	6.535	14.706				
13	1.633	1.874	2.197	2.654	3.353	4.551	7.079	15.931				
14	1.759	2.018	2.366	2.859	3.611	4.901	7.624	17.157				
15	1.885	2.162	2.535	3.063	3.869	5.251	8.168	18.382				

Table 9. The fraction of soil water available under plant stress conditions, a-factor, in relation to osmotic pressure, evaporative demand and critical leaf water suction Ψ_c for medium textured soils

E_{max} mm/day	Osmotic pressure											
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
$\Psi_c = 13$												
1	.103	.124	.147	.170	.194	.220	.247	.275	.305	.337	.370	.405
2	.175	.200	.225	.252	.280	.310	.341	.373	.407	.441	.477	.514
3	.258	.286	.315	.345	.376	.408	.441	.475	.509	.544	.579	.614
4	.349	.379	.410	.441	.473	.505	.537	.570	.602	.633	.665	.696
5	.441	.471	.502	.532	.562	.591	.621	.650	.678	.706	.734	.761
6	.527	.555	.583	.610	.637	.663	.689	.715	.740	.764	.788	.812
7	.601	.626	.651	.675	.698	.722	.744	.767	.789	.810	.831	.852
8	.662	.684	.706	.728	.749	.769	.789	.809	.828	.847	.866	.884
9	.713	.733	.752	.771	.790	.808	.826	.843	.861	.878	.894	.911
10	.755	.773	.790	.807	.824	.840	.856	.872	.888	.903	.918	.933
11	.790	.806	.822	.837	.852	.867	.882	.896	.910	.924	.938	.952
12	.820	.835	.849	.863	.877	.890	.903	.917	.930	.942	.955	.967
13	.846	.859	.872	.885	.897	.910	.922	.934	.946	.958	.970	.981
14	.868	.880	.892	.904	.915	.927	.938	.949	.961	.972	.982	.993
15	.887	.898	.909	.920	.931	.942	.952	.963	.973	.983	.993	1.023
$\Psi_c = 10$												
1	.170	.197	.225	.256	.288	.323	.360	.399	.441	.485	.532	.582
2	.262	.294	.328	.364	.401	.441	.482	.525	.569	.613	.658	.703
3	.367	.404	.441	.479	.519	.558	.598	.638	.678	.717	.756	.794
4	.477	.513	.550	.586	.622	.658	.693	.727	.761	.794	.826	.858
5	.576	.609	.641	.673	.704	.735	.765	.794	.823	.851	.878	.905
6	.657	.686	.714	.741	.768	.794	.820	.845	.869	.893	.917	.940
7	.722	.746	.771	.794	.817	.840	.862	.884	.905	.926	.946	.966
8	.773	.794	.815	.836	.856	.876	.896	.915	.933	.952	.970	.987
9	.814	.833	.852	.870	.888	.905	.923	.940	.956	.973	.989	1.032
10	.847	.864	.881	.897	.913	.929	.945	.960	.975	.990	1.030	1.147
11	.875	.891	.906	.920	.935	.949	.963	.977	.991	1.028	1.133	1.262
12	.899	.912	.926	.940	.953	.966	.979	.991	1.026	1.122	1.236	1.377
13	.919	.931	.944	.956	.968	.980	.992	1.025	1.112	1.215	1.339	1.491
14	.936	.947	.959	.970	.982	.993	1.024	1.104	1.198	1.308	1.442	1.606
15	.951	.961	.972	.983	.993	1.023	1.097	1.183	1.283	1.402	1.545	1.721
$\Psi_c = 7$												
1	.267	.305	.346	.391	.440	.494	.551	.612	.676	.743	.811	.879
2	.395	.440	.489	.540	.592	.646	.700	.754	.807	.860	.911	.962
3	.531	.577	.624	.670	.716	.761	.805	.848	.890	.931	.970	1.083
4	.648	.688	.728	.766	.804	.840	.875	.910	.943	.976	1.063	1.444
5	.737	.770	.802	.834	.865	.895	.924	.952	.890	1.052	1.329	1.805
6	.802	.829	.857	.883	.909	.934	.959	.983	1.045	1.262	1.595	2.166
7	.850	.874	.897	.920	.942	.964	.985	1.039	1.219	1.473	1.861	2.527
8	.888	.908	.929	.948	.968	.987	1.035	1.188	1.393	1.683	2.127	2.888
9	.918	.936	.953	.971	.988	1.032	1.165	1.336	1.567	1.894	2.393	3.249
10	.941	.958	.974	.989	1.030	1.147	1.294	1.485	1.741	2.104	2.659	3.610
11	.961	.976	.990	1.028	1.133	1.262	1.424	1.633	1.915	2.314	2.924	3.971
12	.978	.991	1.026	1.122	1.236	1.377	1.553	1.782	2.089	2.525	3.190	4.332
13	.992	1.025	1.112	1.215	1.339	1.491	1.683	1.930	2.263	2.735	3.456	4.693
14	1.024	1.104	1.198	1.308	1.442	1.606	1.812	2.079	2.437	2.946	3.722	5.054
15	1.097	1.183	1.283	1.402	1.545	1.721	1.941	2.227	2.611	3.156	3.988	5.415
$\Psi_c = 4$												
1	.439	.506	.581	.662	.749	.839	.930	1.269				
2	.627	.694	.761	.827	.891	.953	1.124	2.538				
3	.768	.820	.871	.919	.965	1.083	1.686	3.807				
4	.857	.897	.936	.973	1.063	1.444	2.248	5.076				
5	.915	.947	.978	1.052	1.329	1.805	2.810	6.345				
6	.955	.981	1.045	1.262	1.595	2.166	3.372	7.614				
7.	.984	1.039	1.219	1.473	1.861	2.527	3.934	8.883				
8	1.035	1.188	1.393	1.683	2.127	2.888	4.497	10.152				
9	1.165	1.336	1.567	1.894	2.393	3.249	5.059	11.422				
10	1.294	1.485	1.741	2.104	2.659	3.610	5.621	12.691				
11	1.424	1.633	1.915	2.314	2.924	3.971	6.183	13.960				
12	1.553	1.782	2.089	2.525	3.190	4.332	6.745	15.229				
13.	1.683	1.930	2.263	2.735	3.456	4.693	7.307	16.498				
14	1.812	2.079	2.437	2.946	3.722	5.054	7.869	17.767				
15	1.941	2.227	2.611	3.156	3.988	5.415	8.431	19.036				

Table 10. The fraction of soil water available under plant stress conditions, the a-factor, in relation to osmotic pressure, evaporative demand and critical leaf water suction Ψ_c for coarse textured soils

