CROWAR

a computer program to calculate crop water
requirements

ing. W.A.J.M. Kroonen

C O N T E N T S

PREFACE

DOORENBOS and PRUITT (1977) provide guidelines for predicting crop water requirements in FAO drainage and irrigation paper 24. Their calculation procedure includes the use of several tables. In routine base calculations, the frequent use of tables is time consuming and error prone. At the International Institute of Land Reclamation and Improvement (ILRI), where research is being done on the efficiency of irrigation systems around the world, the need was felt for a computer program that could serve in determining crop water requirements fast, easily and reliable on routine basis.

In the department of Agrohydrology of the Institute for Land and Water Management Research (ICW), where calculations of crop evapotranspiration are often subject of study, the need for such a program was also felt.

In close cooperation with Ir. Vos and Dr. Bos of ILRI and with Dr. Feddes of ICW the CROWAR program was developed to serve as a tool to estimate total water demand of an (irrigation) project. The calculation method can be used in design, construction and evaluation of (irrigation) projects around the world. I am greatly indebted to Ir. Vos, Dr. Bos and Dr. Feddes for their kind advice and support in preparing this report.

Wageningen, March 1985   Ing. W.A.J.M. Kroonen

1. INTRODUCTION

CROWAR is a user's friendly, fully interactive computer program to calculate crop water requirements in a fast and easy way. To use it, no knowledge of computer systems is needed. The user is guided by the program to respond to its questions.

Users of the program should always maintain a critical attitude, since the calculation methods used were developed and tested under certain field conditions, which may differ considerably from the agronomical and environmental conditions in the project under study.

Chapter 2 deals with the calculation method which consists of three major parts. Firstly the 'reference crop evapotranspiration' is calculated (Section 2.2), using the modified Penman method. This method is recommended by DOORENBOS and PRUITT (1977) for its accuracy in predicting evapotranspiration for periods as short as 10 days.

The second part deals with the selection of crop coefficients for the various crops, taking into consideration the stages of growth, the length of the growing season and the prevailing climatological conditions (Section 2.3).

The third part combines calculated crop evaporation data with effective precipitation, resulting in total water demand (Section 2.4).

In Chapter 3 the program itself is dealt with. Section 3.1 discusses the structure of the program, that reflects the calculation procedure. In section 3.2 an overview of the required input data is given, Section 3.3 provides instructions for use of the program. The output obtained with CROWAR is discussed in Section 3.4.

crop in question, it refers to a disease free crop, growing in large fields, not short of water and fertilizers.

Effects of local conditions and agricultural practices on crop water requirements are not considered. These local effects include size of fields, advection, salinity, irrigation and cultivation practices, climatological variations in time, distance and altitude, and soil water availability.

An attempt to include the effect of these local conditions in a computer program would make the program too complex, since the variety in the different conditions is extremely wide. Therefore the user will have to consider these local effects himself and adjust water demand accordingly.

To translate ET_{crop} values to total water demand, i.e. the amount of water that has to be supplied by the irrigation system, the program calculates both weighed contribution per crop to the total evapotranspiration of the project and the amount of effective precipitation.

DOORENBOS and PRUITT (1977) give many variables used in the calculation of ET_o in tables. Since the use of tables in computer programs involves a lot of inefficiency in data storage and data manipulation, these tables are not used in the program. The tables have been replaced by functions or formulae, as discussed further on with one exception, see Section 2.2.6, and Table 1.

Throughout this text, the use of symbols will be in accordance with DOORENBOS and PRUITT (1977).

2.2. Reference crop evapotranspiration

For the calculation of ET_o, in DOORENBOS and PRUITT (1977) four different methods are presented. One of these methods is the modified Penman method, which is well known for its good results in predicting the effect of climate on crop water requirements (DOORENBOS and PRUITT, 1977 and CHO-TNO, 1981). Therefore the modified Penman method was selected as being the best. To use the method meteorological data are needed on temperature, humidity, wind speed and sunshine (duration).

PENMAN (1948) describes evaporation from a large open water surface as:

$$L \ E_o = \frac{s(Q^*-G) + \gamma L \ E_a}{s + \gamma} \qquad (W.m^{-2}) \qquad (2)$$

where: L   = latent heat of evaporization of water ($J.kg^{-1}$)

E_o = open water evaporation   ($kg.m^{-2}.s^{-1}$)

s   = slope of the saturation water vapour pressure-temperature curve at air temperature   ($mbar.K^{-1}$)

$Q*$ = net radiation   ($W.m^{-2}$)

G   = water heat flux   ($W.m^{-2}$)

γ = psychrometric constant, at sea level approx. 0.66 $mbar.K^{-1}$

                                                       ($mbar.K^{-1}$)

E_a is the so-called isothermal evaporation, the evaporation of a water surface with the same temperature as the air:

$$E_a = \frac{f(u)}{L}(e_a(T_2) - e_d) \qquad (kg.m^{-2}.s^{-1}) \qquad (3)$$

where: f(u)   = function of the wind speed, $f(u) = 7.4 + 4.0\ u_2$

                                                 ($W.m^{-2}.mbar^{-1}$)

u_2 = wind speed at 2 m height   ($m.s^{-1}$)

$e_a(T_2)$ = saturation vapour pressure at air temperature T at 2 m height   (mbar)

e_d = actual vapour pressure at 2 m height (mbar)

In eq. (2) two 'terms' can be distinguished: the energy (radiation) term and the aerodynamic (wind and humidity) term. The relative impor-tance of these two terms is dependent on the climatological conditions encountered. In the modified Penman formula as given by DOORENBOS and PRUITT (1977), the units used are all converted to equivalent mm's evaporation of water per day ($mm.d^{-1}$). The two terms mentioned above can be recognized easily:

$$ET_o = c[W\ R_n + (1-W)\ f(u)(e_a - e_d)] \qquad (mm.d^{-1}) \qquad (4)$$

where: ET_o = reference crop evapotranspiration   ($mm.d^{-1}$)

c   = correction factor to adjust ET_o to day and night weather conditions   (-)

W   = temperature dependent weighing factor (-)

R_n = net radiation   ($mm.d^{-1}$)

f(u) = wind function   ($mm.d^{-1}.mbar^{-1}$)

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E_o = open water evaporation $\qquad\qquad (kg.m^{-2}.s^{-1})$

s = slope of the saturation water vapour pressure-temperature
curve at air temperature $\qquad (mbar.K^{-1})$

Q^* = net radiation $\qquad\qquad\qquad\qquad (W.m^{-2})$

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where: $f(u)$ = function of the wind speed, $f(u) = 7.4 + 4.0\ u_2$
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u_2 = wind speed at 2 m height $\qquad (m.s^{-1})$

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conditions $\qquad\qquad\qquad\qquad\qquad\qquad (-)$

W = temperature dependent weighing factor $(-)$

R_n = net radiation $\qquad\qquad\qquad\qquad\qquad (mm.d^{-1})$

$f(u)$ = wind function $\qquad\qquad\qquad\qquad (mm.d^{-1}.mbar^{-1})$

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2.2.1. Vapour pressure deficit $(e_a - e_d)$

Data on air humidity have to be provided to CROWAR either as mean relative humidity (%) or as mean vapour pressure (mbar) for each time step (month or decade). Relative humidity can be calculated from vapour pressure when saturation vapour pressure is known (eq. 5). In CROWAR an empirical formula is used to calculate the saturation vapour pressure e_a (FEDDES et al., 1978):

$$e_a = 1.3332 \; e^{((1.08872 \, T - 276.4884)/(0.0583 \, T - 2.19386))} \quad \text{(mbar)} \quad (5)$$

where: T = mean air temperature (K)

Vapour pressure deficit $(e_a - e_d)$ can now be calculated as:

$$(e_a - e_d) = e_a(1 - R_{hum}/100) \quad \text{(mbar)} \quad (6)$$

where: R_{hum} = mean relative humidity (%)

2.2.2. Wind function f(u)

The modified wind function in DOORENBOS and PRUITT (1977) reads as:

$$f(u) = 0.27(1 + v_2/100) \quad (\text{mm.d}^{-1}.\text{mbar}^{-1}) \quad (7)$$

where: v_2 = total wind run at 2 m height (km.d^{-1})

For wind speed measurements at other heights than 2 m, DOORENBOS and PRUITT (1977) use a factor to correct these data. The correction factors are given in a table. CROWAR calculates the correction factor (f_w) woth a power function that describes the data in the table with sufficient accuracy:

$$f_w = 1.1552 \; h_w^{-0.1874} \quad (-) \quad (8)$$

where: h_w = height of wind speed measurement (m)

2.2.3. Weighing factors W and (1-W)

In the original Penman formula the two terms (radiation term and aerodynamic term) are weighed by $s/s + \gamma$ and $\gamma/s + \gamma$ respectively.

