Crop water requirements

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by
J. Doorenbos
Water Management Specialist
FAO Land and Water Development Division
and
W.O. Pruitt
Consultant
University of California
in consultation with
A. Aboukhaled (Lebanon)
J. Damagnez (France)
N.G. Dastane (India)
C. Van Den Berg (Netherlands)
P.E. Rijtema (Netherlands)
O.M. Ashford (WMO)
M. Frère (FAO)
and
FAO Field Staff

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SUMMARY

This publication is intended to provide guidance in determining crop water requirements and their application in planning, design and operation of irrigation projects.

Part I.1 presents suggested methods to derive crop water requirements. The use of four well-known methods for determining such requirements is defined to obtain reference crop evapotranspiration (ETo), which denotes the level of evapotranspiration for different climatic conditions. These methods are the Blaney-Criddle, the Radiation, the Penman and Pan Evaporation methods, each requiring a different set of climatic data. To derive the evapotranspiration for a specific crop, relationships between crop evapotranspiration (ETcrop) and reference crop evapotranspiration (ETo) are given in Part I.2 for different crops, stages of growth, length of growing season and prevailing climatic conditions. The effect of local conditions on crop water requirements is given in Part I.3; this includes local variation in climate, advection, soil water availability and agronomic and irrigation methods and practices. Calculation procedures are presented together with examples. A detailed discussion on selection and calibration of the presented methodologies together with the data sources is given in Appendix II. A computer programme on applying the different methods is given in Appendix III.

Part II discusses the application of crop water requirements data in irrigation project planning, design and operation. Part II.1 deals with deriving the field water balance, which in turn forms the basis for predicting seasonal and peak irrigation supplies for general planning purposes. Attention is given to irrigation efficiency and water requirements for cultural practices and leaching of salts. In Part II.2 methods are presented to arrive at field and scheme supply schedules with emphasis towards the field water balance and field irrigation management. Criteria are given for operating the canal system using different methods of water delivery, and for subsequent design parameters of the system. Suggestions are made in Part II.3 on refinement of field and project supply schedules once the project is in operation.

The presented guidelines are based on measured data and experience obtained covering a wide range of conditions. Local practical, technical, social and economic considerations will, however, affect the planning criteria selected. Therefore caution and a critical attitude should still be taken when applying the presented methodology.

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CONVERSION FACTORS

Length

1 foot	=	30.48	cm
1 foot	=	0.305	m
1 inch	=	2.54	cm
1 yard	=	91.44	cm
1 statute mile	=	1.61	km
1 US naut. mile	=	1.85	km
1 Int. naut. mile	=	1.85	km

Area

1 in^2	=	6.45	cm^2
1 ft^2	=	929.03	cm^2
1 yd^2	=	0.835	m^2
1 acre	=	0.405	ha
1 sq. stat. mile	=	2.59	km^2

Volume

1 in^3	=	16.39	cm^3
1 ft^3	=	28316.8	cm^3
1 ft^3	=	28.32	litre (l)
1 gallon (US)	=	3.79	l
1 gallon (Imp.)	=	4.55	l
1 acre foot	=	1233.5	m^3

Temperature

$^{\circ}F = 1.8^{\circ}C + 32$

$^{\circ}C = (^{\circ}F - 32)\ 5/9$

Velocity

1 knot	=	0.515	m/sec
	=	1.85	km/hr
1 foot/sec	=	0.305	m/sec
	=	1.095	km/hr
1 foot/min	=	0.51	cm/sec
	=	0.18	km/hr
1 mile/min	=	2682	cm/sec
	=	1.61	km/min
1 m/sec (24 hr)	=	86.4	km/day
1 foot/sec (24 hr)	=	26.33	km/day
1 mile/hour (24 hr)	=	38.6	km/day
1 knot (24 hr)	=	44.5	km/day

Pressure

1 atmosphere	=	76	cm Hg
1 atm	=	1.013	bar
1 inch Hg	=	0.0334	atm
1 inch H_2O	=	2.49	mbar
1 mbar	=	0.75	mm Hg
1 lb/in^2	=	51.72	mm Hg

Radiation to equivalent depth of evaporation

1 cal/cm^2	=	1/59	mm
1 cal/cm^2 min	=	1	mm/hr
1 mW/cm^2	=	1/70	mm/hr
1 mW/cm^2 (24 hr)	=	0.344	mm/day
1 cal/cm^2 min (24 hr)	=	24	mm/day
1 $Joule/cm^2$ min (24 hr)	=	5.73	mm/day

CLIMATOLOGICAL NOMENCLATURE

Where climatic data are not used as direct input data but general levels of climatic variables are needed, the following nomenclature is used:

TEMPERATURE

General

hot	Tmean	$>30^\circ$C
cool	Tmean	$<15^\circ$C

$$\text{Tmean} = \frac{\text{Tmax} + \text{Tmin}}{2}$$

data collected from max/min thermometer or thermograph records.

HUMIDITY

RHmin, minimum relative humidity

Blaney-Criddle (I.1.1)

low	$<20\%$
medium	20-50%
high	$>50\%$

Crop coeff. (I.2)

dry	$<20\%$
humid	$>70\%$

RHmin is lowest humidity during daytime and is reached usually at 14.00 to 16.00 hrs. From hygrograph or wet and dry bulb thermometer. For rough estimation purposes when read at 12.00 hrs subtract 5 to 10 for humid climates and up to 30 for desert climates.

RHmean, mean relative humidity

Radiation method (I.1.2)

low	$<40\%$
medium-low	40-55%
medium-high	55-70%
high	$>70\%$

Pan method (I.1.4)

low	$<40\%$
medium	40-70%
high	$>70\%$

RHmean is average of maximum and minimum relative humidity or RHmean = (RHmax + RHmin)/2. Whereas for most climates RHmin will vary strongly, RHmax equals 90 to 100% for humid climates, equals 80 to 100% for semi-arid and arid climates where Tmin is 20-25°C lower than Tmax. In arid areas RHmax may be 25-40% when Tmin is 15°C lower than Tmax.

WIND

General

light	<2 m/sec	<175 km/day
moderate	2-5 m/sec	175-425 km/day
strong	5-8 m/sec	425-700 km/day
very strong	>8 m/sec	>700 km/day

For rough estimation purposes sum of several wind-speed observations divided by number of readings in m/sec or multiplied by 86.4 to give wind run in km/day.

With 2 m/sec: wind is felt on face and leaves start to rustle
With 5 m/sec: twigs move, paper blows away, flags fly
With 8 m/sec: dust rises, small branches move
With > 8 m/sec: small trees start to move, waves form on inland water etc.

RADIATION

Blaney-Criddle (I.1.1)

sunshine n/N	
low	$<.6$
medium	.6-.8
high	$>.8$

Ratio between daily actual (n) and daily maximum possible (N) sunshine duration.

n/N > 0.8: near bright sunshine all day
n/N 0.6 - 0.8: some 40% of daytime hours full cloudiness or partially clouded for 70% of daytime hours.

or

cloudiness	tenth	oktas
low	>5	>4
medium	2-5	1.5-4
high	<2	<1.5

Mean of several cloudiness observations per day on percentage or segments of sky covered by clouds.

4 oktas : 50% of the sky covered all daytime hours by clouds or half of daytime hours the sky is fully clouded
1.5 oktas : less than 20% of the sky covered all daytime hours by clouds or each day the sky has a full cloud cover for some 2 hours.

Part I- CALCULATION OF CROP WATER REQUIREMENTS

Prediction methods for crop water requirements are used owing to the difficulty of obtaining accurate field measurements. The methods often need to be applied under climatic and agronomic conditions very different from those under which they were originally developed. Testing the accuracy of the methods under a new set of conditions is laborious, time-consuming and costly, and yet crop water requirement data are frequently needed at short notice for project planning. To meet this need, guidelines are presented to calculate water requirements of crops under different climatic and agronomic conditions, based on the recommendations formulated by the FAO Group on Crop Water Requirements during its meetings held in Lebanon (1971) and Rome (1972). The guidelines were subsequently refined using the comments received and experience obtained in applying them as presented in the 1975 draft version of this paper. For a detailed description of the presented methodology see Appendix II.

Crop water requirements are defined here as "the depth of water needed to meet the water loss through evapotranspiration (ETcrop) of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment". To calculate ETcrop a three-stage procedure is recommended:

(1) The effect of climate on crop water requirements is given by the reference crop evapotranspiration (ETo) which is defined as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water". The four methods presented, the Blaney-Criddle, Radiation, Penman and Pan Evaporation method, are modified to calculate ETo using the mean daily climatic data for 30- or 10-day periods. ETo is expressed in mm per day and represents the mean value over that period.[1] Primarily the choice of method must be based on the type of climatic data available and on the accuracy required in determining water needs. Climatic data needed for the different methods are:

Method	Temperature	Humidity	Wind	Sunshine	Radiation	Evaporation	Environ.
Blaney-Criddle	*	0	0	0			0
Radiation	*	0	0	*	(*)		0
Penman	*	*	*	*	(*)		0
Pan evaporation		0	0			*	*

* measured data; 0 estimated data; (*) if available, but not essential

Concerning accuracy, only approximate possible errors can be given since no base-line type of climate exists. The modified Penman method would offer the best results with minimum possible error of plus or minus 10 percent in summer, and up to 20 percent under low evaporative conditions. The Pan method can be graded next with possible error of 15 percent, depending on the location of the pan. The Radiation method, in extreme conditions, involves

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[1] ETo will, however, vary from year to year and a frequency distribution analysis of ETo for each year of climatic record is recommended; the selected ETo value for planning is thus not based on average conditions but on the likely range of conditions and on an assessment of tolerable risk of not meeting crop water demands.

a possible error of up to 20 percent in summer. The Blaney-Criddle method should only be applied for periods of one month or longer; in humid, windy, mid-latitude winter conditions an over and under prediction of up to 25 percent has been noted (I.1). A comprehensive computer programme employing all four methods is given in Appendix III.

(2) The effect of the crop characteristics on crop water requirements is given by the crop coefficient (kc) which presents the relationship between reference (ETo) and crop evapotranspiration (ETcrop) or ETcrop = kc . ETo. Values of kc given are shown to vary with the crop, its stage of growth, growing season and the prevailing weather conditions. ETcrop can be determined in mm per day as mean over the same 30- or 10-day periods. Since the same reference is used, i.e. ETo, the presented crop coefficients apply to each of the four methods (I.2).

(3) The effect of local conditions and agricultural practices on crop water requirements includes the local effect of variations in climate over time, distance and altitude, size of fields, advection, soil water availability, salinity, method of irrigation and cultivation methods and practices, for which local field data are required (I.3).

Before calculating ETcrop, a review should be made of specific studies carried out on crop water requirements in the area and available measured climatic data. Meteorological and research stations should be visited and environment, siting, types of instruments and observation and recording practices should be appraised to evaluate accuracy of available data. If limited data from several meteorological stations are available for the project area, an improved analysis will result by preparing maps including isolines of equal values of needed climatic variables. Data relevant to crop type and crop development stages, and agricultural practices, should be collected.