E_{max} mm/day	Osmotic pressure											
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
Ψ_c = 13												
1	.108	.135	.163	.191	.220	.251	.282	.314	.347	.381	.417	.453
2	.182	.211	.242	.273	.305	.338	.372	.407	.442	.478	.514	.550
3	.264	.297	.329	.363	.397	.432	.466	.501	.536	.570	.604	.638
4	.354	.388	.422	.455	.489	.522	.555	.588	.620	.651	.682	.712
5	.445	.478	.510	.542	.573	.603	.633	.662	.690	.718	.745	.771
6	.529	.559	.588	.617	.644	.671	.697	.723	.748	.772	.795	.818
7	.602	.629	.654	.679	.703	.727	.750	.772	.794	.815	.836	.856
8	.663	.686	.709	.731	.752	.773	.793	.813	.832	.851	.869	.887
9	.713	.734	.754	.773	.792	.810	.828	.846	.863	.880	.896	.913
10	.755	.773	.791	.808	.825	.842	.858	.874	.889	.904	.919	.934
11	.790	.807	.822	.838	.853	.868	.883	.897	.911	.925	.938	.952
12	.820	.835	.849	.863	.877	.891	.904	.917	.930	.943	.955	.967
13	.845	.859	.872	.885	.898	.910	.922	.934	.946	.958	.969	.981
14	.867	.880	.892	.904	.915	.927	.938	.949	.960	.971	.982	.992
15	.887	.898	.909	.920	.931	.942	.952	.962	.973	.983	.993	1.018
Ψ_c = 10												
1	.174	.207	.241	.277	.314	.353	.394	.436	.480	.525	.572	.620
2	.267	.304	.343	.383	.424	.466	.508	.552	.595	.639	.682	.725
3	.372	.412	.453	.493	.534	.575	.615	.655	.694	.732	.769	.806
4	.480	.519	.557	.595	.632	.668	.703	.737	.770	.803	.834	.864
5	.577	.612	.646	.679	.711	.741	.771	.800	.828	.855	.882	.908
6	.658	.688	.717	.745	.772	.798	.823	.848	.872	.896	.919	.941
7	.722	.748	.772	.796	.820	.842	.864	.886	.907	.927	.947	.967
8	.773	.795	.816	.837	.858	.877	.897	.916	.934	.952	.970	.987
9	.814	.833	.852	.870	.888	.906	.923	.940	.956	.972	.988	1.027
10	.847	.864	.881	.898	.914	.929	.945	.960	.975	.989	1.025	1.141
11	.875	.890	.905	.920	.935	.949	.963	.977	.990	1.023	1.127	1.256
12	.898	.912	.926	.939	.952	.965	.978	.991	1.021	1.116	1.230	1.370
13	.918	.931	.943	.956	.968	.980	.991	1.020	1.106	1.209	1.332	1.484
14	.935	.947	.958	.970	.981	.992	1.019	1.098	1.192	1.302	1.435	1.598
15	.950	.961	.971	.982	.992	1.018	1.092	1.177	1.277	1.395	1.537	1.712
Ψ_c = 7												
1	.270	.314	.361	.412	.465	.521	.580	.640	.702	.765	.828	.890
2	.397	.448	.501	.554	.608	.662	.715	.767	.818	.868	.917	.964
3	.533	.582	.631	.678	.724	.769	.812	.854	.894	.933	.971	1.077
4	.649	.691	.731	.770	.808	.844	.878	.912	.945	.976	1.058	1.436
5	.737	.771	.804	.836	.867	.896	.925	.953	.980	1.047	1.322	1.795
6	.801	.830	.857	.884	.910	.935	.959	.982	1.039	1.256	1.587	2.155
7	.850	.874	.897	.920	.942	.963	.984	1.034	1.213	1.465	1.851	2.514
8	.887	.908	.928	.948	.967	.986	1.030	1.182	1.386	1.675	2.116	2.873
9	.917	.935	.953	.970	.987	1.027	1.159	1.330	1.559	1.884	2.380	3.232
10	.941	.957	.973	.988	1.025	1.141	1.288	1.477	1.732	2.093	2.645	3.591
11	.960	.975	.989	1.023	1.127	1.256	1.417	1.625	1.905	2.303	2.909	3.950
12	.977	.990	1.021	1.116	1.230	1.370	1.545	1.773	2.079	2.512	3.174	4.309
13	.991	1.020	1.106	1.209	1.332	1.484	1.674	1.921	2.252	2.722	3.438	4.668
14	1.019	1.098	1.192	1.302	1.435	1.598	1.803	2.068	2.425	2.931	3.703	5.027
15	1.092	1.177	1.277	1.395	1.537	1.712	1.932	2.216	2.598	3.140	3.967	5.386
Ψ_c = 4												
1	.441	.514	.593	.676	.762	.849	.934	1.261				
2	.628	.698	.766	.832	.895	.955	1.118	2.523				
3	.768	.821	.872	.920	.966	1.077	1.677	3.784				
4	.857	.897	.936	.972	1.058	1.436	2.236	5.046				
5	.914	.946	.977	1.047	1.322	1.795	2.795	6.307				
6	.954	.980	1.039	1.256	1.587	2.155	3.354	7.568				
7	.983	1.034	1.213	1.465	1.851	2.514	3.913	8.830				
8	1.030	1.182	1.386	1.675	2.116	2.873	4.472	10.091				
9	1.159	1.330	1.559	1.884	2.380	3.232	5.031	11.353				
10	1.288	1.477	1.732	2.093	2.645	3.591	5.590	12.614				
11	1.417	1.625	1.905	2.303	2.909	3.950	6.149	13.875				
12	1.545	1.773	2.079	2,512	3.174	4.309	6.709	15.137				
13	1.674	1.921	2.252	2.722	3.438	4.688	7.268	16 398				
14	1.803	2.068	2.425	2.931	3.703	5.027	7,827	17.660				
15	1.932	2.216	2.598	3.140	3.967	5.386	8.386	18.921				

3.2. Simplified method

For the application of the reuse model on a regional scale the trial and error calculations of the soil moisture availability factor a are too time consuming. Therefore a less time consuming calculation procedure has to be established.

The first simplification applied is neglecting the differences between the major soil types. As can be seen in Table 8, 9 and 10 the variation in the a factor is much greater as a result of variation in osmotic suction and evaporative demand than of soil type. The formulation of the a factor as a function of E_{max} and Ψ_o can be split up in two parts. Given the osmotic suction and the critical leaf water suction the theoretical evaporative demand can be calculated where reduction starts at field capacity. Above this boundary value for the evaporative demand the relation between the a factor and E_{max} is linear (see eq. 19a).