DOORENBOS and PRUITT (1977) named these weighing factors W and (1-W).
The values of W and (1-W) are related to temperature and elevation.

The slope of the saturation vapour pressure curve (s) can be calculated using e_a (eq. (5)) and temperature T as (FEDDES et al., 1978):

$$s = 13.7315 \ e_a / (0.0583 \ T - 2.19386)^2 \qquad (-) \qquad\qquad (9)$$

The psychrometric constant γ depends on atmospheric pressure and can be calculated as (STEENBERGEN, 1972):

$$\gamma = \frac{c_p \ P_a}{L \ \epsilon} \qquad (mbar.K^{-1}) \qquad\qquad (10)$$

where: c_p = specific heat of dry air at constant pressure $(J.kg^{-1}.K^{-1})$

P_a = atmospheric pressure $\qquad\qquad$ (mbar)

ϵ = ratio of molecular weight water vapour/dry air (-)

The only remaining unknown variable in eq. (10) is atmospheric pressure p_a, that depends mainly on elevation. To calculate p_a at different altitudes the following formula is used (SMITHSONIAN INSTITUTE, 1951):

$$P_a = P_o \left[\frac{288 - 0.0065 \ h}{288} \right]^{5.256} \qquad (mbar) \qquad\qquad (11)$$

where: p_o = atmospheric pressure at sea level (mbar)

$\qquad$ h = altitude above sea level $\qquad$ (m)

When s and γ are known, the weighing factor W can be calculated as:

$$W = \frac{s}{s + \gamma} \qquad (-) \qquad\qquad (12)$$

2.2.4. Net radiation R_n

Net radiation can be calculated for a given latitude and date when data on temperature, humidity and sunshine are available. Net radiation (R_n) consists of two components: net shortwave radiation (R_{ns}) and net longwave radiation (R_{nl}), see Fig. 1.

The source of shortwave radiation is direct and scattered sun radiation. The amount of incoming shortwave radiation at the top of the
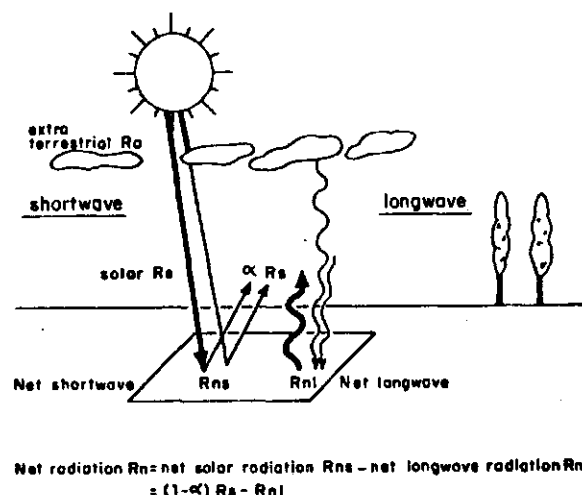
Net radiation Rn= net solar radiation Rns – net longwave radiation Rnl
= (1-∝) Rs - Rnl

Fig. 1. Illustration of the radiation balance

atmosphere is called 'extra-terrestrial' or 'Angot' radiation (R_a), which depends on latitude and time of year only. The amount that reaches the earth-surface depends on cloud cover and day length.

The shortwave radiation that reaches the earth-surface is partly reflected and lost to the atmosphere. The ratio of reflectance (α) depends on the nature of the surface. For water α is approx. 0.05, for most crops α is 0.20 to 0.25. In CROWAR α is set equal to 0.25.

Net shortwave radiation can be calculated as:

$$R_{ns} = (1-\alpha)(0.25+0.50 \text{ n/N}) R_a \qquad (\text{mm.d}^{-1}) \qquad (13)$$

where: R_{ns} = net shortwave radiation (mm.d^{-1})

    n = observed number of hours of daily bright sunshine (h)

    N = max. number of hours of daily bright sunshine (h)

    R_a = incoming extra-terrestrial shortwave radiation (mm.d^{-1})

The three components mentioned above can be recognized clearly in eq. (13). The constants in the second term (0.25 and 0.50) are choosen as mean values that can be used in most circumstances. In CROWAR the values of n have to be provided as input data, N and R_a will be calculated as discussed in Section 2.2.5.

The surface of the earth radiates part of its absorbed energy as longwave radiation. This outgoing longwave radiation is usually larger than the incoming longwave radiation from the clouds. Net longwave radiation is therefore a loss. To estimate net longwave radiation (R_{nl}), data on temperature, vapour pressure, sunshine and max. sunshine are needed:

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$$R_{nl} = \sigma \ T^4 (0.34-0.044 \ \sqrt{e_d})(0.1+0.9 \ n/N) \qquad (\text{mm.d}^{-1}) \qquad (14)$$

where: σ = constant of Stefan Boltzmann ($\text{mm.d}^{-1}.\text{K}^{-4}$)

All necessary variables are already calculated, so net longwave radiation can be estimated according eq. (14). When both net shortwave and net longwave radiation are calculated, total net radiation R_n can be computed as:

$$R_n = R_{ns} - R_{nl} \qquad (\text{mm.d}^{-1}) \qquad (15)$$

2.2.5. Calculation of N and R_a

For a given latitude and number of day the max. number of hours of bright sunshine N (day length) can be calculated after GOUDRIAAN and VAN LAAR (1978) with a small adaption as:

$$N = 12 \ \frac{\pi + 2 \ \arcsin((\sin 50'+x)/y)}{\pi} \qquad (\text{h}) \qquad (16)$$

with

$$x = \sin \beta \sin \phi \qquad (-) \qquad (17a)$$
$$y = \cos \beta \cos \phi \qquad (-) \qquad (17b)$$

where: ϕ = latitude (rad) (positive on the northern hemisphere)

   β = declination of the sun

$$\beta = -23.45 \ \cos(360(n_d+10)/365) \qquad (\text{rad}) \qquad (18)$$

where: n_d = number of day (-)

(e.g. Jan. 1st = 1)

Eq. (16) differs slightly from the formula of Goudriaan and Van Laar. The original formula calculates the day length starting when the centre of the solar disk rises above the horizon. The actual day length is slightly longer: the day starting when the upper edge of the solar disk reaches the horizon. At sunset a similar reasoning applies.

To compensate for this small discrepancy sin 50' is included in the formula. This represents the sine of the angle between the centre

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and the edge of the sun (angle = 50', SMITHSONIAN INSTITUTE, 1951).

To calculate the extra-terrestrial radiation R_a, the same input data are required as for the calculation of N, i.e. latitude and number of day. Given the latitude and the time of year (number of day), R_a can be calculated as (DE BRUIN, 1977):

$$R_a = \frac{1353}{\pi}\left(\frac{\bar{d}}{d}\right)^2 (H \sin \phi \sin \delta + \cos \phi \cos \delta \sin H) \qquad (W.m^{-2}) \qquad (19)$$

where: $\bar{d}$ = average distance earth-sun   (astonomical units)

       d = actual distance earth-sun   (au)

       H = half day length   (rad)

       δ = declination of the sun acc. to De Bruin (rad)

During the polar night ($-\tan \phi \tan \delta > 1$) the half day length H = 0. During the polar day ($-\tan \phi \tan \delta < -1$) the half day length H = π. For all other cases H can be calculated as:

$$\cos H = -\tan \phi \tan \delta \qquad (-) \qquad (20)$$

According to De Bruin the declination of the sun δ can be calculated as:

$$\sin \delta = \sin q \sin \ell \qquad (-) \qquad (21)$$

where: q = constant (q = 0.397949)   (rad)

       ℓ = true astronomical length of the sun (rad)

$$\ell = m + \ell_o + 2 e \sin m + 1.25 e^2 \sin 2 m \qquad (rad) \qquad (22)$$

where: m = average anomaly of the sun (rad)

       ℓ_o = constant (ℓ_o = -1.3551 rad) (rad)

       e = constant (e = 0.01675 rad) (rad)

The average anomaly of the sun m is only dependent on the number of days since the perihelium (i.e. since Jan. 3rd):

$$m = \frac{2 \pi}{365.24}(nd-3) \qquad (rad) \qquad (23)$$

The ratio $\bar{d}/d$ (relative sun distance) can be found as:

$$\frac{\bar{d}}{d} = \frac{1 + e\,\cos(1-\ell_o)}{1 - e^2} \qquad (-) \tag{24}$$

The unit of R_a (W.m^{-2}) is converted to mm's equivalent water evaporization by multiplication with 0.0352. The values of R_a, as calculated by CROWAR in the way indicated above show a good agreement with the data on extra-terrestrial radiation in the SMITHSONIAN TABLES (1951). The minor differences with the data presented in Table 10 of DOORENBOS and PRUITT (1977) are the result of using a slightly different value for L (latent heat of evaporization). CROWAR uses a value for L, valid at 20°C.