CALCULATION PROCEDURES

1. Reference crop evapotranspiration (ETo)

Collect and evaluate available climatic and crop data; based on meteorological data available and accuracy required, select prediction method to calculate ETo.
Compute ETo for each 30- or 10-day period using mean climatic data.
Analyse magnitude and frequency of extreme values of ETo for given climate.

2. Crop coefficient (kc)

Select cropping pattern and determine time of planting or sowing, rate of crop development, length of crop development stages and growing period.
Select kc for given crop and stage of crop development under prevailing climatic conditions and prepare for each a crop coefficient curve.

Crop evapotranspiration (ETcrop)

Calculate ETcrop for each 30- or 10-day period: ETcrop = kc . ETo.[1/]

3. Factors affecting ETcrop under prevailing local conditions

Determine effect of climate and its variability over time and area.
Evaluate the effect of soil water availability together with agricultural and irrigation practices.
Consider relationship between ETcrop and level of crop production.

[1/] Step 2 will need to be repeated for alternative cropping patterns to obtain the optimum as influenced by climate, soil, land and water availability, management criteria and production criteria.

1. CALCULATION OF REFERENCE CROP EVAPOTRANSPIRATION (ETo)

1.1 BLANEY-CRIDDLE METHOD

This method is suggested for areas where available climatic data cover air temperature data only.

The original Blaney-Criddle equation (1950) involves the calculation of the consumptive use factor (f) from mean temperature (T) and percentage (p) of total annual daylight hours occurring during the period being considered. An empirically determined consumptive use crop coefficient (K) is then applied to establish the consumptive water requirements (CU) or $CU = K.f = K(p.T/100)$ with T in ^oF. CU is defined as 'the amount of water potentially required to meet the evapotranspiration needs of vegetative areas so that plant production is not limited by lack of water'. The effect of climate on crop water requirements is, however, insufficiently defined by temperature and day length; crop water requirements will vary widely between climates having similar values of T and p. Consequently the consumptive use crop coefficient (K) will need to vary not only with the crop but also very much with climatic conditions.

For a better definition of the effect of climate on crop water requirements, but still employing the Blaney-Criddle temperature and day length related f factor, a method is presented to calculate reference crop evapotranspiration (ETo). Using measured temperature data as well as general levels of humidity, sunshine and wind, an improved prediction of the effect of climate on evapotranspiration should be obtainable. The presented crop coefficients given under I.2 are considered to be less dependent on climate.

Recommended Relationships

The relationship recommended, representing mean value over the given month, is expressed as:

$$ETo = c\left[p(0.46T + 8)\right] \quad \text{mm/day}$$

where: ETo = reference crop evapotranspiration in mm/day for the month considered
T = mean daily temperature in ^oC over the month considered
p = mean daily percentage of total annual daytime hours obtained from Table 1 for a given month and latitude
c = adjustment factor which depends on minimum relative humidity, sunshine hours and daytime wind estimates

Figure 1 can be used to estimate ETo graphically using calculated values of $p(0.46T + 8)$. The value of $p(0.46T + 8)$ is given on the X-axis and the value of ETo can be read directly from the Y-axis. Relationships are presented in Figure 1 for (i) three levels of minimum humidity (RHmin); (ii) three levels of the ratio actual to maximum possible sunshine hours (n/N); and (iii) three ranges of daytime wind conditions at 2 m height (Uday).[1/] Information on general monthly or

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[1/] Note that air humidity refers here to minimum daytime humidity and that wind refers to daytime wind. If estimates of 24 hour mean wind are available, these need to be converted to daytime wind. Generally $Uday/Unight \cong 2$ and mean 24-hr wind data should be multiplied by 1.33 to obtain mean daytime wind. For areas with either predominantly night or daytime wind, the following factor can be used:

Uday/Unight ratio	1.0	1.5	2.0	2.5	3.0	3.5	4.0
correction for Uday	1.0	1.2	1.33	1.43	1.5	1.56	1.6

seasonal weather conditions and approximate range of RHmin, n/N and Uday for a given site may be obtained from published weather descriptions, from extrapolation from nearby areas or from local information. The nomenclature used to depict general levels of humidity, sunshine and wind is given under Climatological Nomenclature in the introductory pages of this publication.

After determining ETo, ETcrop can be predicted using the appropriate crop coefficient (kc), or ETcrop = kc . ETo (1.2).

Additional Considerations

Since the empiricism involved in any ET prediction method using a single weather factor is inevitably high, this method should only be used when temperature data are the only measured weather data available. It should be used with scepticism (i) in equatorial regions where temperatures remain fairly constant but other weather parameters will change; (ii) for small islands and coastal areas where air temperature is affected by the sea temperature having little response to seasonal change in radiation; (iii) at high altitudes due to the fairly low mean daily temperatures (cold nights) even though daytime radiation levels are high; and (iv) in climates with a wide variability in sunshine hours during transition months (e.g. monsoon climates, mid-latitude climates during spring and autumn). The Radiation Method is preferable under these conditions even when the sunshine or radiation data need to be obtained from regional or global maps in the absence of any actual measured data.

At high latitudes (55^{o} or more) the days are relatively long but radiation is lower as compared to low and medium latitude areas having the same day length values. This results in an undue weight being given to the day length related p factor. Calculated ETo values should be reduced by up to 15 percent for areas at latitudes of 55^{o} or more. Concerning altitude, in semi-arid and arid areas ETo values can be adjusted downwards some 10 percent for each 1 000 m altitude change above sea level.

Calculation of mean daily ETo should be made for periods no shorter than one month. Since for a given location climatic conditions and consequently ETo may vary greatly from year to year, ETo should preferably be calculated for each calendar month for each year of record rather than by using mean temperatures based on several years' records.

The use of crop coefficients (K) employed in the original Blaney-Criddle approach is rejected because (i) the original crop coefficients are heavily dependent on climate, and the wide variety of K values reported in literature makes the selection of the correct value difficult; (ii) the relationship between p(0.46T + 8) values and ETo can be adequately described for a wide range of temperatures for areas having only minor variation in RHmin, n/N and U; and (iii) once ETo has been determined the crop coefficients (kc) presented herein can be used to determine ETcrop.

Sample Calculations

The simple calculation procedure to obtain the mean daily value of p(0.46T + 8) in mm is illustrated using measured mean daily temperature and the day length factor for one month. With monthly humidity, wind and sunshine data (in this case obtained from published weather descriptions), the value of ETo for that month can be obtained using Figure 1. A format for the necessary calculation procedures is also given.

EXAMPLE:

Given:

Cairo, Arab Republic of Egypt; latitude 30°N; altitude 95 m; July.

Calculation:

(monthly data)		
Tmax	Σ Tmax daily values/31	35 °C
Tmin	Σ Tmin daily values/31	22 °C
T daily mean	$\frac{\Sigma \text{ Tmean}}{31}$ or $\frac{\Sigma \text{Tmax}}{31} + \frac{\Sigma \text{Tmin}}{31} \div 2$	28.5 °C
p	from Table 1 for 30°N	0.31
p(0.46T + 8)	0.31(0.46 x 28.5 + 8)	6.6 mm/day
RHmin	from Climates of Africa, Griffith (1972)	medium
n/N	" " " " " "	high to medium
U2 daytime	" " " " " "	moderate
ETo	Fig. 1 - Block II and Block V (line 2)	8.0 mm/day

Yearly data (using measured temperature data)

	J	F	M	A	M	J	J	A	S	O	N	D
Tmean °C	14	15	17.5	21	25.5	27.5	28.5	28.5	26	24	20	15.5
p	0.24	0.25	0.27	0.29	0.31	0.32	0.31	0.30	0.28	0.26	0.24	0.23
p(0.46T + 8)	3.5	3.8	4.4	5.2	6.2	6.7	6.6	6.4	5.7	5.0	4.2	3.5

using general information and references on humidity, sunshine and wind (Climates of Africa, Griffith, 1972):

	RHmin	n/N	U daytime	Block Fig. 1	Line Fig. 1
Oct-March	medium	medium	light/mod	V	1-2[1]
April-May	low/med	high/med	moderate	IV, V, I & II[1]	2
June-July	medium	high/med	moderate	II & V[1]	2
Aug-Sept	medium	high/med	light/mod	II & V[1]	1-2[1]

using Figure 1:

	J	F	M	A	M	J	J	A	S	O	N	D
ETo mm/day	2.8	3.3	4.1	6.5	8.0	8.2	8.0	7.2	6.2	4.6	3.5	2.7
mm/month	87	92	127	195	248	246	248	223	186	142	105	83

[1] interpolation required; for instance for May between Blocks IV, V, I and II of p(0.46T + 8) = 6.2 mm/day and ETo = (8.3 + 7.1 + 9.0 + 7.7) ÷ 4 = 8.0 mm/day.

Table 1

Mean Daily Percentage (p) of Annual Daytime Hours for Different Latitudes

Latitude North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
South[1/]	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60°	.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
58	.16	.21	.26	.32	.37	.40	.39	.34	.28	.23	.18	.15
56	.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
54	.18	.22	.26	.31	.36	.38	.37	.33	.28	.23	.19	.17
52	.19	.22	.27	.31	.35	.37	.36	.33	.28	.24	.20	.17
50	.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
48	.20	.23	.27	.31	.34	.36	.35	.32	.28	.24	.21	.19
46	.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
44	.21	.24	.27	.30	.33	.35	.34	.31	.28	.25	.22	.20
42	.21	.24	.27	.30	.33	.34	.33	.31	.28	.25	.22	.21
40	.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35	.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30	.24	.25	.27	.29	.31	.32	.31*	.30	.28	.26	.24	.23
25	.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20	.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15	.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10	.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

[1/] Southern latitudes: apply 6 month difference as shown.