Using equation (18) the following relation between E_b and Ψ_c and Ψ_o has been found:

$$E_b = 2.0415(\Psi_c - \Psi_o) - 0.2175 \tag{20}$$

where: E_b = maximum evaporative demand ($mm.day^{-1}$) that can be sustained when the soil is at field capacity

For values of E_{max} above E_b the a factor is a linear relation of E_{max}; the slope of this relation is determined by the osmotic suction. By polynomial curve fitting the following general relation has been found for this case:

$$a = E_{max} \sum_{n=o}^{6} a_n \Psi_o^n \qquad \text{for } E_{max} > E_b \tag{21a}$$

where: a_n = coefficients related to Ψ_c (see Table 11)

For E_{max} values below E_b the relation with E_{max} is not linear. The following general relation has been found by curve fitting for these circumstances:

$$a = \sum_{n=o}^{4} \alpha_n E_{max}^n + \Psi_o(\beta_o + \beta_1 E_{max}) + \Psi_o^2(\delta_o + \delta_1 \Psi_{max}) \tag{21b}$$

Table 11. Coefficients of equation (21a)

Ψ_c	13	10	7	4
a_o	0.06033	0.2984	0.07787	0.1173
a_1	-	-0.1846	-	0.04599
a_2	-	0.05114	-	0.03290
a_3	0.00002642	-0.004965	0.005658	-
a_4	-	-	-0.001943	-0.09730
a_5	0.0000007870	0.00002140	0.0002202	-
a_6	-	-	-	0.001088

where α_n, β_o, β_1, δ_o and δ_1 are coefficients related to Ψ_c (see Table 12).

The goodness of fit of the simplified approach with the theoretical calculations is rather good. In Fig. 4, 5, 6 and 7 both calculations are compared within the range of E_{max} from 3-10 mm.day^{-1} and Ψ_o from 0 to 5.5 bar.

Table 12. Coefficients of equation (21b)

Ψ_c	13	10	7	4
α_o	0.04005	0.08829	0.1509	0.2705
α_1	0.04571	0.07737	0.1305	0.1603
α_2	0.01299	0.009430	0.0009200	0.02180
α_3	-0.001489	-0.001427	-0.001077	-0.00889
α_4	0.00004473	0.00004736	0.00004700	0.0006530
β_o	0.05933	0.08133	0.1168	0.1620
β_1	-0.002444	-0.04444	-0.009600	-0.2000
δ_o	0.002825	0.002153	0.00006400	-0.005000
δ_1	-0.0002850	-0.0002107	-0.00004800	0.001000