2.2.6. Adjustment factor c

Adjustment of ET$_o$ may be substantially when climatological conditions differ considerably from the averages assumed in the method described above. These average conditions include a wind run during daytime approx. two times that during nighttime. The value of the adjustment factor (c) will be high in situations where high wind speed, low humidity and high radiation values prevail.

For the calculation of the correction factor, data are needed on day-time wind speed (U_{day}), ratio day-time wind speed/ night-time wind speed (U_{day}/U_{night}), highest relative humidity and incoming shortwave radiation. The user has to supply information on wind speed ratio and the value of the highest relative humidity that occurs. Values for this ratio and RH_{max} may be given by the user if available. When no data are available, default values will be used. Ratio is then set to 2 and RH_{max} is set to (R_{hum} + 100)/2.

When values for ratio and RH_{max} are given by the user, this can be done as values for each time step if these data are available, or as a mean, general value that will be applied for all time steps.

Day-time wind speed and incoming shortwave radiation will be computed by the program. Day-time wind speed is calculated from mean wind run used in the calculation of ET$_o$ and wind ratio. Incoming shortwave radiation is calculated as described in Section 2.2.4.

The actual correction factor can be read from a table given by DOORENBOS and PRUITT (1977) by interpolation (see Table 1).

Table 1. Adjustment factor (c) in presented Penman equation

	RH_{max} = 30%				RH_{max} = 60%				RH_{max} = 90%			
R_s mm/day	3	6	9	12	3	6	9	12	3	6	9	12
U_{day} m/sec												
U_{day}/U_{night} = 4.0												
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.79	.84	.92	.97	.92	1.00	1.11	1.19	.99	1.10	1.27	1.32
6	.68	.77	.87	.93	.85	.96	1.11	1.19	.94	1.10	1.26	1.33
9	.55	.65	.78	.90	.76	.88	1.02	1.14	.88	1.01	1.16	1.27
U_{day}/U_{night} = 3.0												
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.76	.81	.88	.94	.87	.96	1.06	1.12	.94	1.04	1.18	1.28
6	.61	.68	.81	.88	.77	.88	1.02	1.10	.86	1.01	1.15	1.22
9	.46	.56	.72	.82	.67	.79	.88	1.05	.78	.92	1.06	1.18
U_{day}/U_{night} = 2.0												
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.69	.76	.85	.92	.83	.91	.99	1.05	.89	.98	1.10	1.14
6	.53	.61	.74	.84	.70	.80	.94	1.02	.79	.92	1.05	1.12
9	.37	.48	.65	.76	.59	.70	.84	.95	.71	.81	.96	1.06
U_{day}/U_{night} = 1.0												
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.64	.71	.82	.89	.78	.86	.94	.99	.85	.92	1.01	1.05
6	.43	.53	.68	.79	.62	.70	.84	.93	.72	.82	.95	1.00
9	.27	.41	.59	.70	.50	.60	.75	.87	.62	.72	.87	.96

2.3. Crop coefficients

To predict crop evapotranspiration, ET_{crop}, reference crop evapo-transpiration ET_o, calculated as described in Section 2.2, has to be combined with the crop coefficients (K_c).

The difference between this K_c crop coefficient, that relates to reference crop evapotranspiration ET_o, and other types of crop coefficients (f), which relate ET_{pot} directly to E_o in the original Penman formula, should be clearly realized.

The value of the K_c crop coefficient is affected by crop characteristics, planting/sowing date, crop development stage, length of the

growing season, climatological conditions and, in the early development stage, the frequency of irrigation/rainfall

In CROWAR standard data on 19 different crops are presently available. The selection of these crops was made to include the main crops. In addition, the user can also choose to define one or more crops himself. In that case he has to enter the name and the K_c values for these crops (max. 6). The 19 standard crops are:

1. Alfalfa
2. Artichokes
3. Barley
4. Beans (green)
5. Citrus
6. Corn (sweet)
7. Corn (grain)
8. Cotton
9. Grass (pasture)
10. Grass (meadow)

11. Opnions
12. Fruit (e.g. Peaches)
13. Potatoes
14. Rice
15. Soya beans
16. Sugar beets
17. Sugar cane
18. Tomatoes
19. Wheat

For these standard crops the data on K_c-values and crop development stages, as given in DOORENBOS and PRUITT (1977), are available in CROWAR. For the calculation of K_c-values and the timing of the development stages, 7 groups of crops are distinguished:

1. Field and vegetable crops (12 crops)
2. Rice (1 crop)
3. Sugar cane (1 crop)
4. Grass/Alfalfa (3 crops)
5. Fruit (1 crop)
6. Citrus (1 crop)
7. User defined crops (max. 6 crops)

Ad 1. Field and vegetable crops

The growing season of this group is divided into four stages (see Fig. 2):

- Initial stage, germination and early growth, soil not or hardly covered.
- Crop development stage, from end of initial stage to the point of reaching effective full ground cover (70%-80%).
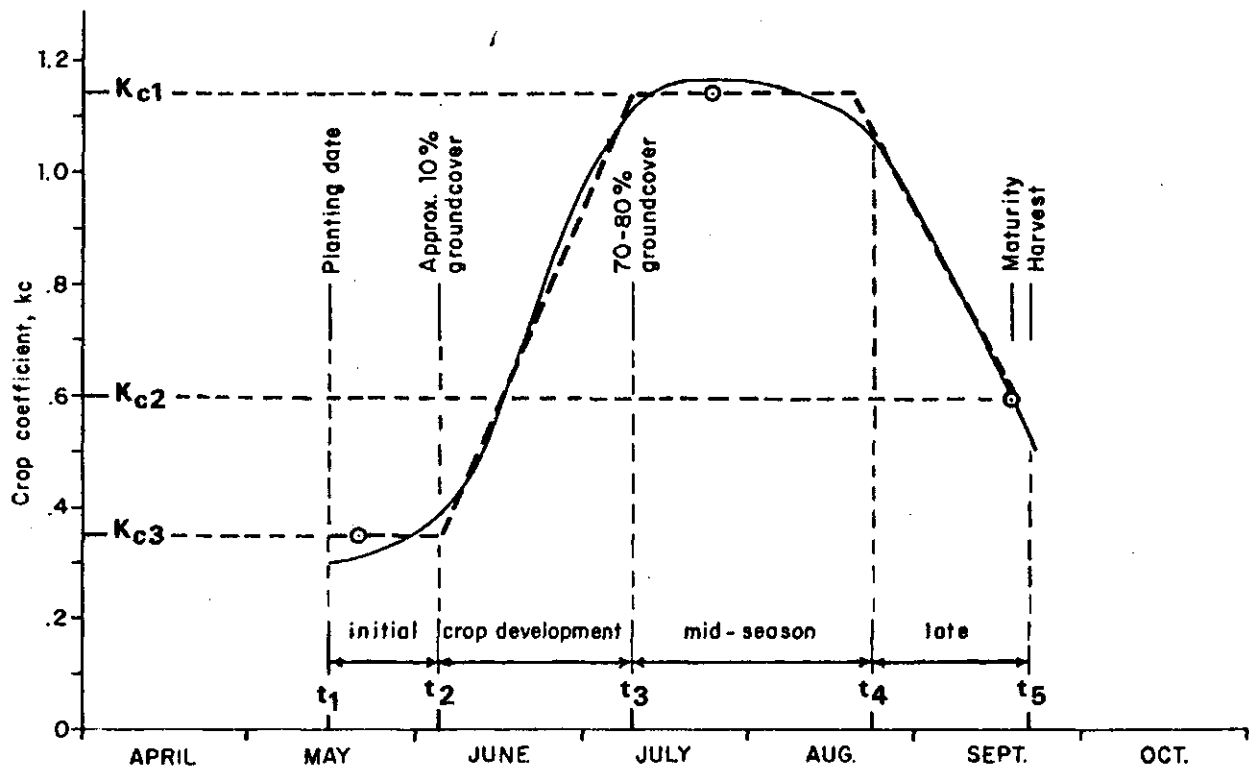
Fig. 2. K_c-value of field and vegetable crops during the growing
season

- Mid season stage, from effective full ground cover to start of
  maturing (discolouring/leaves falling).
- Late season stage, from end of mid season to full maturity/harvest.