Format for Calculation of Blaney-Criddle Method

DATA	Country: UAR Period: July	Place: Cairo	Latitude: 30°N Longitude: 30	Altitude: 95m	
T mean 28.5°C	T mean	data	28.5		
latitude 30° month July	p	Table 1	0.31		
		calc p(0.46T + 8)		6.6	
RHmin %		estimate	med.		
n/N		estimate	high/med		
U2 daytime m/sec		estimate	Mod.		
		Fig. 1 Block/line		II,V ¦ 2	
	ETo	Fig. 1			8.0 mm/day

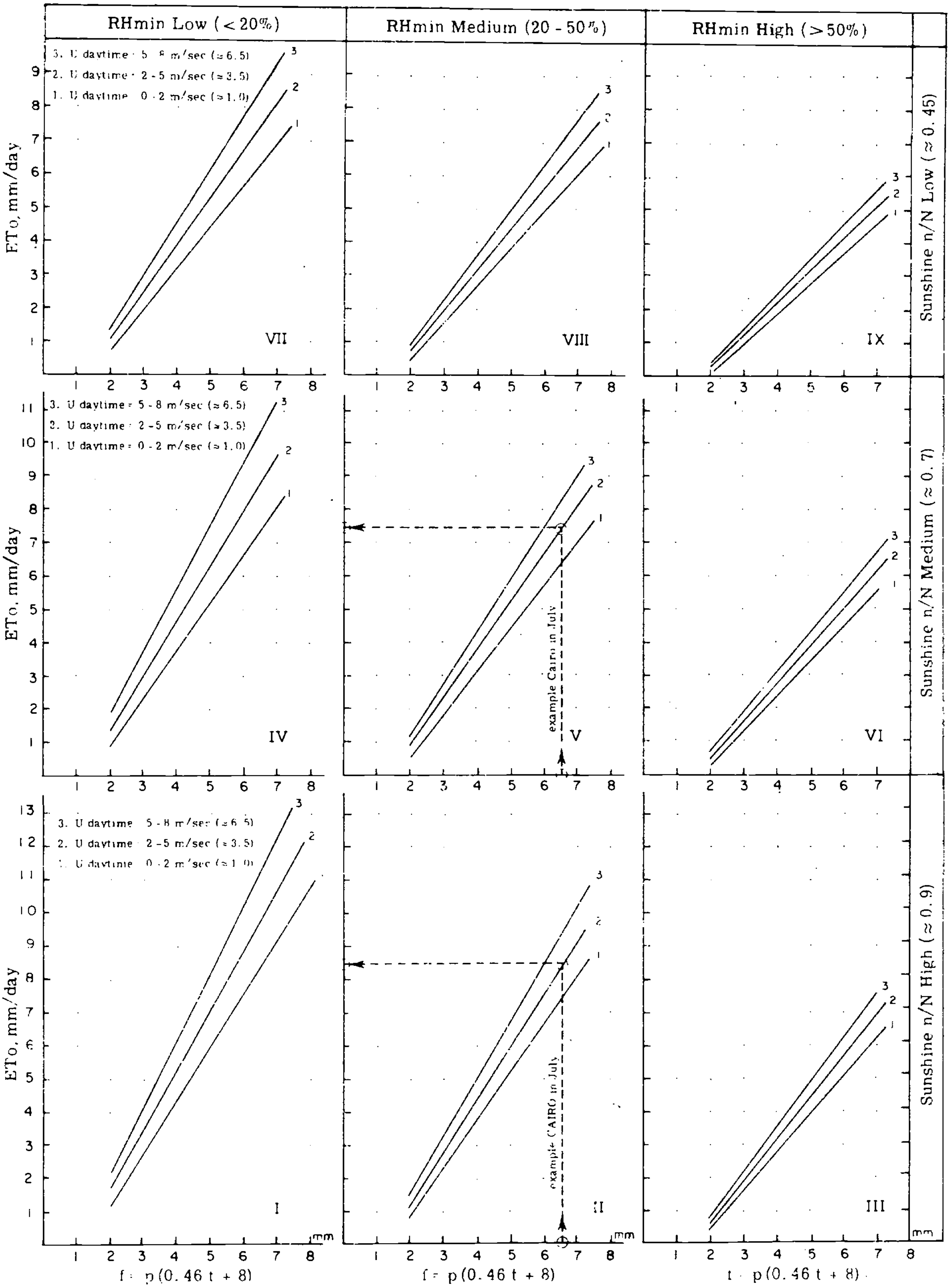

Fig. 1 Prediction of ETo from Blaney-Criddle f factor for different conditions of minimum relative humidity, sunshine duration and day time wind.

1.2 RADIATION METHOD

The Radiation Method is essentially an adaptation of the Makkink formula (1957). This method is suggested for areas where available climatic data include measured air temperature and sunshine, cloudiness or radiation, but not measured wind and humidity. Knowledge of general levels of humidity and wind is required, and these are to be estimated using published weather descriptions, extrapolation from nearby areas or from local sources.

Relationships are given between the presented radiation formula and reference crop evapotranspiration (ETo), taking into account general levels of mean humidity and daytime wind (Figure 2).

The Radiation method should be more reliable than the presented Blaney-Criddle approach. In fact, in equatorial zones, on small islands, or at high altitudes, the Radiation method may be more reliable even if measured sunshine or cloudiness data are not available; in this case solar radiation maps prepared for most locations in the world should provide the necessary solar radiation data.[1]

Recommended Relationships

The relationship recommended (representing mean value over the given period) is expressed as:

$$ETo = c(W \cdot Rs) \quad mm/day$$

where: ETo = reference crop evapotranspiration in mm/day for the periods considered
Rs = solar radiation in equivalent evaporation in mm/day
W = weighting factor which depends on temperature and altitude
c = adjustment factor which depends on mean humidity and daytime wind conditions

To calculate solar radiation (Rs) from sunshine duration or cloudiness data, to determine the weighting factor (W) from temperature and altitude data and to select the appropriate adjustment as given by the relationship between W.Rs and ETo in Figure 2 for different mean humidity and daytime wind conditions, the following procedure is suggested.

(a) Solar radiation (Rs)

The amount of radiation received at the top of the atmosphere (Ra) is dependent on latitude and the time of year only; values are given in Table 2. Part of Ra is absorbed and scattered when passing through the atmosphere. The remainder, including some that is scattered but reaches the earth's surface, is identified as solar radiation (Rs). Rs is dependent on Ra and the transmission through the atmosphere, which is largely dependent on cloud cover. Radiation is expressed in several units; converted into heat it can be related to the energy required to evaporate water from an open water surface. The unit equivalent evaporation in mm/day is employed here (reference is made to the

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[1] See for instance: Solar Radiation and Radiation Balance Data; Routine Observations for the Whole World. Published under WMO auspices in Leningrad, USSR.
WMO, Data on the Intern. Geoph. Year. Forms E1, E2 and E3.
J.N. Black (1956). Distribution of solar radiation over the earth's surface.
H.E. Landsberg (several volumes) World Survey of Climatology, Elsevier.

conversion factors in the introductory pages).

Rs can be measured directly but is frequently not available for the area of investigation. In this case, Rs can also be obtained from measured sunshine duration records as follows:

$$Rs = (0.25 + 0.50\ n/N)\ Ra$$ [1]

where n/N is the ratio between actual measured bright sunshine hours and maximum possible sunshine hours. Values of N for different months and latitudes are given in Table 3. Data for n, for instance using the Campbell Stokes sunshine recorder, should be available locally. Both n and N are expressed in mean daily values, in hours. Values of Ra in mm/day for different months and latitudes are given in Table 2. Rs is obtained in mean equivalent evaporation in mm/day for the period considered.

EXAMPLE:

Given:

Cairo; latitude 30°N; July; sunshine (n) mean 11.5 h/day.

Calculation:

Ra	from Table 2	= 16.8 mm/day
N	from Table 3	= 13.9 h/day
Rs	(0.25 + 0.50 n/N)Ra	= (0.25 + 0.50 x 11.5/13.9)16.8
		= 11.2 mm/day

Cloudiness observations can be used to calculate Rs. Several daily visual observations of cloud cover are needed for sufficiently long periods. Cloudiness is expressed in oktas (0 to 8) and sometimes in tenths (0 to 10) which must first be converted to the n/N ratio. It is preferable to use locally derived relationships between cloudiness and sunshine since scatter in conversion factors from location to location has been noted. An indicative conversion can be obtained from the following table:

Cloudiness (oktas)	0	1	2	3	4	5	6	7	8
n/N ratio	.95	.85*	.75	.65	.55	.45	.35	.15	-

Cloudiness (tenths)	0	1	2	3	4	5	6	7	8	9	10
n/N ratio	.95	.85	.8	.75	.65	.55	.5	.4	.3	.15	-

EXAMPLE:

Given:

Cairo; latitude 30°N; July; cloudiness, oktas 1.

Calculation:

Ra	from Table 2	= 16.8 mm/day
n/N	from Table given or locally determined conversion factor	= 0.85
Rs	(0.25 + 0.50 n/N)Ra	= (0.25 + 0.50 x 0.85)16.8
		= 11.3 mm/day

---

[1] For practical purposes values of 0.25 and 0.50 can be used. For some regions local values have been determined and these are listed in Appendix VI.

(b) Weighting factor (W)

The weighting factor (W) reflects the effect of temperature and altitude on the relationship between Rs and ETo.[1] Values of W as related to temperature and altitude are given in Table 4. Temperature reflects the mean air temperature in °C for the period considered. Where temperature is given as Tmax and Tmin, the temperature (Tmax + Tmin)/2 should be used.

EXAMPLE:
Given:
Cairo; altitude 95 m; Tmean 28.5°C.
Calculation:
W from Table 4 = 0.77

(c) Adjustment factor (c)

The adjustment factor (c) is given by the relationship between the radiation term (W.Rs) and reference crop evapotranspiration (ETo) and is shown graphically in Figure 2. It depends greatly on general levels of mean relative humidity (RHmean) and daytime wind (07.00-19.00 hours) at 2 m height above the soil surface.[2]

EXAMPLE:
Given:

Cairo; latitude 30°N; altitude 95 m; July; Rs = 11.2 mm/day; W = 0.77;
W.Rs = 8.6 mm/day; wind daytime = moderate; RHmean = medium.
Calculation:
From Fig. 2 RHmean = medium
Uday = moderate Block II & III, line 2
ETo (for W.Rs = 8.6 mm/day) (8.7 + 8.0)/2 = 8.4 mm/day

Additional Considerations

With the inclusion of calculated or measured radiation and with partial consideration of temperature, only general levels of daytime wind and mean relative humidity need to be selected.

Except for equatorial zones, climatic conditions for each month or shorter period vary from year to year, and consequently ETo varies. Calculations should preferably be made for each month or period for each year of record rather than using mean radiation and mean temperature data based on several years of record. A value of ETo can then be obtained to ensure that water requirements will be met with a reasonable degree of certainty.

Sample Calculations

Using mean daily temperature and sunshine hour data, the example provides the necessary calculations to obtain the mean daily value of ETo in mm for each month. A format for the necessary calculation procedures is also given.

---

[1] $W = \Delta/(\Delta + \gamma)$ where Δ is the rate of change of the saturation vapour pressure with temperature and γ is the psychrometric constant.

[2] See note 1/ on page 3.

EXAMPLE:

Given:

Cairo; latitude 30°N; altitude 95 m; July. Tmean = 28.5°C; sunshine (n) mean = 11.5 h/day; wind daytime U=moderate; RHmean = medium.