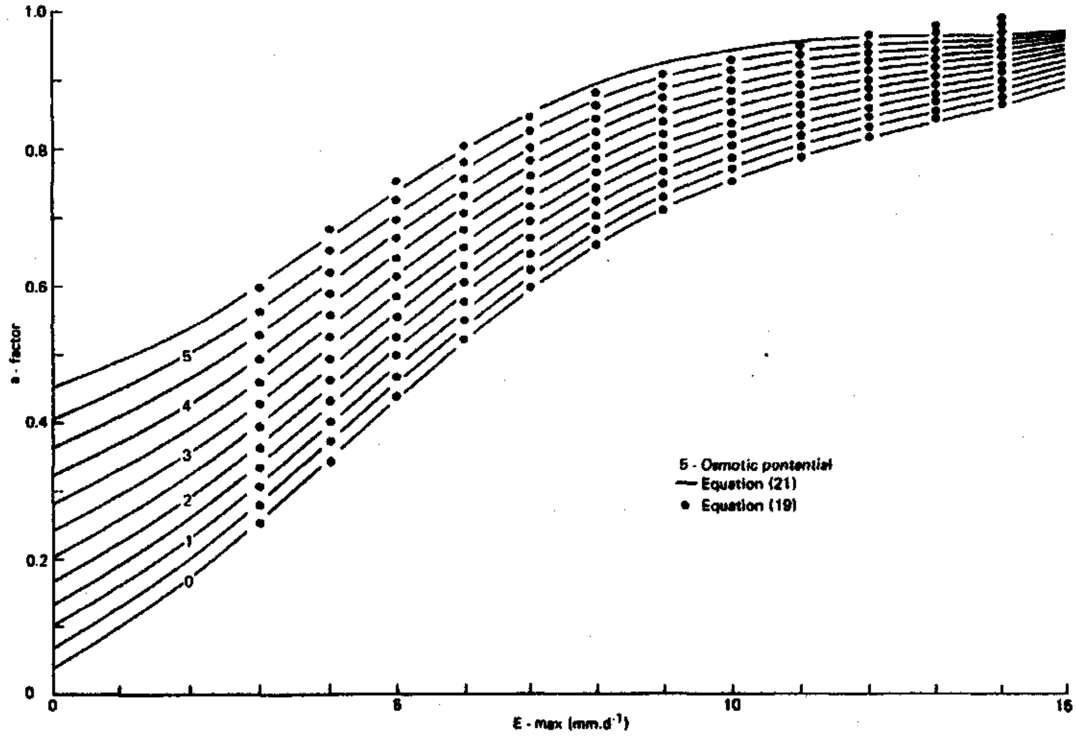


Fig. 4. Factor a for different osmotic functions; Ψ_c = 13 bar

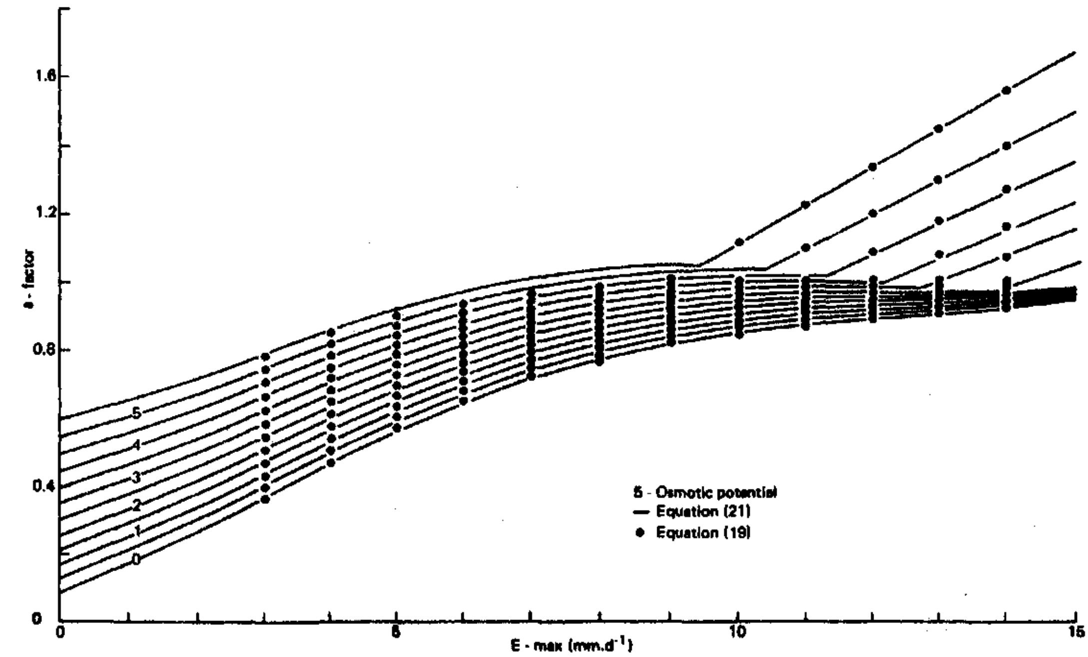


Fig. 5. Factor a for different osmotic suctions; $_c$ = 10 bar

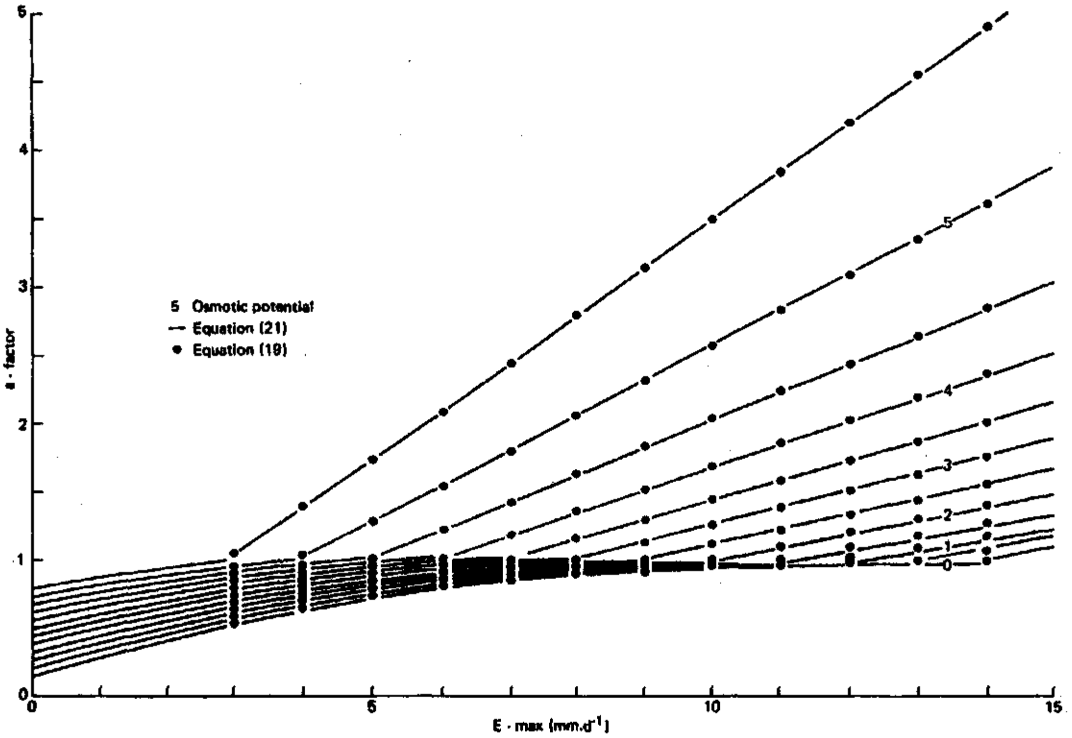


Fig. 6. Factor a for different osmotic suctions; Ψ_c = 7 bar

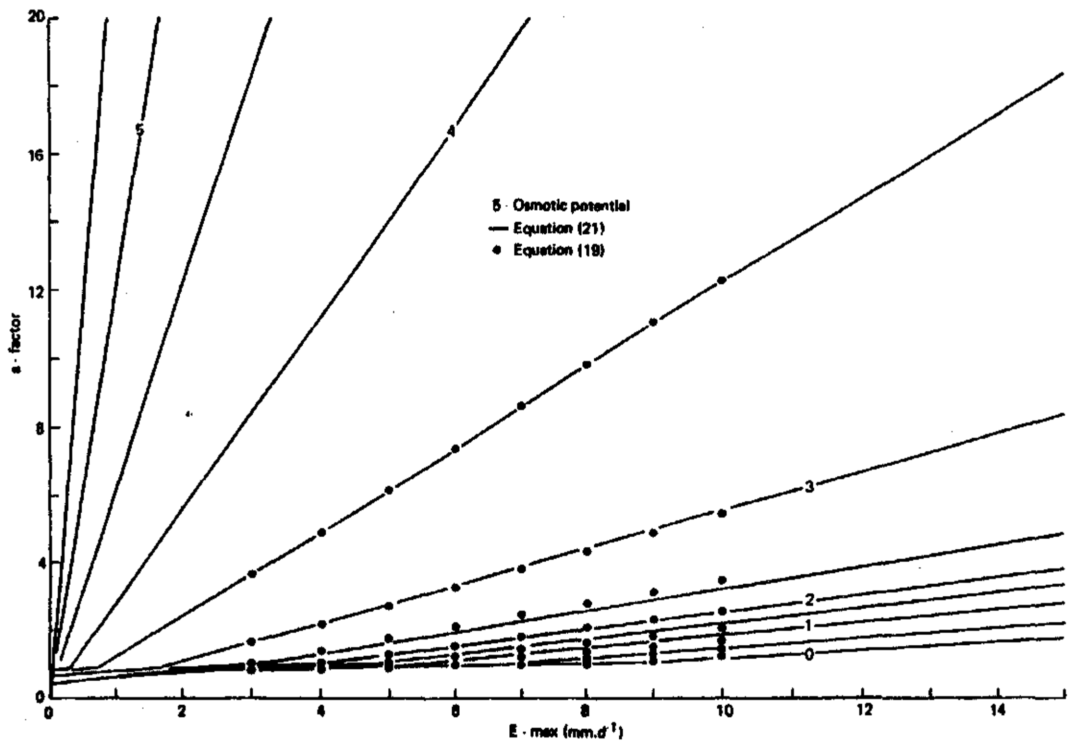


Fig. 7. Factor a for different osmotic suctions; Ψ_c = 4 bar

3.3. Calculation of osmotic pressure

Soil water contains dissolved salts which may be present in sufficient concentration to restrict water uptake by plants. The dependence of the osmotic pressure on concentration is given by Van 't Hoff's equation:

$$\Psi_o = \frac{nRT}{V} \tag{22}$$

where: $\frac{n}{v}$ = number of moles per volume ($mol.m^{-3}$)

R = gas constant

T = absolute temperature (^oK)

When expressing Ψ_o in bar and taking the temperature at 25^oC (t = 298 ^oK) the gas constant R equals 0.08206. This equation applies for an ideal solution of a non-dissociating substance. For a completely dissociating salt like NaCl both ions Na^+ and Cl^- contribute to the osmotic pressure. In the soil solution several ions have to be accounted for. Especially at high concentrations the complexation of separate ions becomes important (ABDEL KHALIK and BLÖMER, 1984). For the calculation of the osmotic pressure with equation (22) it is therefore necessary to evaluate first the total molality of all ions and complexes together.

For the present model approach a more convenient calculation procedure has been pursued. The relation between osmotic pressure and electrical conductivity as given by RICHARDS (1954) offers such a possibility:

$$\Psi_o = 0.36\ EC \tag{23}$$

where: EC = electrical conductivity ($mmho.cm^{-1}$)

In the salinity submodel of the overall reuse model the Cl^- ion has been selected as a tracer ion because it is not involved in precipitation/dissociation reactions nor in adsorption. The Cl^- concentration in the soil solution will be known at all times as an output of this salinity submodel.