The value of K_c during the growing season can be characterized by
5 dates on the time axis and 3 levels on the K_c axis. These points of
interest are:

t_1 : Planting/sowing date

t_2 : End of initial stage

t_3 : Start of mid season stage

t_4 : End of mid season stage

t_5 : Harvest date

K_{c1}: K_c-value during initial stage

K_{c2}: K_c-value during mid season

K_{c3}: K_c-value at harvest

When these 5 dates and 3 levels are known, the K_c-value at any time
during the growing season can be calculated. The time of planting/
sowing (t_1) has to be given by the user of the program. For each crop,
data on one or more standard cropping patterns are available in CROWAR.
The user can make a choice from these standard patterns. By this choice
the other dates $(t_2$ through $t_5)$ can be calculated by the program.

To be able to choose the correct values for K_{c2} and K_{c3}, CROWAR
needs information on the prevailing climatological conditions (humidity
and wind). This information is derived from the meteorological input
data that was used for the calculation of ET_o. The only remaining
unknown variable is K_{c1}, the K_c-value during the initial stage. This
value can be calculated as a function of ET_o and the frequency of
irrigation/rainfall during the initial stage (see Fig. 3). ET_o can be
calculated as described in Section 2.2, the frequency of irrigation/
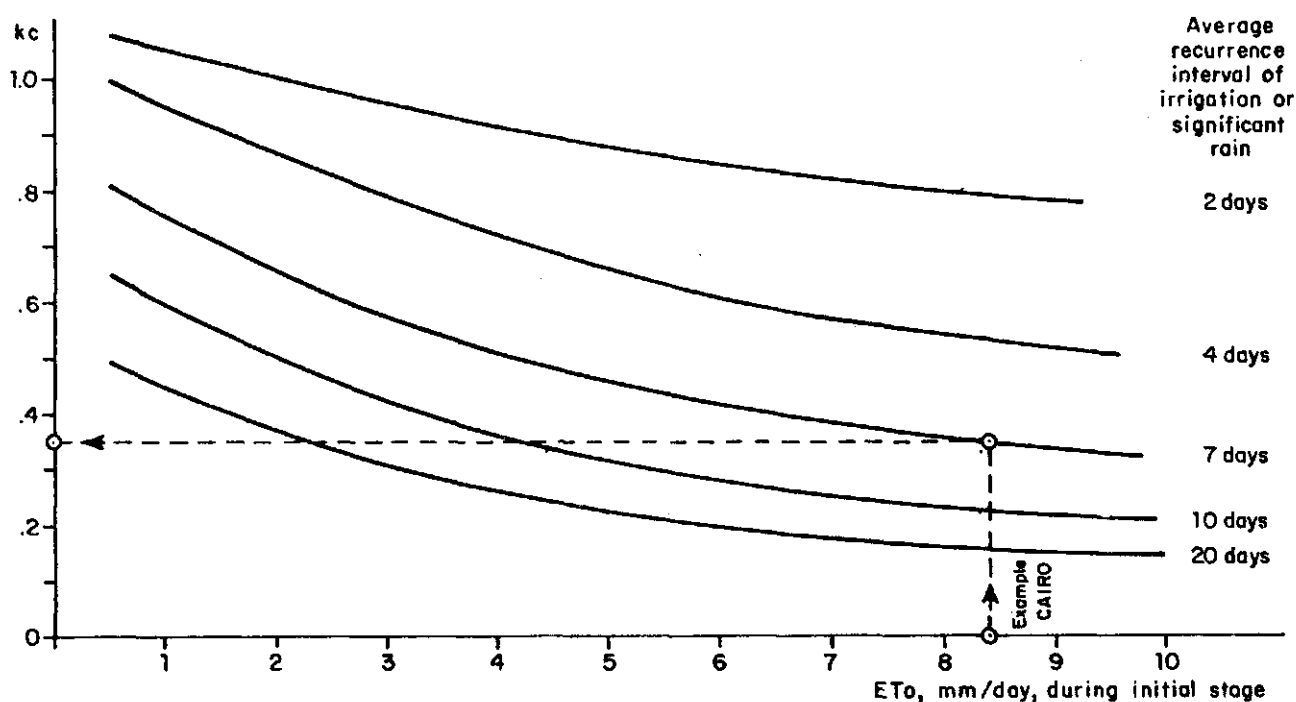rainfall has to be entered by the user.

Fig. 3. Average kc value for initial crop development stage as related
to level of ET_o and frequency of irrigation and/or significant
rain

Ad 2. Rice

To choose the appropriate K_c-value and to time the crop development stages for rice, GROWAR needs only additional information about the continent. The user can choose between humid Asia, humid Australia, humid S-America, Europe and the USA.

Ad 3. Sugar cane

For sugar cane the user can choose between 3 patterns: a 12 month virgin crop, a 24 month ratoon crop, first year and 24 month ratoon crop, second year. When a pattern is selected, all data needed to calculate the K_c-values are available.

Ad 4. Grass/Alfalfa

For grass and alfalfa, CROWAR uses mean K_c-values, as given by DOORENBOS and PRUITT (1977). The user has to provide additional information on start and end of growing season (killing frost).

Ad 5. Deciduous fruits (Peaches, apricots, pears, plums)

In CROWAR data on these crops are available for several options: cold winter (killing frost)/mild winter, with ground cover crop/no ground cover crop. The user will have to make choices for these options.

Ad 6. Citrus

CROWAR will ask the user to make two choices:

1. Size of the trees:

   - large, mature trees, > 70% ground cover;
   - trees giving approx. 50% ground cover;
   - trees giving < 20% ground cover.

2. Weed control programma:

   - clean cultivated;
   - no weed control.

Ad 7. User defined crops

When, for some reason (e.g. crop not in group of standard crops or standard K_c-value not accurate due to local conditions), the standard crops in CROWAR do not apply, the user can define his own crops to a maximum of 6 user defined crops per run. To define a crop the user has to enter a name for the crop, the start and the end of the growing season and the K_c-value for each time step during the growing season. CROWAR automatically preceeds a name of a user defined crop with an '*' (asterisk).

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When all information mentioned above has been entered correctly, CROWAR is able to determine the value of the K_c crop coefficients for all time steps. When timing of the crop development stages is done automatically by CROWAR on the basis of standard patterns, these standard patterns are adapted for projects on the southern hemisphere by a six month shift, if needed.

2.4. Total water demand

When both ET_o and the K_c-values are known, ET_{crop} can be calculated according to eq. (1). This can be done for one or more crops.

To calculate the water demand of an (irrigation) project, the values of ET_{crop} for the different crops in the project need to be weighed, since each crop occupies only a certain percentage of the total area (see Table 2).

Table 2 shows the values for ET_{crop} in a project with 3 crops. The data for the monts April through December are not shown for reasons of space.

In January, the growing season of crop 1 has not started, crop 1 does not occupy any space in the project yet. Crop 2 occupies 25% of the total area, so in January the weighed ET_{crop} for crop 2 is: 25% x 38 mm = 9.5 mm. Crop 3 has a weighed ET_{crop} in January of: 25% x 42 mm = 10.5 mm. Total weighed ET_{crop} for January = 20 mm.

The total ET_{crop} for crop 1 over the entire year is 952 mm. Since crop 1 occupies 50% of the total area, the weighed total ET_{crop} for crop 1 over the year = 50% x 952 mm = 476 mm.

When the weighed total ET_{crop}-values per month (or per crop for that matter) are cumulated, the overall weighed ET_{crop} for the whole year is found (812 mm in the Table 2). This figure represents the actual amount of water the project needs for its crop evapotranspiration over the year.