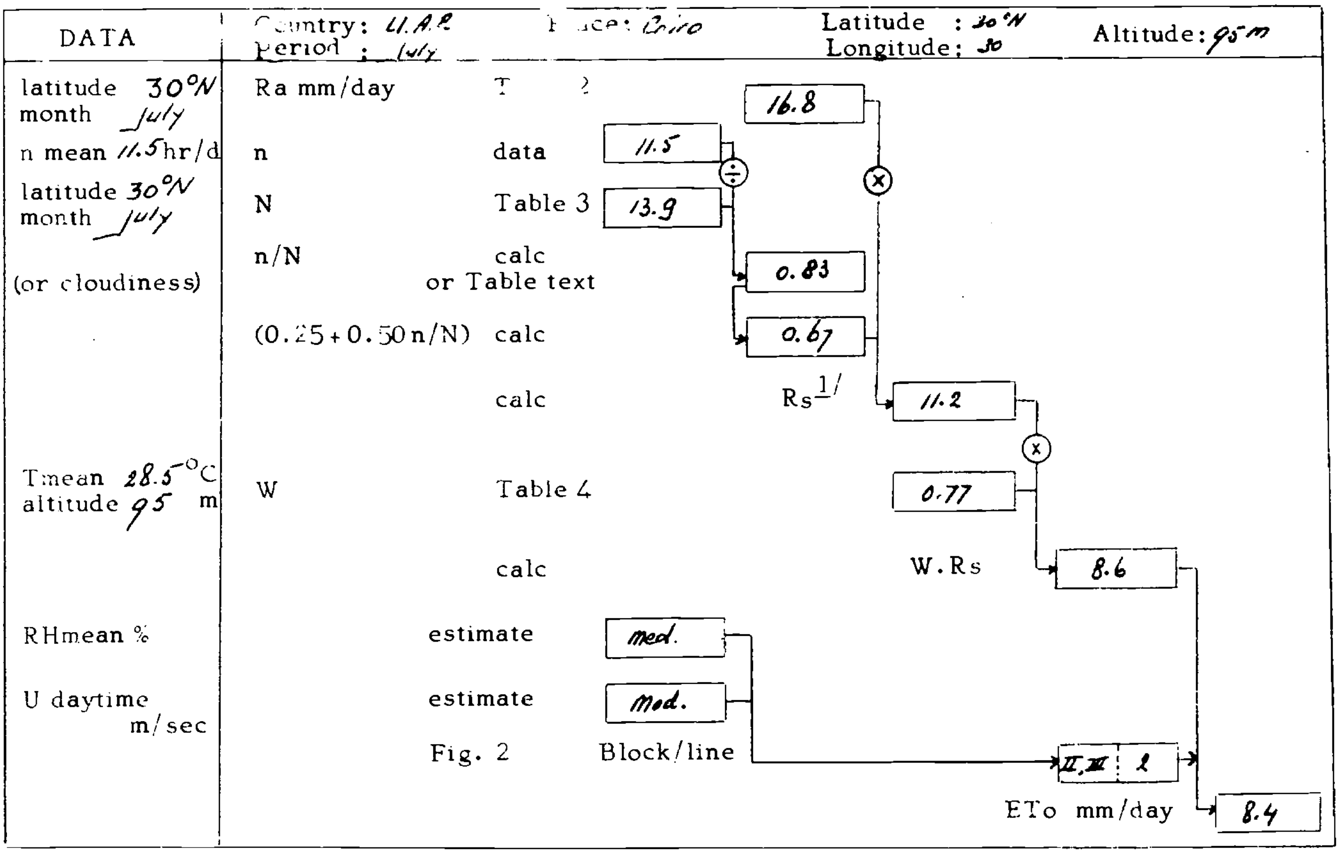
Calculation:

Ra	from Table 2		= 16.8	mm/day
Rs	(0.25 + 0.50 n/N)Ra	n	= 11.5	h/day
	from Table 3	N	= 13.9	h/day
		n/N	= 0.83	
		Rs	= 11.2	mm/day
W	from Table 4		= 0.77	
W.Rs			= 8.6	mm/day
ETo	from Fig. 2, Blocks II and III, line 2		= 8.4	mm/day

Yearly data: Cairo, with solar radiation (Rs) given in mm/day.

	J	F	M	A	M	J	J	A	S	O	N	D
Tmean °C	14	15	17.5	21	25.5	27.5	28.5	28.5	26	24	20	15.5
Rs mm/day	5.0	6.4	8.5	9.9	10.9	11.4	11.2	10.4	9.1	7.1	5.5	4.6
RHmean	III	III	III	II	II	II	av.II & III	av.II & III	III	III	av.III & IV	av. III & IV
Wind daytime	av. 1&2	av. 1&2	av. 1&2	av. 1&2	2	2	2	av. 1&2	av. 1&2	av. 1&2	av. 1&2	av. 1&2
W	0.61	0.62	0.65	0.70	0.74	0.76	0.77	0.77	0.75	0.73	0.68	0.63
(W.Rs)	3.0	4.0	5.5	6.9	8.1	8.7	8.6	8.0	6.8	5.2	3.7	2.9
To mm/day	2.5	3.4	4.8	6.7	8.2	8.8	8.4	7.4	6.0	4.5	3.0	2.2
mm/month	78	95	149	201	254	264	260	229	180	140	90	68

Format for Calculation of Radiation Method



DATA | Country: U.A.R. Period: July | Place: Cairo | Latitude: 30°N Longitude: 30 | Altitude: 95 m

latitude 30°N month July	Ra mm/day	T 2	16.8
n mean 11.5 hr/d	n	data	11.5
latitude 30°N month July	N	Table 3	13.9
(or cloudiness)	n/N	calc or Table text	0.83
	(0.25+0.50n/N)	calc	0.67
		calc	Rs[1/] 11.2
Tmean 28.5 °C altitude 95 m	W	Table 4	0.77
		calc	W.Rs 8.6
RHmean %		estimate	med.
U daytime m/sec		estimate	Mod.
	Fig. 2	Block/line	II,III ¦ 2
		ETo mm/day	8.4

1/ as measured or obtained from regional or worldwide maps of solar radiation.

Table 2 Extra Terrestrial Radiation (Ra) expressed in equivalent evaporation in mm/day

Northern Hemisphere													Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Lat	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	50°	17.5	14.7	10.9	7.0	4.2	3.1	3.5	5.5	8.9	12.9	16.5	18.2
4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	48	17.6	14.9	11.2	7.5	4.7	3.5	4.0	6.0	9.3	13.2	16.6	18.2
4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3	46	17.7	15.1	11.5	7.9	5.2	4.0	4.4	6.5	9.7	13.4	16.7	18.3
5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	44	17.8	15.3	11.9	8.4	5.7	4.4	4.9	6.9	10.2	13.7	16.7	18.3
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	42	17.8	15.5	12.2	8.8	6.1	4.9	5.4	7.4	10.6	14.0	16.8	18.3
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8*	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Table 3 Mean Daily Duration of Maximum Possible Sunshine Hours (N) for Different Months and Latitudes

Northern Lats	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Southern Lats	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
50	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9*	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1

Table 4 Values of Weighting Factor (W) for the Effect of Radiation on ETo at Different Temperatures and Altitudes

Temperature °C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
W at altitude m																				
0	0.43	.46	.49	.52	.55	.58	.61	.64	.66	.68	.71	.73	.75	.77*	.78	.80	.82	.83	.84	.85
500	.45	.48	.51	.54	.57	.60	.62	.65	.67	.70	.72	.74	.76	.78	.79	.81	.82	.84	.85	.86
1 000	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.80	.82	.83	.85	.86	.87
2 000	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.88
3 000	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.88	.88	.89
4 000	.55	.58	.61	.64	.66	.69	.71	.73	.76	.78	.79	.81	.83	.84	.85	.86	.88	.89	.90	.90

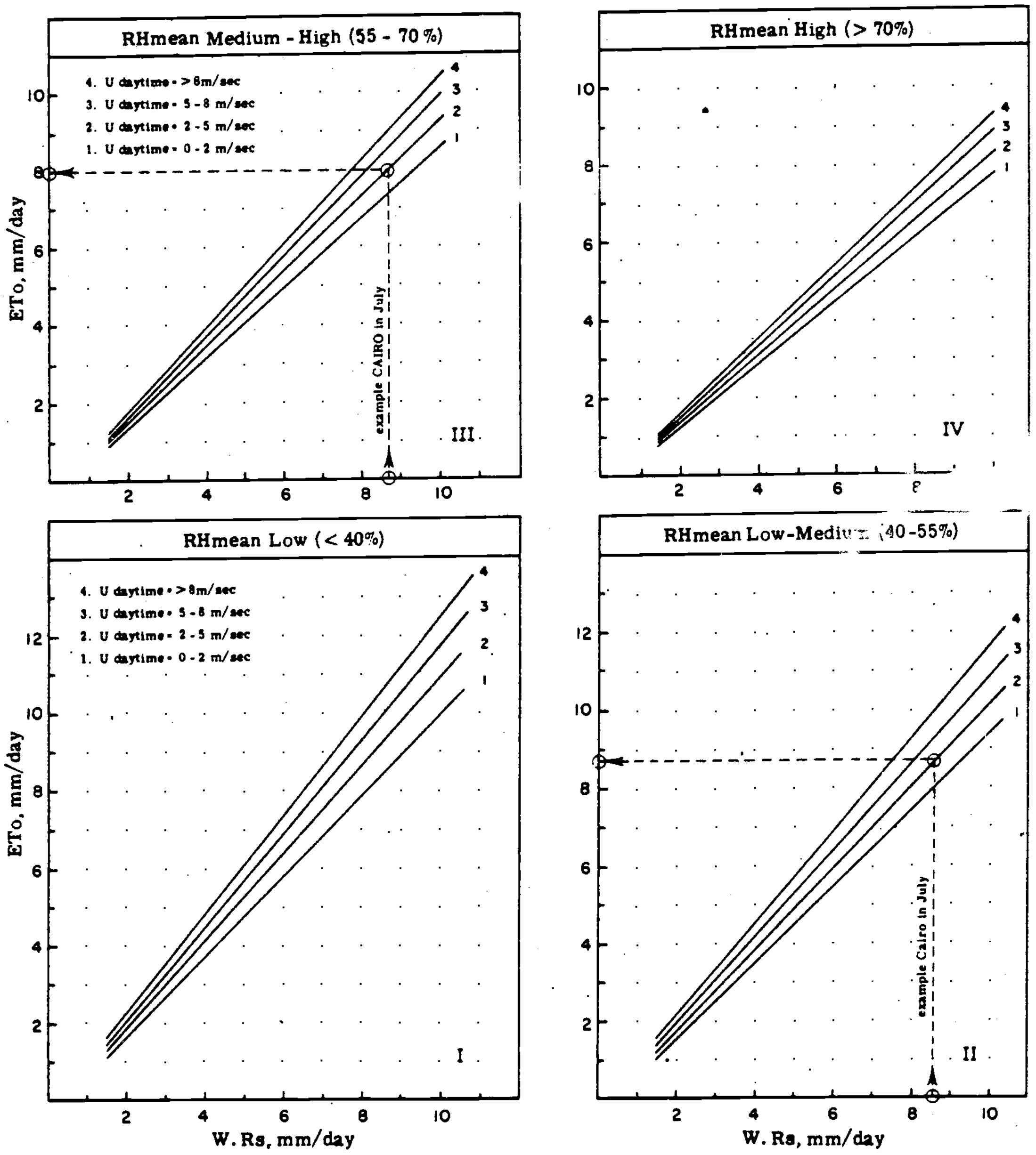


Fig. 2 Prediction of ETo from W. RS for different conditions of mean relative humidity and day time wind.