For all water samples collected in the Eastern Nile Delta during 1980, 1981, 1982 and 1983 the model 'COMPLEX' (ABDEL KHALIK and BLÖMER, 1984) has been used to calculate the total molality of cations, anions and complexes together. Using the fundamental equation (22) the osmotic pressure has been calculated. By curve fitting of Ψ_o against the Cl^- concentration the following empirical relation for the Eastern Nile Delta has been found (see also Fig. 8):

$$\Psi_o = 0.1409[Cl^-]^{0.793} \tag{24}$$

where $[Cl^-]$ = Cl^- concentration ($eq.m^{-3}$)

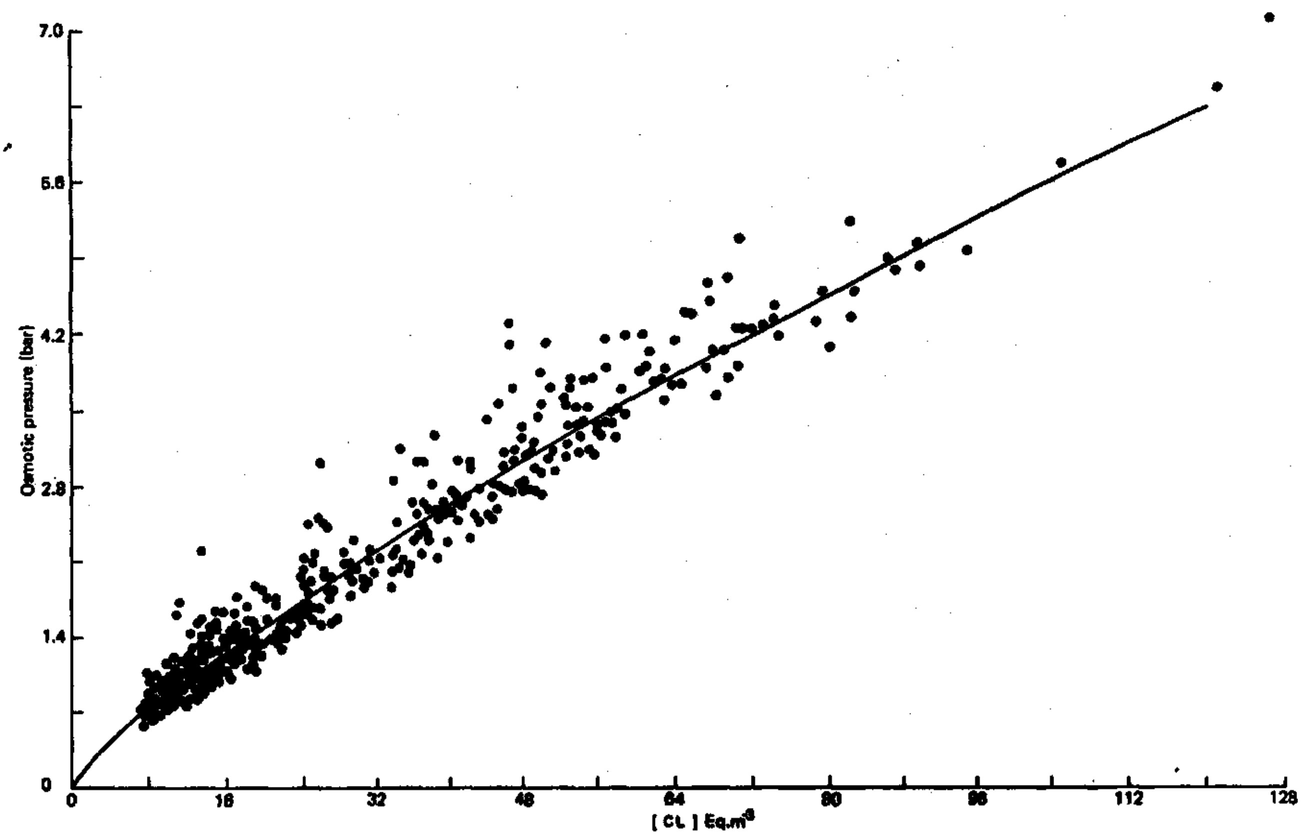


Fig. 8. Relation between the Cl^- concentration ($eq.m^{-3}$) and osmotic pressure (bar)

4. EVAPOTRANSPIRATION OF RICE FIELDS

For rice fields with a standig water layer on the soil surface the calculation procedure of actual evapotranspiration will be different. As long as a standing water layer is on the field the available moisture in the plant rootzone will be assumed constant because any water taken by the crop for transpiration will be replenished from the standing water layer reservoir. This means that the evapotranspiration is not governed by the soil moisture balance, but by the standing water layer balance:

$$\frac{dh^*}{dt} = - E_r - f_i \tag{25}$$

where: h^* = height of the standing water layer above soil surface (m)
f_i = infiltration rate at the soil surface ($m.day^{-1}$)

For the evapotranspiration rate two possibilities exist:

$$E_r = E_{max} \quad \text{if} \quad a \leqq 1 \tag{26a}$$

$$E_r = \frac{E_{max}}{a} \quad \text{if} \quad a > 1 \tag{26b}$$

If the phreatic waterlevel is below soil surface for the infiltration rate through the soil surface the following relation can be assumed, considering a puddled layer below the soil surface:

$$f_i = \frac{h^*}{C_p} \quad \text{if} \quad h(t_o) < d_d \tag{27a}$$

where: C_p = resistance of the puddled layer (days)

In this approach it will be assumed that if the initial groundwater table is below soil surface it will stay below soil surface during the time step. If the initial phreatic water level is at soil surface (the subsoil is saturated) and the capacity of the drainage system is less than the potential infiltration at the soil surface, infiltration is inhibited by this restricted capacity. Defining a critical boundary value for the standing water layer h_b^* as the value of h^* at which the unrestricted infiltration capacity equals the drain discharge and leakage/seepage the following equality must hold:

$$\frac{d_d + h_b^*}{C_d} + \frac{d_d + h_b^* - h_{aq}}{C_{aq}} = \frac{h_b^*}{C_p} \tag{28}$$

where: h_b^* = lower boundary value for the standing water layer for restricted infiltration capacity at the soil surface (m)

For the value of this critical depth it follows:

$$h_b = \frac{d_d\left(\frac{1}{C_d} + \frac{1}{C_{aq}}\right) - h_{aq}\left(\frac{1}{C_{aq}}\right)}{\frac{1}{C_p} - \frac{1}{C_d} - \frac{1}{C_{aq}}} \tag{28a}$$

Under these conditions the equation for infiltration becomes:

$$f_i = (h^*(t)+d_d)\left(\frac{1}{C_d} + \frac{1}{C_{aq}}\right) - h_{aq}\left(\frac{1}{C_{aq}}\right)$$

$$\text{if} \quad h(t_o) = d_d \quad \text{and} \quad h^*(t) > h_b^* \tag{27b}$$

By substitution of equation (26) and (27) in the general mass balance quation for the boundary conditions mentioned four variants of this equation occur (see Table 13).

The algorithmn for the standing water layer balance is identical to that of the soil moisture balance described in Chapter 2.3.