However, not all this water has to be supplied by the irrigation system. Part of the need for water is satisfied by precipitation. But not all precipitation can be used by the crops, part of it being lost by interception, part by percolation. Also part of the precipitation falls on land that is not cropped at that time. Only the 'effective precipitation' (P_{ef}) that falls on the cropped area can be used by the crops. The height of the effective precipitation is influenced by:

Table 2. Example of cropped area (%), monthly values of ET_{crop}, total ET_{crop} and weighed total ET_{crop} for three crops

	% cropped	ET_{crop} (mm)					
		January	February	March	....	total	weighed total
Crop 1	50%	–	86	114	...	952	476
Crop 2	25%	38	42	56	...	720	180
Crop 3	25%	42	68	–	...	624	156
Total		80	196	170	...	2296	–
Weighed total		20	71	71	...	–	812

. Total rainfall. Rain storms of large magnitude and high intensity
will supply water in excess of that which can be stored in the soil
profile. The excess quantity is lost to surface runoff or to percola-
tion. In cases with light precipitation, these losses will not occur
as frequently, so the effectiveness of rainfall in cases with light
precipitation is relatively higher than that in cases with high-inten-
sity precipitation.

. Evapotranspiration rate. When the crops have a high water use rate,
soil moisture will be depleted rapidly. A large amount of water can
therefore be stored in the soil profile again. When the rate of evapo-
transpiration is very low, storage capacity for rainfall will be
provided at a much slower rate. So, the higher the evapotranspiration
rate, the higher the effectiveness of precipitation.

. Net irrigation application depth. The application depth is dependent
upon the soil water storage capacity of the root zone. A high appli-
cation depth indicates good storage capacity, and therefore a rela-
tively high effectiveness.

To compute the amount of effective precipitation a method has been
developed by the US DEPARTMENT OF AGRICULTURE (1967), which involves
the three factors mentioned above. This method uses tables and graphs
to derive effective precipitation. VOS (1984) found an empirical
expression that describes the relations in the graphs and tables
accurately on a monthly basis (see Fig. 4):

$$P_{ef} = f(1.253 \ P^{0.824} - 2.935) \ 10^{0.001 \ ET_{crop}} \qquad (mm) \qquad (25)$$
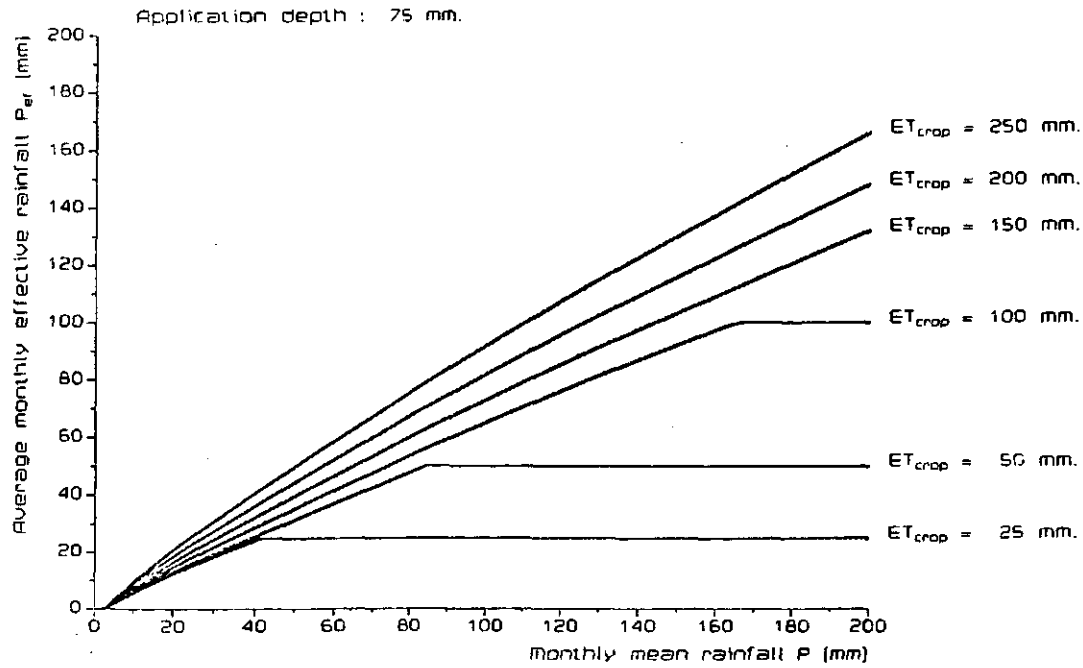
Fig. 4. Effective precipitation

where: P   = monthly total precipitation   (mm)

       f   = correction factor, dependent on the net application
                depth of irrigation (D_a) (-)

       ET_{crop} = monthly total (weigthed) ET_{crop} (mm)

The value of f can be found by:

$$f = 0.133 + 0.201 \ln(D_a) \qquad if \qquad D_a < \quad 75 \ mm \qquad (26a)$$

$$f = 0.946 + 7.3 \ 10^{-4} \ D_a \qquad if \qquad D_a > = 75 \ mm \qquad (26b)$$

For each time step effective precipitation still has to be correc-
ted for total percentage of cropped area. In Table 2, in January 50%
of the total area is cropped, thus 50% of the effective precipitation
in January can be used by the crops.

Total water demand can now be calculated as the difference between
total weighed ET_{crop} and total effective precipitation on the cropped
area.

In Table 3 the yearly total weighed ET_{crop} is 812 mm. The yearly
total effective precipitation on the cropped area is 236 mm. Therefore
the yearly total water demand is: 812 - 236 = 576 mm. To convert these

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Table 3. Example of monthly values of weighed total ET_{crop}, calculation steps to derive effective precipitation on the cropped area and total water demand. All figures except percentages in mm's

	January	February	March	....	Total	Weighed total
Weighed total ET_{crop}	20	71	71	...	–	812
Precipitation	24	40	27	...	416	
Eff. prec.	17	28	21	...	316	
% cropped	50%	100%	75%	...	–	
Eff. prec. cropped area	9	28	16	...	236	
Water demand	11	43	55	...	576	

results from mm's to m^3's, multiplication with the total area pertaining to the project will suffice.

3. PROGRAM DESCRIPTION

CROWAR is written in standard Fortran-77 (ANSI X3.9-1978), full language. System-dependency is restricted to a minimum:

- Logical Unit Numbers (LUN's), these are set in the data block of the main program.
- Date routine call in subroutine PRTPEN.
- Escape sequences to set the terminal to 80 or 132 char/line in output routines PRTPEN, PRTCRP, PRTTWD and the main module.

The program has been developed and tested on a Digital Equipment VAX 11/750 under the VMS operating system. CROWAR requires a minimum of 52 Kbytes of working memory to be executed. Copies of the program on magnetic tape, for which a small charge for tape and postage costs will be made, can be obtained from the author on request at the following adress:

Institute for Land and Water Management Research (ICW)
P.O. Box 35
6700 AA WAGENINGEN
The Netherlands

3.1. Structure of the program

CROWAR consists of 1 main program and 25 subroutines. Fig. 5 shows the hierarchic structure of the program.

A short description of all modules:

CROWAR: Main module, welcomes the user and performs subsequent CALL's to first level subroutines.

First level subroutines:

RDDATA: Performs input of all data for calculation of reference crop evapotranspiration from either terminal or data file. If desired, stores input data in a data file for later re-use.

PENCAL: Computes reference crop evapotranspiration (ET_o), as discussed in Section 2.2.