1.3 PENMAN METHOD

For areas where measured data on temperature, humidity, wind and sunshine duration or radiation are available, an adaptation of the Penman method (1948) is suggested; compared to the other methods presented it is likely to provide the most satisfactory results.

The original Penman (1948) equation predicted evaporation losses from an open water surface (Eo). Experimentally determined crop coefficients ranging from 0.6 in winter months to 0.8 in summer months related Eo to grass evapotranspiration for the climate in England. The Penman equation consisted of two terms: the energy (radiation) term and the aerodynamic (wind and humidity) term. The relative importance of each term varies with climatic conditions. Under calm weather conditions the aerodynamic term is usually less important than the energy term. In such conditions the original Penman Eo equation using a crop coefficient of 0.8 has been shown to predict ETo closely, not only in cool, humid regions as in England but also in very hot, and semi-arid regions. It is under windy conditions and particularly in the more arid regions that the aerodynamic term becomes relatively more important and thus errors can result in predicting ETo when using 0.8 Eo.

A slightly modified Penman equation is suggested here to determine ETo, involving a revised wind function term. The method uses mean daily climatic data; since day and night time weather conditions considerably affect the level of evapotranspiration, an adjustment for this is included.

The procedures to calculate ETo may seem rather complicated. This is due to the fact that the formula contains components which need to be derived from measured related climatic data when no direct measurements of needed variables are available. For instance, for places where no direct measurements of net radiation are available, these can be obtained from measured solar radiation, sunshine duration or cloudiness observations, together with measured humidity and temperature. Computation techniques and tables are given here to facilitate the necessary calculations. A format for calculation is also given.

<u>Recommended Relationships</u>

The form of the equation used in this method is:

$$ETo = c\left[\underbrace{W.Rn}_{\text{radiation term}} + \underbrace{(1-W).f(u).(ea-ed)}_{\text{aerodynamic term}}\right]$$

where: ETo = reference crop evapotranspiration in mm/day
W = temperature-related weighting factor
Rn = net radiation in equivalent evaporation in mm/day
f(u) = wind-related function
(ea-ed) = difference between the saturation vapour pressure at mean air temperature and the mean actual vapour pressure of the air, both in mbar
c = adjustment factor to compensate for the effect of day and night weather conditions

Additional Considerations

Due to the interdependence of the variables composing the equation, the correct use of units in which variables need to be expressed is important. Use of the correct units is shown in the examples presented.

The suggested wind function applies to conditions found during summer, with moderate winds, RHmax of about 70 percent and day-night wind ratios of 1.5 to 2.0; no adjustment is required for these conditions. However, if 24-hour wind totals are used there will be an under-prediction of ETo by 15 to 30 percent in areas where daytime wind greatly exceeds night time wind, where RHmax approaches 100 percent, and where radiation is high. Conversely, for areas experiencing moderate to strong wind, where night time humidity (RHmax) is low, and where radiation is low, the equation will over-predict ETo; this over-prediction increases with decreasing ratios of Uday/Unight. Under these conditions an adjustment factor (c) should be applied.

Description of Variables and their Method of Calculation

(a) Vapour pressure (ea-ed)

Air humidity affects ETo. Humidity is expressed here as saturation vapour pressure deficit (ea-ed): the difference between the mean saturation water vapour pressure (ea) and the mean actual water vapour pressure (ed).

Air humidity data are reported as relative humidity (RHmax and RHmin in percentage), as psychrometric readings (T°C of dry and wet bulb) from either ventilated or non-ventilated wet and dry bulb thermometers, or as dewpoint temperature (Tdewpoint °C). Time of measurement is important but is often not given. Fortunately actual vapour pressure is a fairly constant element and even one measurement per day may suffice for the type of application envisaged. Depending on the available humidity data, case I, II or III will apply. Vapour pressure must be expressed in mbar; if ed is given in mm Hg, multiply by 1.33 to find mbar. Tables 5 and 6 are given to obtain values of ea and ed from available climatic data.

EXAMPLES: For all cases altitude is 0 m.

I <u>Given</u>:
Tmax 35°C; Tmin 22°C; RHmax 80%; RHmin 30%.
<u>Calculation</u>:

Tmean		= 28.5 °C
RHmean		= 55 %
ea at 28.5°C	Table 5	= 38.9 mbar
ed	= ea x RHmean/100	= 21.4 mbar
(ea-ed)		= 17.5 mbar

II <u>Given</u>:
Tmax 35°C; Tmin 22°C; Tdrybulb 24°C; Twetbulb 20°C.[1]
<u>Calculation</u>:

Tmean		= 28.5 °C
ea at 28.5°C	Table 5	= 38.9 mbar
ed at Tdrybulb 24°C	Table 6a	
Twetbulb depr. 4°C	Table 6a	= 20.7 mbar
(ea-ed)		= 18.2 mbar

---

[1] Conversion of readings to humidity data from dry and wet bulb thermometers changes when they are force-ventilated (Assmann type) or non-ventilated; Tables 6a and 6b to be used respectively.

III Given:

Tmax 35°C; Tmin 22°C; Tdewpoint 18°C.

Calculation:

Tmean		= 28.5 °C
ea at 28.5°C	Table 5	= 38.9 mbar
ed at Tdewpoint	Table 5	= 20.6 mbar
(ea-ed)		= 18.3 mbar

In many regions RH during the night is near 100%. Here Tmin ≅ Twetbulb ≅ Tdewpoint and ed can then be determined from ea at Tmin. The more arid the climate, the less likely is Tdewpoint ≅ Tmin.

DO NOT USE:

IV Given:

Tmax 35°C; Tmin 22°C; RHmax 80%; RHmin 30%.

Calculation:

ea at Tmax	Table 6a	= 56.2 mbar
ed at Tmax	ea x RHmin	= 16.9 mbar
(ea-ed) at Tmax		= 39.3 mbar
ea at Tmin	Table 6a	= 26.4 mbar
ed at Tmin	ea x RHmin	= 21.1 mbar
(ea-ed) at Tmin		= 5.3 mbar
(ea-ed) mean		= 22.3 mbar

Not recommended because the wind function f(u) used here was derived using (ea-ed) as obtained in cases I, II and III and does not correspond to example in case IV. Much greater divergence may occur in mean (ea-ed) between the first cases and the fourth for situations other than evident here and serious errors could result if case IV is used (average of ea at Tmax and Tmin ≠ ea at Tmean).

(b) Wind function f(u)

The effect of wind on ETo has been studied for different climates (see Appendix II) resulting in a revised wind function[2] and defined in this publication as:

$$f(u) = 0.27 \left(1 + \frac{U}{100}\right)$$

where U is 24-hr wind run in km/day at 2 m height. This expression is valid when (ea-ed) is expressed in mbar and is calculated according to the methods shown in cases I, II or III. Table 7 can be used for values of f(u) for wind run at 2 m height.

Where wind data are not collected at 2 m height, the appropriate corrections for wind measurements taken at different heights are given below:

Measurement height m	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0
Correction factor	1.35	1.15	1.06	1.00	0.93*	0.88	0.85	0.83

EXAMPLE:

Given:

Wind speed at 3 m height is 250 km/day.

Calculation:

U	above conversion	= 232 km/day
f(u)	Table 7	= 0.90

(c) Weighting factor (1-W)

(1-W) is a weighting factor for the effect of wind and humidity on ETo.[1] Values of (1-W)

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[1] $W = \Delta / (\Delta + \gamma)$ where Δ is the rate of change of the saturation vapour pressure with temperature and γ is the psychrometric constant.

[2] The similarity of the revised wind function with Penman's original function $f(u) = 0.26(1 + U/100)$ in which U is in miles/day is purely coincidental.

as related to temperature and altitude are given in Table 8. For temperature use (Tmax + Tmin)/2.

EXAMPLE:
Given:
Altitude 95 m; Tmax 35°C; Tmin 22°C.
Calculation:
Tmean = 28.5 °C
(1-W) Table 8 = 0.23

(d) Weighting factor (W)

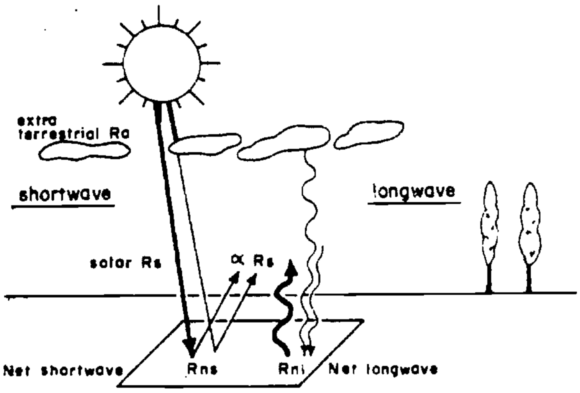
W is the weighting factor for the effect of radiation on ETo. Values of W as related to temperature and altitude are given in Table 9. For temperature use (Tmax + Tmin)/2.

EXAMPLE:
Given:
Altitude 95 m; Tmax 35°C; Tmin 22°C.
Calculation:
Tmean = 28.5 °C
W Table 9 = 0.77

(e) Net radiation (Rn)

Net radiation (Rn) is the difference between all incoming and outgoing radiation. It can be measured, but such data are seldom available. Rn can be calculated from solar radiation or sunshine hours (or degree of cloud cover), temperature and humidity data.

In Figure 3 different portions of the radiation balance are shown. The amount of radiation received at the top of the atmosphere (Ra) is dependent on latitude and the time of the year only; values are given in Table 10. Part of Ra is absorbed and scattered when passing through the atmosphere. The remainder, including some that is scattered but reaches the earth's surface, is identified as solar radiation (Rs). Rs is dependent on Ra and the transmission through the atmosphere, which is largely dependent on cloud cover. Part of Rs is reflected back directly by the soil and crop and is lost to the atmosphere. Reflection (α) depends on the nature of the surface cover and is approximately 5 to 7 percent for water and around 15 to 25 percent for most crops. This fraction varies with degree of crop cover and wetness of the exposed soil surface. That which remains is net shortwave solar radiation (Rns).



Net radiation Rn = net solar radiation Rns - net longwave radiation Rnl
= (1-α) Rs - Rnl

Fig. 3 Illustration of the radiation balance

Additional loss at the earth's surface occurs since the earth radiates part of its absorbed energy back through the atmosphere as longwave radiation. This is normally greater than the downcoming longwave atmospheric radiation. The difference between outgoing and incoming longwave radiation is called net longwave radiation (Rnl). Since outgoing is greater than incoming, Rnl represents net energy loss.