Table 13. Standing water layer balance equation based on the general condition for initial phreatic waterlevel, the a-factor and the current condition for $h^*(t)$

Condition for $h(t_o)$	Condition for a	Condition for $h^*(t)$	Equation for $\frac{dh^*(t)}{dt}$
$h(t_o) < d_d$	$a \leq 1$	$h^*(t_o) > 0$	$-E_{max} - \frac{h^*(t)}{C_p}$
	$a > 1$	$h^*(t) > 0$	$-\frac{E_{max}}{a} - \frac{h^*(t)}{C_p}$
$h(t_o) = d_d$	$a \leq 1$	$0 < h^*(t) \leq h_b^*$	$-E_{max} - \frac{h^*(t)}{C_p}$
		$h^*(t) > h_b^*$	$-E_{max} - (h^*(t)+d_d)\left(\frac{1}{C_d} + \frac{1}{C_{aq}}\right) + h_{aq}\frac{1}{C_{aq}}$
	$a > 1$	$0 < h^*(t) \leq h_b^*$	$-\frac{E_{max}}{a} - \frac{h^*(t)}{C_p}$
		$h^*(t) > h_b^*$	$-\frac{E_{max}}{a} - (h^*(t)+d_d)\left(\frac{1}{C_d} + \frac{1}{C_{aq}}\right) + h_{aq}\frac{1}{C_{aq}}$

5. DESCRIPTION OF THE COMPUTER PROGRAMME

The evapotranspiration submodel is one of the four submodels calculating the water and salt balance of an area with one crop for one irrigation interval. This submodels are: the irrigation efficiency submodel (BOELS, 1985), the evapotranspiration submodel, the drainage water generation submodel, and the salt distribution submodel.

5.1. *Input and output*

The following input is required for the evapotranspiration subroutine:

$M(t_o)$	= initial soil moisture available for evapotranspiration (m)
$h^*(t_o)$	= initial height of standing water layer (m)
d_w	= effective crop rootzone (m)
E_{max}	= atmospheric evaporative demand ($m.day^{-1}$)
t	= length of the irrigation interval (day)
crop type	(1, 2, 3 or 4)
$\bar{c}_w(t_o)$	= average initial Cl^- concentration in the crop rootzone ($eq.m^{-3}$)
d_d	= drainage depth (m)
soil type	(1, 2, 3, 4, 5, 6, 7, 8, 9 or 10)
C_p	= resistance puddled layer (day)
C_d	= drainage resistance (day)
C_{aq}	= seepage/leakage resistance (day)
h_{aq}	= piezometric pressure in the aquifer with respect to drain level (m)

The following output is produced by the evapotranspiration subroutine:

E_r	= average actual evapotranspiration rate ($m.day^{-1}$)
f_c	= average capillary flux ($m.day^{-1}$)
$M(t)$	= remaining soil moisture available for evapotranspiration at the end of the irrigation interval (m)

5.2. Programme structure

In the first section of the subroutine initialization of constants takes place (see Fig. 9). These constants concern the a factor, the maximum capillary flux and the boundary values for the soil moisture content and the standing water layer in the case of rice cultivation.

If an initial standing water layer is present on the field the calculation of evapotranspiration will follow the procedure described for the rice field. In this part the time that the rice fields fall dry is calculated and if this happens within the given irrigation interval for the remaining part of the time step the evapotranspiration of the rice crop will be treated as a normal field crop.

For the normal field crop the calculations are based on the soil moisture balance and the capillary rise is calculated for (each part of) the time step.

Finally the actual evapotranspiration of the field crops is calculated from the ultimate soil water balance and the average rate of evapotranspiration and capillary flux is calculated.

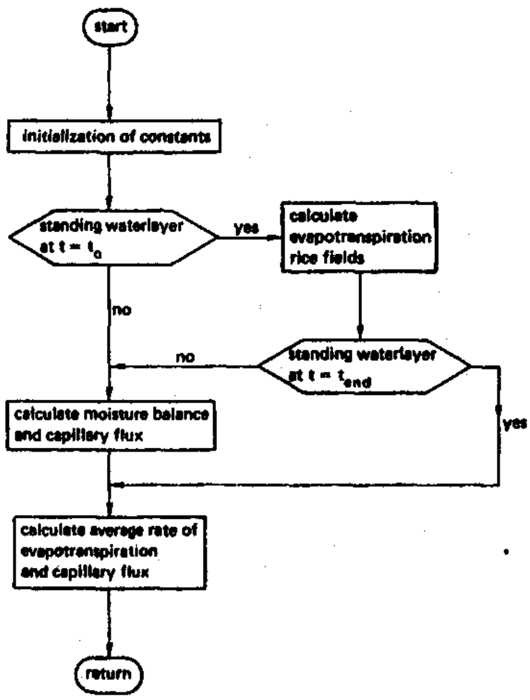


Fig. 9. General structure of subroutine 'EVA'

5.2.1. Initialization of constants

In this section of the programma (see Fig. 10) first the sums that are used in the programme are put at zero. This applies to the capillary flux, $\sum f_c$, and the evapotranspiration $\sum E$. The initial value of the irrigation interval length, t_{int}, and the initial moisture available for evapotranspiration, $M(t_o)$, have to be saved, because during the calculation process these values may be changed.

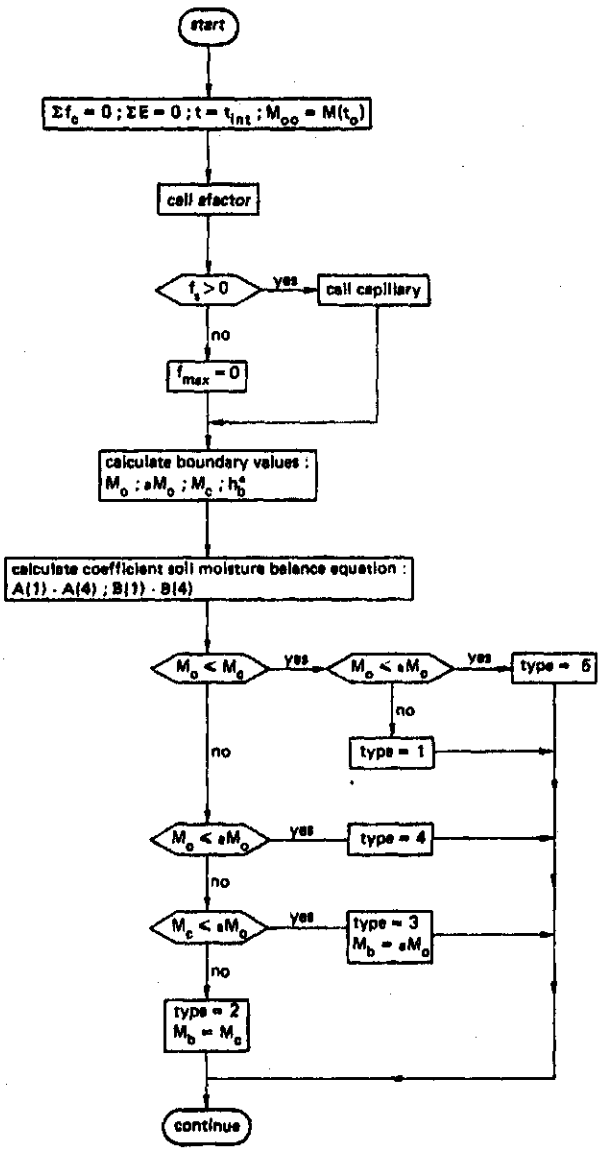


Fig. 10. Flow diagramme 'Initialization of constants' in subroutine 'EVA'

In subroutine 'AFACTOR' the factor a is calculated based on the crop type code. This crop type code depends on the critical leaf water suction, Ψ_c and is given in Table 14.
Inside subroutine 'AFACTOR' all the constants required for the calculation of this factor (Table 11 and Table 12) have been included in data statements.