PRTPEN: Writes results from PENCAL to output data file (CROWAR.OUT), and (optional) to terminal. Output is 132 char/line wide.

```
   Main            1st level         2nd level        3rd level
   program         subroutines       subroutines      subroutines

+---------+
! CROWAR  !
+---------+
 ! ! ! ! !        +--------+                +--------+
 ! ! ! ! +-----! RDDATA !  +-----------! CORREC !
 ! ! ! !          +--------+  !              +--------+
 ! ! ! !
 ! ! ! !          +--------+  !              +--------+
 ! ! ! +-------! PENCAL !-+  +--------! GRASES !
 ! ! !            +--------+     !             +--------+
 ! ! !                           !
 ! ! !            +--------+     !             +--------+
 ! ! +---------! PRTPEN !  +--------! CITRES !
 ! !              +--------+     !             +--------+
 ! !                            !
 !-!                            !             +--------+
 ! !                            +-------! ORCHES !
 ! !                            !             +--------+      +---- ARTICC
 ! !                            !                             !
 ! !              +-------+----+    +--------+      +---- BARLYC
 ! +----------! CRPCOF !  +--------! RICES  !       !
 !                +-------+-+  !    +--------+      +---- BEANSC
 !                          !  !                     !
 !                +--------+ ! !    +--------+      +---- CORNSC
 +------------! PRTTWD ! !  +--------! SUGCNS !      !
                  +--------+ !  !    +--------+      +---- CORNGC
                           !  !                     !
                           !  !    +--------+      +---- COTTNC
                           ! +-------! VEGTES !----+
                           !  !       +--------+      +---- ONIONC
                           !  !                        !
                           !  !    +--------+      +---- POTATC
                           ! +-------! USRCRP !       !
                           !         +--------+      +---- SOYBNC
                           !                          !
                           !         +--------+      +---- SUGRBC
                           +-----------! PRTCRP !      !
                                       +--------+      +---- TOMATC
```
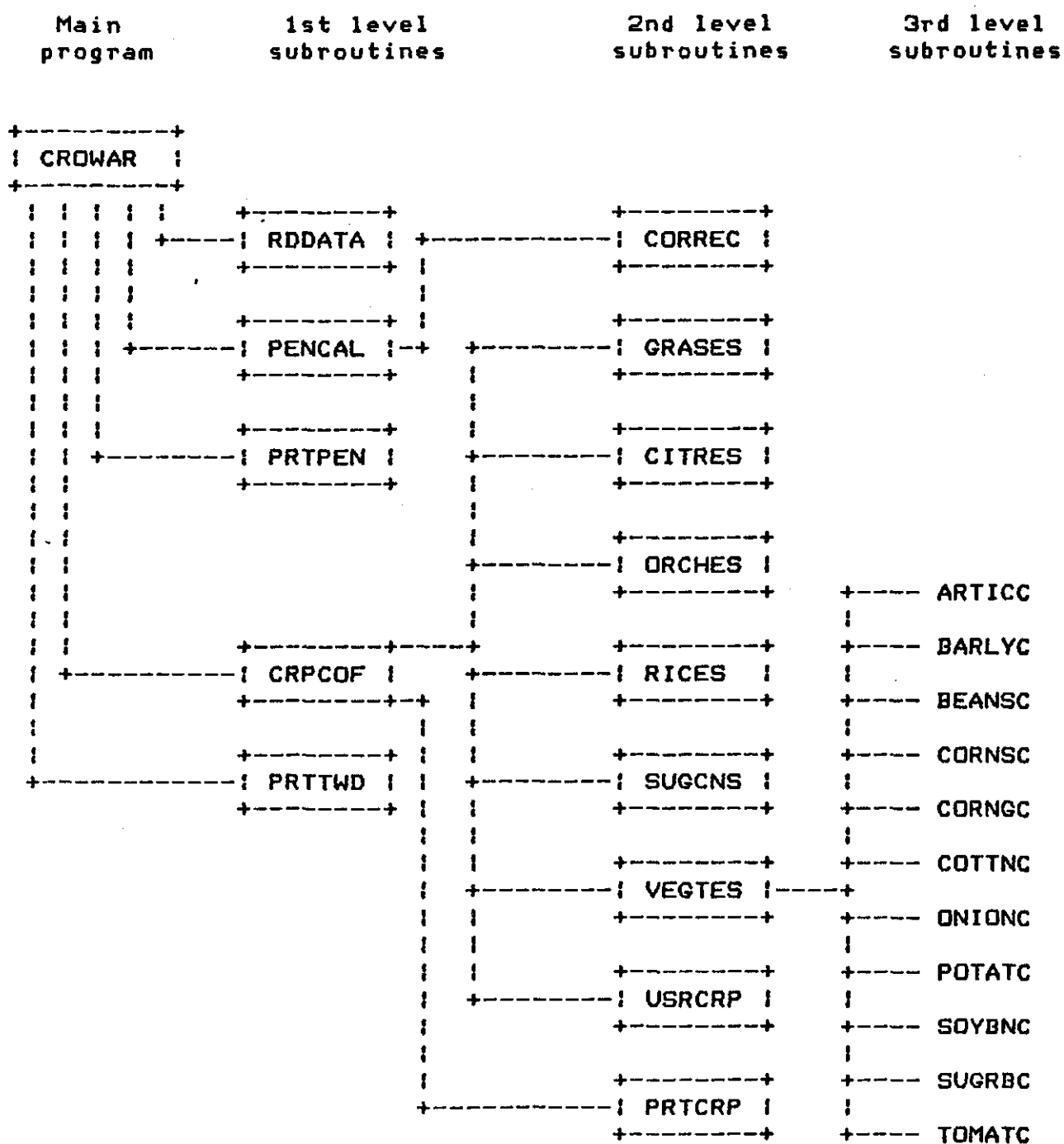
Fig. 5. Structure of CROWAR

CRPCOF: Main routine for selection of crops and subsequent calculation of K_c-values and timing of crop development stages. The user is asked to select a crop, and the correct second level crop routine is CALLED to perform the necessary calculations. After calculations for a crop, results are stored by a CALL to PRTCRP. This can be repeated for all crops in the project.

PRTTWD: Calculates and prints effective precipitation and total water demand of the project, as discussed in section 2.4. Results will be directed to the output data file CROWAR.OUT, and (optionally) to the terminal (132 char/line).

Second level (crop) subroutines:

CORREC: Performs correction for climatological conditions on ET_o, if these differ from assumed general conditions.

GRASES: In this subroutine K_c-values for grass and alfalfa are calculated and crop development stages are timed.

CITRES: As GRASES, but for citrus.

ORCHES: As GRASES, but for deciduous fruit (orchards).

RICES : As GRASES, but for rice.

SUGCNS: As GRASES, but for sugar cane.

VEGTES: This subroutine calls third level crop subroutines for field and vegetable crops (12 crops) and calculates K_c-values for these crops for all time steps.

USRCRP: Allows the user to define a self choosen crop. Name and data on K_c-values for all time steps in the growing season have to be entered.

PRTCRP: This subroutine is not a crop subroutine. It performs output of the results of K_c-calculations for each crop. Results (ET_{crop}) will be directed to output data file CROWAR.OUT, and (optionally) to terminal (132 char/line). Output from PRTCRP can be suppressed.

Third level (field and vegetable crops) subroutines:

ARTICC: Calculates K_c-levels for the mid season stage and at harvest, and the 5 dates that determine K_c-value during the growing season (see Section 2.3) for artichokes.

BARLYC: As ARTICC, but for barley and wheat

BEANSC: As ARTICC, but for beans (green)

CORNSC: As ARTICC, but for sweet corn

CORNGC: As ARTICC, but for grain corn

COTTNC: As ARTICC, but for cotton

ONIONC: As ARTICC, but for onion

POTATC: As ARTICC, but for potatoes

SOYBNC: As ARTICC, but for soya beans

SUGRBC: As ARTICC, but for sugar beets

TOMATC: As ARTICC, but for tomatoes

3.2. Input data

The input data needed, can be divided into four groups:

1. general
2. data for modified Penman calculations
3. data for crop coefficient calculations
4. data for water demand calculations

Ad 1. General

To identify the run, CROWAR will ask the name of the region/project under study and the name of the country in which the region/project lies. These names will be printed on every page of output.

Further general input:

- time step (months or decades)
- number of the first time step (e.g. if time step is months,
  Jan. = 1, Feb. = 2 .....)
- number of the last time step

Ad 2. Data for modified Penman calculations

In order to calculate reference crop evapotranspiration, input data are needed on:

- latitude (degrees.minutes)
- hemisphere (northern of southern)
- altitude (m above sea level)
- height at which wind speed is measured (m)
- unit of wind speed data, $(m.s^{-1})$ or $(km.d^{-1})$
- unit of humidity data, (%) or (mbar)
- unit of sunshine data, $(hours.d^{-1})$ or $(hours.time\ step^{-1})$
- meteorological data, for each time step:

. mean air temperature ($^{\circ}$C)

. mean daily wind speed (m.s^{-1}) or (km.d^{-1})

. mean relative humidity (%) or (mbar)

. mean number of hours of sunshine (h.d^{-1}) or (h.time step^{-1})

The input data will be checked by the program for possible mistakes such as: actual number of hours of sunshine exceeds maximum number of hours of sunshine, negative values for humidity or wind speed.

For adjustment of ET_o for climate, input data are needed on day/ night wind speed ratio and values of highest relative humidity. These data may be entered for each time step (if available) or as a mean, general value, applicable for all time steps. When the user has no data available, default values can be used.

Ad 3. Data for crop coefficient calculations

The input data needed for the calculation of K_c-values depend upon the crop under consideration. In section 2.3 the required input data are discussed. Data on frequency of irrigation/rainfall that are used for the calculations for several field and vegetable crops, will be asked only once.

Ad 4. Data for water demand calculations

Together with the meteorological data mentioned under ad 2, CROWAR will ask for the precipitation data for each time step. These precipitation data are not used for the ET_o calculation, but for the calculation of total water demand.