Total net radiation (Rn) is equal to the difference between Rns and Rnl, or Rn = Rns - Rnl. Radiation can be expressed in different units; converted into heat it can be related to the energy required to evaporate water from an open surface and is given here as equivalent evaporation in mm/day. To calculate Rn the different steps involved are:

(i) If measured solar radiation (Rs) is not available, select Ra value in mm/day from Table 10 for given month and latitude.

(ii) To obtain solar radiation (Rs), correct Ra value for ratio of actual (n) to maximum possible (N) sunshine hours; Rs = (0.25 + 0.50 n/N)Ra.[1] Values for N for a given month and latitude are given in Table 11. Both n and N are expressed in hours as mean daily values for the period considered.

When only visual cloud observations are available, they can be used to calculate Rs. Several daily visual observations of cloudiness over a sufficiently long period are needed. Cloudiness is expressed in oktas (0 to 8) and sometimes in tenths (0 to 10) which must first be converted into equivalent values of n/N. The following table can be used as a rough guide:[2]

Cloudiness oktas	0	1	2	3	4	5	6	7	8
n/N ratio	.95	.85	.75	.65	.55	.45	.3	.15	-

Cloudiness tenths	0	1	2	3	4	5	6	7	8	9	10
n/N ratio	.95	.85	.8	.75	.65	.55	.5	.4	.3	.15	-

(iii) To obtain net shortwave radiation (Rns), the solar radiation (Rs) must be corrected for reflectiveness of the crop surface, or Rns = (1 - α)Rs. For most crops α = 0.25. To simplify steps (ii) and (iii), Table 12 can be used to calculate Rns from the ratio n/N and α = 0.25.

(iv) Net longwave radiation (Rnl) can be determined from available temperature (T), vapour pressure (ed) and ratio n/N data. Values for the function f(T), f(ed) and f(n/N) are given in Tables 13, 14 and 15 respectively.

(v) To obtain total net radiation (Rn), the algebraic sum of net shortwave radiation (Rns) and net longwave radiation (Rnl) is calculated. Rnl always constitutes a net loss so Rn = Rns - Rnl.

EXAMPLE:

Given:

Cairo; latitude 30°N; altitude 95 m; July. Tmean 28.5°C; RHmean 55%; sunshine n mean 11.5 hr/day

Calculation:

Ra	Table 10			= 16.8 mm/day
Rs (0.25 + 0.50 n/N)Ra		n	= 11.5 hr	
	Table 11	N	= 13.9 hr	
		n/N	= 0.83	= 11.2 mm/day
Rns (1 - α)Rs	Table 12			= 8.4 mm/day
Rnl f(T).f(ed).f(n/N)	Table 13	f(T)	= 16.4	
	Table 14	f(ed)	= 0.13[3]	
	Table 15	f(n/N)	= 0.85	= 1.8 mm/day
Rn = Rns - Rnl				= 6.6 mm/day

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[1] For practical purposes 0.25 and 0.50 can be used. For some regions local values have been determined and are listed in Appendix VI.

[2] Variations in conversion factors from location to location have been noted when using cloudiness data to obtain the ratio n/N. Where available locally derived conversion factors should be used. Sometimes sky observations are made which are expressed in only four classes; here conversion is approximately: clear day = 1 okta; partial cloud = 3 oktas; cloud = 6 oktas; overcast = 8 oktas.

[3] From vapour pressure calculation under (a) case I, II or III.

(f) Adjustment factor (c)

The Penman equation given assumes the most common conditions where radiation is medium to high, maximum relative humidity is medium to high and moderate daytime wind about double the night time wind. However, these conditions are not always met. For instance, coastal areas with pronounced sea breezes and calm nights generally have day/night wind ratios of 3 to 5; parts of the Middle East have dry winds during the day and calm wind conditions during the night with maximum relative humidity approaching 100 percent. For such conditions correction to the Penman equation is required. Table 16 presents the values of c for different conditions of RHmax, Rs, Uday and Uday/Unight. Examples (Near East):

RHmax 90%; Rs 12 mm/day; Uday 3 m/sec; Uday/Unight 3: c = 1.28 (Table 16)
RHmax 60%; Rs 6 mm/day; Uday 3 m/sec; Uday/Unight 2: c = 0.91 (Table 16)

The information for using Table 16 may be difficult to obtain from available climatic records but it can usually be derived for the different seasons from published weather descriptions or from local sources. The conditions involving very low c values may seldom occur and may persist only for a few days in most climates. Table 16 does reveal a rather common need for c values smaller than 1.0 for low radiation, non-summer conditions (similar factors no doubt caused the use of winter crop coefficients of 0.6 as compared to 0.8 for mid-summer in the original 1948 Penman method).

EXAMPLE:
Given:
Cairo; July. Rs 11.2 mm/day; RHmax 80%; Uday 3.2 m/sec; Unight 2.1 m/sec; Uday/Unight 1.5.
Calculation:
c value Table 16 = 1.06 (by interpolation)

Sample Calculations

Reference crop evapotranspiration (ETo) can be calculated using:

$$\text{ETo} = c\left[W.Rn + (1-W).f(u).(ea-ed)\right]$$

EXAMPLE:
Given:
Cairo; July. W = 0.77; Rn = 6.6; (1-W) = 0.23; f(u) = 0.90; (ea-ed) = 17.5; c = 1.01.
Calculation:
ETo = 1.01 (0.77 x 6.6 + 0.23 x 0.90 x 17.5) = 8.8 mm/day

Using mean daily data for each month calculation of ETo in mm/day for each month:

Cairo; latitude 30°N; altitude 95 m

	J	F	M	A	M	J	J	A	S	O	N	D
T mean °C	14	15	17.5	21	25.5	27.5	28.5	28.5	26	24	20	15.5
RHmean	65	65	63	50	45	50	55	57	60	64	68	68
n hours	7.4	8.0	8.9	9.7	10.8	11.4	11.5	11.1	10.4	9.6	8.6	7.5
U km/day	173	181	207	207	232	251	232	181	164	190	164	155
Rs mm/day	4.9	6.4	8.5	9.8	10.8	11.3	11.3	10.4	9.1	7.1	5.4	4.5
RHmax % (est)	95	95	95	70	65	70	75	80	80	90	95	95
Uday m/sec (est)	2.5	2.5	3.0	3.0	3.3	3.5	3.3	2.5	2.3	2.5	2.3	2.3[1]
c	0.9	0.95	1.02	1.0	1.0	1.0	1.01	1.01	1.01	0.95	0.93	0.93
ETO mm/day	2.7	3.8	5.0	7.0	8.9	9.4	8.8	7.6	6.1	4.8	3.2	2.3
mm/month	84	106	154	210	276	282	273	236	183	149	96	71

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[1] Based on general climatic descriptions for Cairo; day/night wind ratio is some 1.5 produced by calm morning and mid-day conditions, with breezes in late afternoon; an exception would be the April and May 'Khamsin' winds which blow day and night but somewhat stronger during daytime.

Table 5 Saturation Vapour Pressure (ea) in mbar as Function of Mean Air Temperature (T) in °C 1/

Temperature °C	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ea mbar	6.1	6.6	7.1	7.6	8.1	8.7	9.3	10.0	10.7	11.5	12.3	13.1	14.0	15.0	16.1	17.0	18.2	19.4	20.6*	22.0

Temperature °C	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
ea mbar	23.4	24.9	26.4	28.1	29.8	31.7	33.6	35.7	37.8*	40.1	42.4	44.9	47.6	50.3	53.2	56.2	59.4	62.8	66.3	69.9

1/ Also actual vapour pressure (ed) can be obtained from this table using available Tdewpoint data.
(Example: Tdewpoint is 18°C; ed is 20.6 mbar)

Table 6a Vapour Pressure (ed) in mbar from Dry and Wet Bulb Temperature Data in °C
(Aspirated Psychrometer)

Depression wet bulb T°C altitude 0-1 000 m												drybulb T°C	Depression wet bulb T°C altitude 1 000-2 000 m											
0	2	4	6	8	10	12	14	16	18	20	22		0	2	4	6	8	10	12	14	16	18	20	22
73.8	64.9	56.8	49.2	42.2	35.8	29.8	24.3	19.2	14.4	10.1	6.0	40	73.8	65.2	57.1	49.8	43.0	41.8	31.0	25.6	20.7	16.2	12.0	8.1
66.3	58.1	50.5	43.6	37.1	31.1	25.6	20.5	15.8	11.4	7.3		38	66.3	58.2	50.9	44.1	37.9	36.7	26.8	21.8	17.3	13.2	9.2	5.7
59.4	51.9	44.9	38.4	32.5	26.9	21.8	17.1	12.7	8.6	4.9		36	59.4	52.1	45.2	39.0	33.3	32.1	23.0	18.4	14.3	10.4	6.8	3.5
53.2	46.2	39.8	33.8	28.3	23.2	18.4	14.0	10.0	6.2			34	53.2	46.4	40.1	34.4	29.1	24.1	19.6	15.4	11.5	8.0	4.6	1.5
47.5	41.1	35.1	29.6	24.5	19.8	15.4	11.3	7.5	4.0			32	47.5	41.3	35.5	30.2	25.3	20.7	16.6	12.6	9.1	5.8	2.6	
42.4	36.5	30.9	25.8	21.1	16.7	12.6	8.8	5.3				30	42.4	36.7	31.3	26.4	21.9	17.7	13.8	10.2	6.9	3.8	0.9	
37.8	32.3	27.2	22.4	18.0	14.0	10.2	6.7	3.4				28	37.8	32.5	27.5	23.0	18.9	14.9	11.4	8.0	4.9	2.1		
33.6	28.5	23.8	19.4	15.3	11.5	8.0	4.7	1.6				26	33.6	28.7	24.1	20.0	16.1	12.5	9.2	6.0	3.2	0.5		
29.8	25.1	20.7*	16.6	12.8	9.3	6.0	2.9					24	29.8	25.3	21.1	17.2	13.9	10.3	7.2	4.3	1.6			
26.4	22.0	18.0	14.2	10.6	7.4	4.3	1.4					22	26.4	22.3	18.3	14.3	11.5	8.3	5.5	2.7	0.2			
23.4	19.3	15.5	12.0	8.7	5.6	2.7						20	23.4	19.5	15.9	12.6	9.5	6.6	3.9	1.3				
20.6	16.8	13.3	10.0	6.9	4.1	1.4						18	20.6	17.1	13.7	10.6	7.8	5.0	2.5	0.1				
18.2	14.6	11.4	8.3	5.4	2.7							16	18.2	14.9	11.7	8.9	6.2	3.6	1.3					
16.0	12.7	9.6	6.7	4.0	1.5							14	16.0	12.9	10.0	7.3	4.8	2.4	0.3					
14.0	10.9	8.1	5.3	2.8								12	14.0	11.2	8.4	5.9	3.6	1.4						
12.3	9.4	6.7	4.1	1.7								10	12.3	9.6	7.0	4.7	2.6	0.4						
10.7	8.0	5.5	3.1	0.8								8	10.7	8.2	5.8	3.7	1.6							
9.3	6.8	4.4	2.1									6	9.3	7.0	4.8	2.7	0.7							
8.1	5.7	3.4	1.6									4	8.1	6.0	3.8	1.8								
7.1	4.8	2.8	0.8									2	7.1	5.0	2.9	1.0								
6.1	4.0	2.0										0	6.1	4.1	2.1									