Based on the presence of a seepage flux the maximum capillary flux is calculated. In this context the seepage flux is defined as follows:

$$f_s = -\frac{h_{aq}}{C_{aq}} \qquad \text{if } h_{aq} < 0 \tag{29a}$$

$$f_s = 0 \qquad \text{if } h_{aq} \geq 0 \tag{29b}$$

The calculation of f_{max} takes place in subroutine 'CAPILLARY' based on the soil type code and the distance between draindepth and the centre of the effective rootzone. The soil type code has been given in Table 6. The constants required for the calculation of f_{max} (Table 6) have been included in data statements.

Next the boundary values for the available soil moisture and for the standing water layer are calculated. If the current moisture content during the irrigation interval passes such a boundary value a different mathematical formulation has to be used in the calculations.

Next the coefficients A and B for the general form of the differential equation (11) are calculated. The values are given in Table 15.

Table 14. Crop type code in relation Ψ_c

	Crop type code
$\Psi_c > 11.5$	1
$11.5 \leq \Psi_c < 8.5$	2
$8.5 \leq \Psi_c < 5.5$	3
$\Psi_c \leq 5.5$	4

Table 15. Values of the A and B coefficients for the soil moisture balance equation. For the conditions under which these values are applied reference is made to the equation number given in Table (1)

Equation number	A	B
1	0	$f_s - E_{max}$
2	$\frac{E_{max}}{aM_o}$	f_s
3	$\frac{f_{max}}{M_o}$	$f_{max} - E_{max}$
4	$\frac{E_{max}}{aM_o} + \frac{f_{max}}{M_o}$	f_{max}

Based on the seepage conditions and the relative position of the boundary value M_c and aM_o the sequence of solutions starting at field capacity till wilting point is determined. See Table 1.

5.2.2. Evapotranspiration of rice field

If at the beginning of the timestep a standing water layer is present on the field, evapotranspiration will be treated separately. Under these conditions (standing water layer) evapotranspiration will be maximum, either the evaporative demand, or under very saline conditions ($a > 1$) the maximum attainable rate (E_{max}/a) (see Fig. 11).

If the subsoil is saturated and the infiltration rate at the soil surface is limited by the drainage capacity (standing water layer greater than the boundary value h_c^*) the A and B factor are calculated according to equation (27a). Next, the time required for the standing water layer to reach the boundary value h_c^* is calculated with function TT (eq. 12). If this boundary value h_c^* is not reached within the time step the evapotranspiration will remain at its maximum value and the amount (m) is calculated. Programme execution is then transferred to

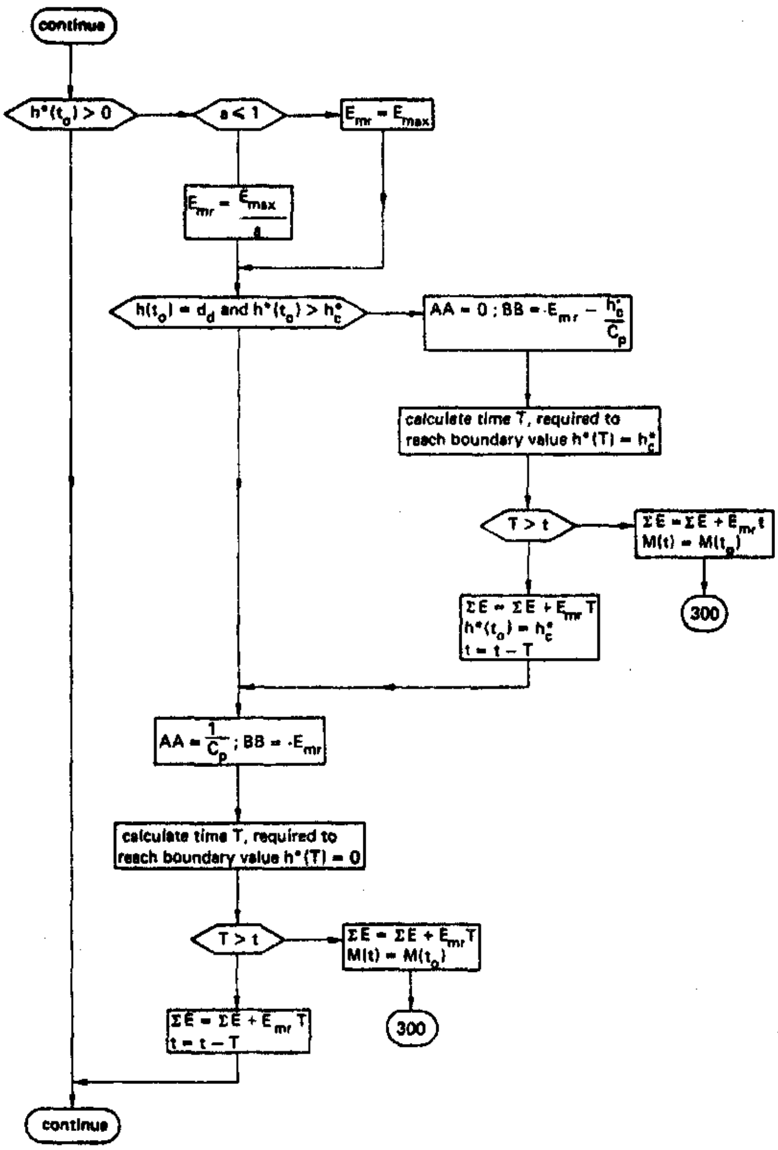


Fig. 11. Flow diagramme 'Evapotranspiration of rice fields' in sub-routine 'EVA'

statement 300 where the average rates of evapotranspiration and capillary flux are calculated. If the boundary value for h_c^* is reached within the time step the amount of evapotranspiration during this part of the time step is calculated and after calculating the remaining part of the time step programme execution is transferred to the case where the standing water layer is less than the boundary value.

If the subsoil is not saturated or if the standing water layer is below the boundary value h_c^* the infiltration rate is determined by the resistance of the puddled layer. The A and B value of equation (10) are calculated accordingly. With function 'TT' the time required for the field to full dry is calculated. If this does not happen within the time step the amount of evapotranspiration is calculated and programme execution is transferred to statement 300. If the rice field does fall dry during the time step, the evapotranspiration during the remaining part of the time step will be considered as for non-rice fields.