Finally the user is asked to give the percentages of the total area occupied by each crop. The sum of the percentages in any time step should not exceed 100%, the sum of all percentages can exceed 100% (e.g. two crops/year).

All input data can be entered from the terminal keyboard during 'conversation' with the program. The data mentioned under ad 2, that form the bulk of the input data, together with the precipitation data, can be read from or stored on a data file. An example of (part of) such a file can be found in Table 4. The text after the '!' is explanatory, it forms no part of the actual input file.

Table 4. Example of input file

VALENCIA (ACEQUTA DE MONCADA)	! Name of the region
SPAIN	! Country
39.00	! Latitude (degrees.minutes)
N	! Northern hemisphere
10	! Altitude (m above sea level)
M	! Time step is months
1	! Number of first month, January (1-12)
12	! Number of last month, December (1-12)
2	! Height of wind run measurements (m)
2	! Unit of wind speed data is $(km.d^{-1})$
1	! Unit of humidity data is (%)
1	! Unit of sunshine data is $(h.d^{-1})$
10.0	! Mean air temperature during first time step (^{o}C)
216	! Mean wind run during first time step $(km.d^{-1})$
70	! Mean relative humidity during first time step (%)
5.16	! Mean number of sunshine hours during first time step $(h.d^{-1})$
24	! Total precipitation during first time step (mm)
10.8	! Ditto during second time step (temperature)
229	! Ditto during second time step (wind run)
.	
.	
.	
.	
11.1	! 12th and last time step (temperature)
229	! 12th and last time step (wind run)
71	! 12th and last time step (rel. humidity)
5.52	! 12th and last time step (sunshine hours)
26	! 12th and last time step (precipitation)

3.3. Instructions for use

Since CROWAR is a fully interactive, user's friendly program, the instructions for use can be very limited.

To be able to use the 132 char/line terminal setting, the host computer should be informed. On a VAX this can be done by means of a 'command procedure' (CROWAR.COM) as shown in Appendix A. This command procedure informs the VAX of the fact that a 132 char/line setting may be used (SET TERMINAL/WIDTH=132) and sets the terminal to 80 char/line (escape-sequence for CIT-101 terminal) before starting the program (RUN CROWAR).

In order to run CROWAR correctly on a VAX computer, the user should have access to the actual CROWAR program and the CROWAR.COM command procedure. CROWAR can then be started by typing: '@CROWAR'.

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After starting the program (i.e. € CROWAR), all the user has to do is answer the questions, raised by the program. With most questions CROWAR shows (between brackets) what kind of input is expected, e.g. (Y/N) means that, in answer to the question, the user should type 'Y' or 'N' (for 'YES' and 'NO').

All character input data, like 'Y' or 'N' should be entered in capitals. Undercast characters do not comply with the ANSI Fortran standard, and are therefore not supported in CROWAR.

Whenever a wrong answer (i.e. not one of the options offered) is given, the program will repeat the same question (that is, when no fatal run time error occurs).

All output data are automatically directed to a data file (see Section 3.4) that can be listed or printed later. At certain points in the program, CROWAR asks if the user wants to see the latest part of the output on the terminal.

3.4. Output

All results obtained with CROWAR are directed to a file, named 'CROWAR.OUT'. This file can be inspected on the terminal or printed on a line printer. The output file is designed for 132 char/line terminals and printers. The output is divided into three parts:

1. Calculation of reference crop evapotranspiration
1. Crop evapotranspiration
3. Total water demand

In the header of every page of output are listed: date, program name, page number, names of the region/project and country and name of the relevant output part. An example of output is given in Fig. 6.

Ad part 1. Calculation of reference crop evapotranspiration

The first part of output (see Fig. 6a) consists of one or two pages. When calculations are performed on decade basis, and the number of decades exceeds 12, a second page is needed. The header of the first page carries some additional information on CROWAR.

The table in this part of output shows four groups of data. The first (INPUT) is a recapitulation of the meteorological input data, where the wind speed is always given in (km.d^{-1}), humidity is always in (%) and sunshine is always in (h.d^{-1}).

The second group (OUTPUT I) shows the values of some variables calculated in the program: saturation vapour pressure EA, extra-terrestrial radiation RA, max. number of hours of sunshine SUNMAX, net short-wave radiation RNS and net longwave radiation RNL.

The third group (OUTPUT II) depicts the terms of the modified Penman formula (eq. (4)): weighing factor W, net radiation RN, wind function F(U), vapour pressure deficit (EA-ED) and correction factor C.

In the fourth group (OUTPUT III) the results of the modified Penman calculations are shown, the reference crop evapotranspiration ET_o in $mm.d^{-1}$ and the cumulated value over the time step in mm.

Strictly speaking most columns in this table could be missed. The data in these columns can be very usefull, however to improve the insight in the (modified) Penman formula.

Ad part 2. Crop evapotranspiration

The second part of output (see Fig. 6b) consists of a variable number of pages. Output from part 2 can be suppressed if desired. If output is not suppressed a new page is added for every crop that is included in the calculations. The name of user defined crops is preceded with an asterisk '*'.

In the tables of part 2 the ET_o value $mm.d^{-1}$ from part 1 is in the first column. When the crop coefficients in the next column are combined (multiplied) with these ET_o values, the ET_{crop} values are found. These are in the third column in $mm.d^{-1}$. The last column shows the cumulated ET_{crop} values over the time step(mm) Under each table total cumulated ET_{crop} over all time steps is given.

Ad part 3. Total water demand

The third part of output (see Fig. 6c) consists of one, two or three pages. When calculations are performed on decade basis, and the number of time steps exceeds 12, more pages are needed.

In the table three groups of data are shown. In the first (upper) group cumulated ET_{crop} values from part 2 are repeated for every crop. The percentage of total area occupied by each crop is also given. Row and column totals of ET_{crop} and weighed ET_{crop} are shown. The calculation procedure for these values is discussed in Section 2.4 (see Table 2).

The second group gives information on the steps in the calculation of effective precipitation, weighed for the cropped area as discussed in Section 2.4 (see Table 3).

The last group (bottom line) of the table gives the water demand in mm per time step and as a total over all time steps in mm. To convert mm to m^3 simply multiply with the total project area.

One may observe small errors in the summations in the output file, e.g. the printed value of the total weighed ET_{crop} over the year may differ slightly from the sum of the printed values for each time step. This is due to the fact that the computer calculates all values with more digits after the decimal point then printed.

PROGRAM CROWAR

[1] CALCULATION OF REFERENCE CROP EVAPOTRANSPIRATION
****

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THE NETHERLANDS

PROGRAM BASED UPON : 'CROP WATER REQUIREMENTS'
BY : J.DOORENBOS AND W.O.PRUITT
IRRIGATION AND DRAINAGE
PAPER 24, REVISED EDITION
F.A.O.   ROME   1977

REGION/PROJECT : VALENCIA (ACEQUTA DE MONCADA)

COUNTRY : SPAIN

LATITUDE : 39.00 DEGREES N

ALTITUDE : 10. M. ABOVE SEA-LEVEL

PERIOD	NR. OF DAYS	RH [%]	N [H]	T [OC]	U2 [CKM/D]	EA [MBAR]	RA [MM/D]	NMAX [H]	RNS [MM/D]	RNL [MM/D]	W [-]	RN [MM/D]	F(U) [MM/D]	EA-ED [MBAR]	C [-]	ETO [MM/D]	CUM.ETO [MM]
				INPUT				OUTPUT I				OUTPUT II				OUTPUT III	
JAN	31	70	5.2	10.0	216.	12.3	6.4	9.8	2.5	1.5	0.55	0.9	0.85	3.7	0.88	1.7	52.4
FEB	28	68	6.1	10.8	229.	13.0	8.6	10.7	3.5	1.7	0.56	1.8	0.89	4.1	0.91	2.4	66.8
MAR	31	69	6.2	12.6	229.	14.6	11.4	11.9	4.4	1.5	0.59	2.9	0.89	4.5	0.95	3.2	98.6
APR	30	68	7.4	14.8	229.	16.8	14.2	13.2	5.6	1.6	0.62	4.1	0.89	5.4	1.01	4.4	130.9
MAY	31	67	8.5	17.7	216.	20.3	16.1	14.3	6.6	1.6	0.66	5.0	0.85	6.7	1.06	5.5	171.6
JUN	30	68	9.8	21.4	216.	25.5	16.8	14.8	7.3	1.6	0.70	5.7	0.85	8.2	1.08	6.5	196.3
JUL	31	70	10.6	24.0	203.	29.8	16.4	14.6	7.6	1.6	0.73	5.9	0.82	9.0	1.09	6.9	213.9
AUG	31	73	9.2	24.6	194.	30.9	14.8	13.6	6.5	1.4	0.73	5.1	0.79	8.3	1.08	5.9	183.5
SEP	30	74	7.7	22.0	194.	26.4	12.3	12.3	5.2	1.4	0.71	3.7	0.79	6.9	1.01	4.3	128.4
OCT	31	74	6.3	18.2	194.	20.9	9.5	11.1	3.8	1.5	0.66	2.3	0.79	5.4	0.94	2.8	87.9
NOV	30	72	5.2	13.6	203.	15.6	7.0	10.0	2.7	1.5	0.60	1.2	0.82	4.4	0.89	1.9	57.4
DEC	31	71	5.5	11.1	229.	13.2	5.8	9.5	2.4	1.7	0.57	0.7	0.89	3.8	0.87	1.6	50.2