Table 6b

Vapour Pressure (ed) in mbar from Dry and Wet Bulb Temperature Data in °C (Non-Ventilated Psychrometer)

Depression wet bulb T°C altitude 0-1 000 m												drybulb T °C	Depression wet bulb T°C altitude 1 000-2 000 m											
0	2	4	6	8	10	12	14	16	18	20	22		0	2	4	6	8	10	12	14	16	18	20	22
73.8	64.7	56.2	48.4	41.2	34.4	28.2	22.4	17.0	12.0	7.4	3.0	40	73.8	64.9	56.7	49.1	42.0	35.6	29.6	34.1	18.9	14.1	9.8	5.6
66.3	57.8	50.0	42.8	36.0	29.8	24.0	18.6	13.6	9.0	4.6	0.6	38	66.3	58.0	50.5	43.4	36.9	31.0	25.4	20.3	15.5	11.1	7.0	3.2
59.4	51.6	44.4	37.6	31.4	25.6	20.2	15.2	10.6	6.2	2.2		36	59.4	51.8	44.8	38.3	32.3	26.8	21.2	16.9	12.5	8.3	4.6	1.0
53.2	45.9	39.2	33.0	27.2	21.8	16.8	12.2	7.8	3.8			34	53.2	46.1	39.7	33.7	28.1	23.0	18.2	13.9	9.7	5.9	2.4	
47.5	40.8	34.6	28.8	23.4	18.4	13.8	9.4	5.4	1.6			32	47.5	41.0	35.1	29.5	24.3	19.6	15.2	11.1	7.3	3.7	0.4	
42.4	36.2	30.4	25.0	20.0	15.4	11.0	7.0	3.2				30	42.4	36.4	30.9	25.7	20.9	16.6	12.4	8.7	5.1	1.7		
37.8	32.0	26.6	21.6	17.0	12.6	8.6	4.8	1.2				28	37.8	32.2	27.1	22.3	17.9	13.8	10.0	6.5	3.1			
33.6	28.2	23.2	18.6	14.2	10.2	6.4	2.8					26	33.6	28.4	23.7	19.3	15.1	11.4	7.8	4.5	1.4			
29.8	24.8	20.2	15.8	11.8	8.0	4.4	1.1					24	29.8	25.0	20.7	16.5	12.7	9.2	5.8	2.8				
26.4	21.8	17.4	13.4	9.6	6.0	2.7						22	26.4	22.0	17.9	14.1	10.5	7.2	4.1	1.2				
23.4	19.0	15.0	11.2	7.6	4.3	1.1						20	23.4	19.2	15.5	11.9	8.5	5.5	2.5					
20.6	16.6	12.8	9.2	5.9	2.7							18	20.6	16.8	13.3	9.9	6.8	3.9	1.1					
18.2	14.4	10.8	7.5	4.3	1.4							16	18.2	14.6	11.3	8.2	5.2	2.5						
16.0	12.4	9.1	5.9	3.0	0.1							14	16.0	12.6	9.6	6.6	3.8	1.3						
14.0	10.7	7.5	4.6	1.7								12	14.0	10.9	8.0	5.2	2.6	0.3						
12.3	9.1	6.1	3.3	0.7								10	12.3	9.3	6.7	4.0	1.6							
10.7	7.7	4.9	2.3									8	10.7	7.9	5.4	3.0	0.6							
9.3	6.5	3.9	1.5									6	9.3	6.7	4.4	2.0								
8.1	5.5	2.9	0.9									4	8.1	5.7	3.4	1.1								
7.1	4.5	2.3										2	7.1	4.7	2.5	0.3								
6.1	3.7	1.5										0	6.1	3.8	1.7									

Table 7

Values of Wind Function $f(u) = 0.27\,(1 + \frac{U_2}{100})$ for Wind Run at 2 m height in km/day

Wind km/day	0	10	20	30	40	50	60	70	80	90
	-	.30	.32	.35	.38	.41	.43	.46	.49	.51
100	.54	.57	.59	.62	.65	.67	.70	.73	.76	.78
200	.81	.84	.86	.89*	.92	.94	.97	1.00	1.03	1.05
300	1.08	1.11	1.13	1.16	1.19	1.21	1.24	1.27	1.30	1.32
400	1.35	1.38	1.40	1.43	1.46	1.49	1.51	1.54	1.57	1.59
500	1.62	1.65	1.67	1.70	1.73	1.76	1.78	1.81	1.84	1.90
600	1.89	1.92	1.94	1.97	2.00	2.02	2.05	2.08	2.11	2.15
700	2.16	2.19	2.21	2.24	2.27	2.29	2.32	2.35	2.38	2.40
800	2.43	2.46	2.48	2.51	2.54	2.56	2.59	2.62	2.64	2.65
900	2.70									

Table 8 Values of Weighting Factor (1-W) for the Effect of Wind and Humidity on ETo at Different Temperatures and Altitudes

Temperature °C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
(1-W) at altitude m																				
0	0.57	.54	.51	.48	.45	.42	.39	.36	.34	.32	.29	.27	.25	.23*	.22	.20	.19	.17	.16	.15
500	.56	.52	.49	.46	.43	.40	.38	.35	.33	.30	.28	.26	.24	.22	.21	.19	.18	.16	.15	.14
1 000	.54	.51	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.20	.18	.17	.15	.14	.13
2 000	.51	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12
3 000	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12	.11
4 000	.46	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12	.11	.10

Table 9 Values of Weighting Factor (W) for the Effect of Radiation on ETo at Different Temperatures and Altitudes

Temperature °C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
W at altitude m																				
0	0.43	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77*	.78	.80	.82	.83	.84	.85
500	.44	.48	.51	.54	.57	.60	.62	.65	.67	.70	.72	.74	.76	.78	.79	.81	.82	.84	.85	.86
1 000	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.80	.82	.83	.85	.86	.87
2 000	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.88
3 000	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.88	.89
4 000	.54	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.89	.90	.90

Table 10 Extra Terrestrial Radiation (Ra) expressed in equivalent evaporation in mm/day

Northern Hemisphere													Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Lat	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	50°	17.5	14.7	10.9	7.0	4.2	3.1	3.5	5.5	8.9	12.9	16.5	18.2
4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	48	17.6	14.9	11.2	7.5	4.7	3.5	4.0	6.0	9.3	13.2	16.6	18.2
4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3	46	17.7	15.1	11.5	7.9	5.2	4.0	4.4	6.5	9.7	13.4	16.7	18.3
5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	44	17.8	15.3	11.9	8.4	5.7	4.4	4.9	6.9	10.2	13.7	16.7	18.3
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	42	17.8	15.5	12.2	8.8	6.1	4.9	5.4	7.4	10.6	14.0	16.8	18.3
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8*	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Table 11 Mean Daily Duration of Maximum Possible Sunshine Hours (N) for Different Months and Latitudes

Northern Lats	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Southern Lats	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
50°	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9*	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Table 12 Conversion Factor for Extra-Terrestrial Radiation ([illegible]) to Net Solar Radiation (Rns) for a Given Reflection α of 0.25 and Different Ratios of Actual to Maximum Sunshine Hours $(1-\alpha)(0.25 + 0.50\ n/N)$

n/N	0.0	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90	.95	1.0
$(1-\alpha)(0.25 + 0.50\ n/N)$	0.19	.21	.22	.24	.26	.28	.30	.32	.34	.36	.37	.39	.41	.43	.45	.47	.49*	.51	.52	.54	.56

Table 13 Effect of Temperature f(T) on Longwave Radiation (Rnl)

T^oC	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
$f(T) = \sigma Tk^4$	11.0	11.4	11.7	12.0	12.4	12.7	13.1	13.5	13.8	14.2	14.6	15.0	15.4	15.9	16.3*	16.7	17.2	17.7	18.1

Table 14 Effect of Vapour Pressure f(ed) on Longwave Radiation (Rnl)

ed mbar	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
$f(ed) = 0.34 - 0.044\sqrt{ed}$	0.23	.22	.20	.19	.18	.16	.15	.14	.13*	.12	.12	.11	.10	.09	.08	.08	.07	.06

Table 15 Effect of the Ratio Actual and Maximum Bright Sunshine Hours f(n/N) on Longwave Radiation (Rnl)

n/N	0	.05	.1	.15	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85	.9	.95	1.0
$f(n/N) = 0.1 + 0.9\ n/N$	0.10	.15	.19	.24	.28	.33	.37	.42	.46	.51	.55	.60	.64	.69	.73	.78	.82*	.87	.91	.96	1.0

Table 16

Adjustment Factor (c) in Presented Penman Equation

	RHmax = 30%				RHmax = 60%				RHmax = 90%			
Rs mm/day	3	6	9	12	3	6	9	12	3	6	9	12
Uday m/sec	Uday/Unight = 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
	Uday/Unight = 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
	Uday/Unight = 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
	Uday/Unight = 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

FORMAT FOR CALCULATION OF PENMAN METHOD

Penman reference crop ETo = c [W.Rn + (1-W)f(u)(ea-ed)]

Country: UAR   Place: Cairo   Latitude : 30°N   Altitude: 95m
Period : July   Longitude: 30°

DATA			
Tmean 28.5 °C	ea mbar	(5) 1/	38.9
RHmean 55 %	RH/100	data	0.55
	ed mbar	calc	21.4
or T wetbulb depression or T dewpoint		(5) or (6)	
	(ea-ed) mbar	calc	17.5
U_2 232 km/day	f(u)	(7)	0.90
Tmean 28.5 °C altitude 95 m	(1-W)	(8)	0.23
	(1-W)f(u)(ea-ed) mm/day	calc	3.6
month July latitude 30°N	Ra mm/day	(10)	16.8
	n hr/day	data	11.5
month July latitude 30°N	N hr/day	(11)	13.9
	n/N	calc	0.83
	(0.25+0.50n/N)	calc (12)	0.67
	Rs mm/day	calc	11.2
(α = 0.25)	Rns mm/day (1 - α)Rs	calc	8.4 2/
Tmean 28.5 °C	f(T)	(13)	16.4
ed 21.4 mbar	f(ed)	(14)	0.13
n/N 0.83	f(n/N)	(15)	0.85
	Rnl = f(T)f(ed)f(n/N) mm/day	calc	1.8
	Rn = Rns - Rnl	calc	6.6
Tmean 28.5 °C altitude 95 m	W	(9)	0.77
	W.Rn	calc	5.1
			8.7
Uday/Unight 1.5 RHmax, Rs 80% 11.2	c	(16)	1.01
	ETo = c[W.Rn + (1-W)f(u)(ea-ed)]	mm/day	8.8

1/ Numbers in brackets indicate Table of reference.