5.2.3. Evapotranspiration non-rice fields

For the non-rice fields calculations are based on the soil moisture balance. The function 'TT' is used to calculate the time required to reach a certain boundary value. The function 'DIF' is used to calculate the moisture content at the end of the time step (eq. 11). In the function 'FCAP' the amount of capillary flux (m) during (part of) the time step is calculated. By substitution of equations (11a) an (11b) into equation (7b) and integration over the time step the following equations are found and programmed in function 'FCAP':

$$C_t = f_{max}\ t\left(1 - \frac{M(t)-M(t_o)}{2M_o}\right) \qquad \text{if } A = 0 \tag{30a}$$

$$C_t = f_{max}\ t - \frac{f_{max}}{aM_o}(Bt+M(t_o)-M(t)) \qquad \text{if } A \neq 0 \tag{30b}$$

where: C_t = amount of capillary flux during time t (m)

Depending on the boundary conditions and the current value of M(t) see Fig. 12 the time required to reach the nearest boundary condition is calculated with the function 'TT' using the proper values for the A and B constants (see Table 15). If the boundary condition is not reached during the time step the available soil moisture content at the end of the time step is calculated with the function 'DIF' and the amount of capillary flux with the function 'FCAP' and programme execution is transferred to statement 300. If the boundary value is reached the amount of capillary flux is calculated and for the remaining part of the time step control is transferred back to the test for the next case.

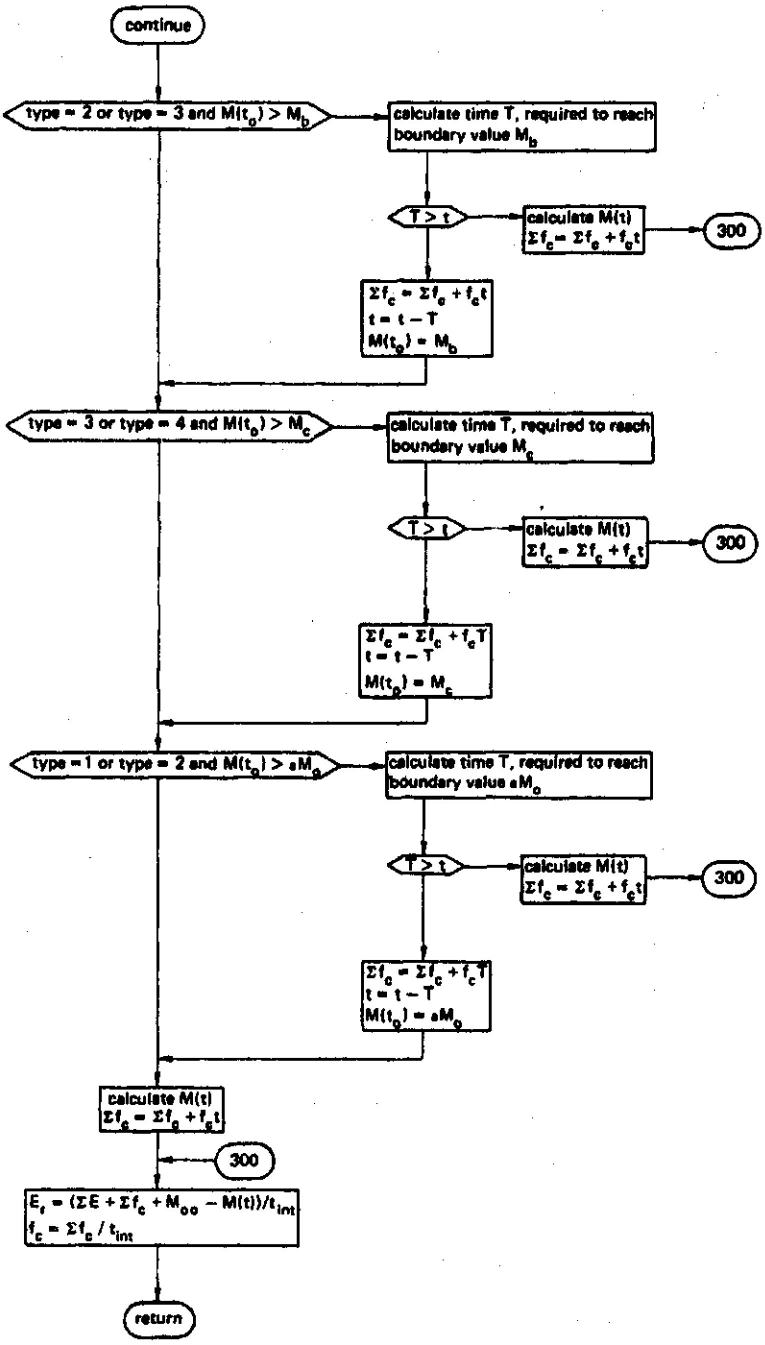


Fig. 12. Flow diagramme 'Evapotranspiration non-rice fields' of subroutine 'EVA'

In the first conditional branch the case with seepage conditions, with the capillary flux less than the seepage flux and no evapotranspiration reduction is calculated (eq. 3).

In the second conditional branch the case with seepage conditions, with the capillary flux smaller than the seepage rate and reduced evapotranspiration is calculated (eq. 4).

In the third conditional branch the case with the capillary flux equal to the seepage flux and no evapotranspiration reduction is calculated (eq. 1).

Finally, as the last possible combination the case with the capillary flux equal to the seepage flux and evapotranspiration reduction is calculated (eq. 2).

In the last section of the programme (statement No. 300) the actual average evapotranspiration rate is calculated from the soil moisture balance and (if applicable) the evapotranspiration realized under rice field conditions. After calculating the average capillary flux the calculations are finished and control is transferred back to the main programme.

LITERATURE

ABDEL KHALIK, M.A. and F. BLÖMER, 1984. Complex, a computer model for solving chemical equilibria on the basis of activities. Reuse of Drainage Water Project Report No. 2, 31 pp. DRI-ICW.

BOELS, D., 1986. Calculation of on-farm irrigation efficiency. ICW-nota 1697 (in press).

RICHARDS, L.A. (Ed.), 1954. Diagnosis and Improvement of Saline and Alkaline Soils. Agriculture Handbook No. 60. USDA.

RIJTEMA, P.E., 1969. Soil moisture forecasting. ICW nota 513.

——— , 1981. Reuse of Drainage Water: Model analysis. ICW nota 1274.

——— , 1982. Reuse of Drainage Water: Data administration and evaporation model. ICW nota 1359.

——— and A. ABOUKHALED, 1975. Crop water use. In: Research on crop water use, salt effected soils and drainage in the Arabic Republic of Egypt. ABOUKHALED et al. FAO, 1975.

——— and D. BOELS, 1985. Formulation for the irrigation water distribution in the Nile Delta. ICW nota 1639.