Fig. 6a. Example of output, part 1

[2] CROP EVAPOTRANSPIRATION
****

REGION/PROJECT : VALENCIA (ACEQUIA DE MONCADA)   COUNTRY : SPAIN

CROP : ARTICHOKES

PERIOD	NR. OF DAYS	ETO [MM/D]	CROP COEFF. [-]	ETCROP [MM/D]	CUM. ETCROP [MM]
JAN	31	1.7	0.95	1.6	49.7
FEB	28	2.4	0.95	2.3	63.5
MAR	31	3.2	0.95	3.0	93.7
APR	30	4.4	0.95	4.1	124.4
MAY	31	5.5	0.93	5.1	159.6
JUN	30	6.5	0.00	0.0	0.0

PERIOD	NR. OF DAYS	ETO [MM/D]	CROP COEFF. [-]	ETCROP [MM/D]	CUM. ETCROP [MM]
JUL	31	6.9	0.00	0.0	0.0
AUG	31	5.9	0.51	3.0	93.0
SEP	30	4.3	0.76	3.3	98.1
OCT	31	2.8	0.95	2.7	83.5
NOV	30	1.9	0.95	1.8	54.6
DEC	31	1.6	0.95	1.5	47.7

TOTAL CUMULATIVE CROP EVAPOTRANSPIRATION :   ****************
                                              *   868. MM. *   FOR CROP : ARTICHOKES
                                              ****

Fig. 6b. Example of output, part 2

PROGRAM CROWAR

[3] TOTAL WATER DEMAND
****

COUNTRY : SPAIN

REGION/PROJECT : VALENCIA (ACEQUTA DE MONCADA)

CROP	PERC. CROPD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	WEIGHED TOTAL
ARTICHOKES	20%	50.	63.	94.	124.	160.	0.	0.	93.	98.	84.	55.	48.	868.	174.
CITRUS	40%	39.	50.	79.	105.	137.	167.	182.	156.	109.	75.	46.	40.	1185.	474.
RICE	15%	0.	0.	0.	0.	0.	216.	235.	220.	154.	84.	0.	0.	909.	136.
TOMATOES	25%	0.	0.	0.	0.	79.	136.	210.	182.	0.	0.	0.	0.	607.	152.
* USER-CROP	25%	47.	57.	79.	0.	0.	0.	0.	0.	0.	57.	43.	43.	326.	81.
1 TOTAL ET-CROP		136.	170.	252.	229.	376.	519.	627.	651.	361.	299.	144.	131.	3895.	—
2 WEIGHED TOTAL ET-CROP		37.	47.	70.	67.	107.	133.	161.	159.	86.	73.	40.	36.	—	1017.
3 PRECIPITATION		24.	40.	27.	30.	33.	29.	11.	8.	71.	45.	72.	26.	416.	
4 EFFECTIVE PRECIPITATION		16.	26.	19.	21.	25.	23.	9.	6.	48.	31.	40.	17.	279.	
5 TOTAL PERCENTAGE CROPPED		85%	85%	85%	60%	85%	80%	80%	100%	75%	100%	85%	85%	—	
6 EFF. PREC. CROPPED AREA		13.	22.	16.	12.	21.	19.	7.	6.	36.	31.	34.	14.	231.	
7 CROP WATER DEMAND, (2-6)		24.	25.	54.	54.	85.	114.	154.	154.	51.	43.	6.	22.	786.	

ALL FIGURES EXCEPT PERCENTAGES ARE IN MM.

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Fig. 6c. Example of output, part 3

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LIST OF USED SYMBOLS

Symbol	Interpretation	Unit as used in calculations
α	surface reflectance coefficient for shortwave radiation	(-)
β	declination of the sun acc. to GOUDRIAAN and VAN LAAR (1978)	(rad)
c	correction factor to adjust ET_o to day and night weather conditions	(-)
c_p	specific heat of dry air at constant pressure ($c_p = 1004$ J.kg^{-1}.K^{-1})	(J.kg^{-1}.K^{-1})
δ	declination of the sun acc. to DE BRUIN (1977)	(rad)
$\bar{d}$	average distance earth-sun	(au)
d	actual distance earth-sun	(au)
D_a	net irrigation application depth	(mm)
ε	ratio of molecular weight water vapour/dry air ($\varepsilon = 0.622$)	(-)
E_a	isothermal evaporation	(kg.m^{-2}.s^{-1})
E_o	open water evaporation	(kg.m^{-2}.s^{-1})
ET_{crop}	crop evapotranspiration	(mm)
ET_o	reference crop evapotranspiration	(mm)
e	constant (e = 0.01675 rad)	(rad)
$e_a(T)$	saturation vapour pressure at air temperature T	(mbar)
e_d	actual vapour pressure	(mbar)
ϕ	latitude (positive on northern hemisphere)	(rad)
f	correction factor, dependent on the net application depth of irrigation (D_a)	(-)
f(u)	wind function	(mm.d^{-1}.mbar^{-1})
f_w	correction factor	(-)
G	water heat flux	(W.m^{-2})
γ	psychrometric constant $\gamma = 0.66$ mbar.K^{-1} at sea level and 295 K)	(mbar.k^{-1})
h	altitude above sea level	(m)
h_m	height of wind speed measurement	(m)
H	half day length	(rad)
K_c	crop coefficient, related to ET_o	(-)
ℓ	true astronomical length of the sun	(rad)
L	latent heat of evaporization of water (L = 2452 10^3 J.kg^{-1} at 293 K)	(J.kg^{-1})

Symbol	Interpretation	Unit as used in calculations
ℓ_o	constant (ℓ_o = -1.3551 rad)	(rad)
m	average anomaly of the sun	(rad)
n	observed number of hours of daily bright sunshine	(h)
n_d	number of day since January 1st	(-)
N	max. number of hours of daily bright sunshine	(h)
P	precipitation	(mm
p_a	atmospheric pressure	(mbar)
P_{ef}	effective precipitation	(mm)
p_o	atmospheric pressure at sea level (p_o = 1013 mbar)	(mbar)
q	constant (q = 0.397949 rad)	(rad)
G*	net radiation in original Penman equation	$(W.m^{-2})$
R_a	incoming extra-terrestrial shortwave radiation	$(mm.d^{-1})$
R_{hum}	relative humidity	(%)
R_n	net radiation in modified Penman equation	$(mm.d^{-1})$
$R_{n\ell}$	net longwave radiation	$(mm.d^{-1})$
R_{ns}	net shortwave radiation	$(mm.d^{-1})$
s	the slope of the saturation vapour pressure curve	(-)
σ	constant of Stefan Boltzmann (σ = 1.98 10^{-9} $mm.d^{-1}.K^{-4}$)	$(mm.d^{-1}.K^{-4})$
T	air temperature Note: in input temperature should be given in °C	(K)
t	time	(d)
u_2	wind speed at 2 m height	$(m.s^{-1})$
v_2	total wind run at 2 m height	$(km.d^{-1})$
x	temporary variable (x = sin β sin ϕ)	(-)
y	temporary variable (y = cos β cos ϕ)	(-)
W	weighing factor in the modified Penman formula (W = s/s+γ)	(-)

VAX/VMS COMMAND PROCEDURE TO START CROWAR

```
$ SET TERMINAL/WIDTH=132
$ WRITE SYS$OUTPUT "<ESC>[?31"
$ DEFINE/USER_MODE SYS$INPUT SYS$COMMAND:
$ RUN CROWAR
```