2/ When Rs data are available Rns = 0.75 Rs.

1.4 PAN EVAPORATION METHOD

Evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from a specific open water surface. In a similar fashion the plant responds to the same climatic variables but several major factors may produce significant differences in loss of water. Reflection of solar radiation from a water surface is only 5-8 percent, from most vegetative surfaces 20-25 percent. Storage of heat within the pan can be appreciable and may cause almost equal evaporation during night and day; most crops transpire only during daytime. Also the difference in water losses from pans and from crops can be caused by differences in turbulence, temperature and humidity of the air immediately above the surfaces. Heat transfer through the sides of the pan can occur, which may be severe for sunken pans. Also the colour of the pan and the use of screens will affect water losses. The siting of the pan and the pan environment influence the measured results, especially when the pan is placed in fallow rather than cropped fi [illegible]. Factors involved in prediction of lake evaporation using pans is discussed by C.F [illegible] 973), WMO Note 126.

Notwithstanding these deficiences, with proper siting the use of pans to predict crop wat requirements for periods of 10 days or longer is still warranted. From the many different types of pans, the use of the U.S. Class A pan and the Colorado sunken pan is presented here.[1] To relate pan evaporation (Epan) to reference crop evapotranspiration (ETo) empirically derived coefficients (Kp) are given which take into account climate and pan environment. If measured data from other types of sunken pans are available, such data should first be related to sunken Colorado pan data (Table 17). The ratios given in Table 17 serve as multiplying factors to obtain fromEpan of different types of pans mentioned, the sunken Colorado pan evaporation data. (The pan area of the Colorado sunken pan is 3 ft^2 or 0.84 m^2.)

Recommended Relationships

Reference crop evapotranspiration (ETo) can be obtained from:

$$ETo = Kp . Epan$$

where: Epan = pan evaporation in mm/day and represents the mean daily value of the period considered
Kp = pan coefficient

Values for Kp are given in Table 18 for the Class A pan and in Table 19 for the sunken Colorado pan for different humidity and wind conditions and pan environment. The Kp values relate

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[1] Description of pans: The Class A evaporation pan is circular, 121 cm (46.5 inches) in diameter and 25.5 cm (10 inches) deep. It is made of galvanized iron (22 gauge) or monel metal (0.8 mm). The pan is mounted on a wooden open frame platform with its bottom 15 cm above ground level. The soil is built up to within 5 cm of the bottom of the pan. The pan must be level. It is filled with water 5 cm below the rim, and water level should not drop to more than 7.5 cm below the rim. Water is regularly renewed to eliminate extreme turbidity. The pan if galvanized is painted annually with alluminium paint.

Sunken Colorado pans are sometimes preferred in crop water requirement studies, since these pans have a water level 5 cm below the rim at soil level height and give a better direct prediction of potential evapotranspiration of grass than does the Class A pan. The pan is 92 cm (36 inches) square and 46 cm (18 inches) deep. It is made of galvanized iron, set in the ground with the rim 5 cm (2 inches) above the ground level. The water level inside the pan is maintained at or slightly below ground level. (Reference is made to Irrigation and Drainage Paper No. 27 Agro-meteorological field stations . FAO Rome, Italy 1976.)

to pans located in an open field with no crops taller than 1 m within some 50 m of the pan. Immediate surroundings, within 10 m, are covered by a green, frequently mowed, grass cover or by bare soils. The pan station is placed in an agricultural area. The pan is unscreened.

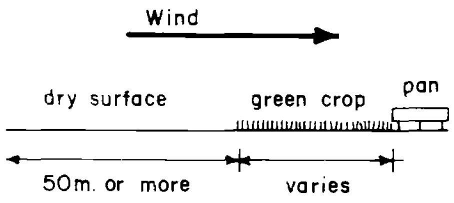
Additional Considerations

In selecting the appropriate value of Kp to relate Class A and Colorado sunken pan data to ETo, it is necessary to consider the ground cover of the pan station itself, that of the surroundings and general wind and humidity conditions. The relative humidity ranges referred to in Tables 18 and 19 are RHmean or (RHmax + RHmin)/2. Wind is reflected as total 24-hr wind run in km/day. Nomenclature used to describe general levels of mean relative humidity and wind are given in Climatological Nomenclature in the introductory pages of this publication.

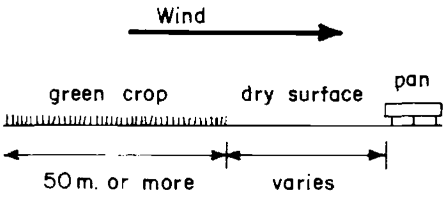
When the pan is located at a station with very poor grass cover, dry bare soil or, undesirably, a concrete or asphalt apron, air temperatures at pan level may be 2 to 5°C higher and relative humidity 20 to 30 percent lower. This will be most pronounced in arid and semi-arid climates during all but the rainy periods. This effect has been accounted for in the figures of Tables 18 and 19. However, in areas with no agricultural development and extensive areas of bare soils - as are found under desert or semi-desert conditions - the values of Kp given for arid, windy areas may need to be reduced by up to 20 percent; for areas with moderate levels of wind, temperature and relative humidity by 5 to 10 percent; no or little reduction in Kp is needed in humid, cool conditions.

In Tables 18 and 19 a separation is made for pans located within cropped plots surrounded by or downwind from dry surface areas (case A) and for pans located within a dry or fallow field but surrounded by irrigated or rainfed upwind cropped areas (case B).

Case A



Case B



Where pans are placed in a small enclosure but surrounded by tall crops, for example 2.5 m high maize, the coefficients in Tables 18 and 19 will need to be increased by up to 30 percent for dry, windy climates, whereas only a 5 to 10 percent increase is required for calm, humid conditions.

The pan coefficients given in Tables 18 and 19 apply to galvanized pans annually painted with aluminium. Little difference in Epan will show when inside and outside surfaces of the pan are painted white. An increase in Epan of up to 10 percent may occur when they are painted black. The material from which the pan is made may account for variations of only a few percent. The level at which the water is maintained in the pan is very important; resulting errors may be up to 15 percent when water levels in Class A pans fall 10 cm below the accepted standard of between 5 and 7.5 cm below the rim. Screens mounted over pans will reduce Epan by up to 10 percent. In an endeavour to avoid pans being used by birds for drinking, a pan filled to the rim with water can be placed near the Class A pan; birds may prefer to use the fully filled pan. Turbidity of the water in the pan does not affect Epan data by more than 5 percent. Overall variation in Epan is not constant with time because of ageing, deterioration and repainting.

Sample Calculations

EXAMPLE:

Given:

Cairo; July. Epan = 11.1 mm/day from Class A pan; RHmean = medium; wind moderate; pan station is located within a cropped area of several hectares; the pan is not screened.

Calculation:

Monthly data: since pan station is covered by grass and is surrounded by some 100 m of cropped area case A applies.

From Table 19 for moderate wind and medium humidity value of Kp = 0.75.

ETo = Kp x Epan = 0.75 x 11.1 = 8.3 mm/day

Yearly data:

	J	F	M	A	M	J	J	A	S	O	N	D
wind	light to moderate				moderate			light to moderate				
RHmean	med. to high			medium						med. to high		
Kp	.8	.8	.8	.77	.75	.75	.75	.77	.77	.8	.8	.8
Epan	3.3	4.5	6.4	8.5	11.2	12.8	11.1	9.7	7.9	6.9	4.3	3.3
ETo mm/day	2.6	3.6	5.1	6.5	8.4	9.6	8.3	7.4	6.0	5.5	3.4	2.6
mm/months	82	100	158	196	260	289	258	231	180	165	102	81

Table 17 Ratios Between Evaporation from Sunken Pans Mentioned and From Colorado Sunken Pan for Different Climatic Conditions and Pan Environments

		Ratio Epan mentioned and Epan Colorado			
Climate		Humid-temperate climate		Arid to semi-arid (dry season)	
Groundcover surrounding pan (50 m or more)		Short green cover	Dry fallow	Short green cover	Dry fallow
	Pan area m^2				
CGI 20 dia. 5 m, depth 2 m (USSR)	20	1.0	1.1	1.05	1.25*
Sunken pan dia. 12 ft, depth 3.3 ft. (Israel)	10.5				
Symmons pan 6 ft^2, depth 2 ft (UK)	3.3				
BPI dia. 6 ft, depth 2 ft (USA)	2.6				
Kenya pan dia. 4 ft, depth 14 in	1.2				
Australian pan dia. 3 ft, depth 3 ft	0.7		1.0		1.0
Aslyng pan 0.33 m^2, depth 1 m (Denmark)	0.3			1.0	
CGI 3000 dia. 61.8 cm, depth 60-80 cm (USSR)	0.3				
Sunken pan dia. 50 cm, depth 25 cm (Netherlands)	0.2	1.0	.95	1.0	.95

EXAMPLE: CGI 20 in semi-arid climate, dry season, placed in dry fallow land; for given month Epan CGI 20 = 8 mm/day.
Corresponding Epan sunken Colorado is 1.25 x 8 = 10 mm/day.

Table 18 Pan Coefficient (Kp) for Class A Pan for Different Groundcover and Levels of Mean Relative Humidity and 24 hour Wind

Class A pan	Case A: Pan placed in short green cropped area				Case B[1] Pan placed in dry fallow area			
RHmean %		low <40	medium 40-70	high >70		low <40	medium 40-70	high >70
Wind km/day	Windward side distance of green crop m				Windward side distance of dry fallow m			
Light <175	1	.55	.65	.75	1	.7	.8	.85
	10	.65	.75	.85	10	.6	.7	.8
	100	.7	.8	.85	100	.55	.65	.75
	1 000	.75	.85	.85	1 000	.5	.6	.7
Moderate 175-425	1	.5	.6	.65	1	.65	.75	.8
	10	.6	.7	.75	10	.55	.65	.7
	100	.65	.75*	.8	100	.5	.6	.65
	1 000	.7	.8	.8	1 000	.45	.55	.6
Strong 425-700	1	.45	.5	.6	1	.6	.65	.7
	10	.55	.6	.65	10	.5	.55	.65
	100	.6	.65	.7	100	.45	.5	.6
	1 000	.65	.7	.75	1 000	.4	.45	.55
Very strong >700	1	.4	.45	.5	1	.5	.6	.65
	10	.45	.55	.6	10	.45	.5	.55
	100	.5	.6	.65	100	.4	.45	.5
	1 000	.55	.6	.65	1 000	.35	.4	.45

Table 19 Pan Coefficient (Kp) for Colorado Sunken Pan for Different Groundcover and Levels of Mean Relative Humidity and 24 hour Wind

Sunken Colorado	Case A: Pan placed in short green cropped area				Case B[1] Pan placed in dry fallow area			
RHmean %		low <40	medium 40-70	high >70		low <40	medium 40-70	high >70
Wind km/day	Windward side distance of green crop m				Windward side distance of dry fallow m			
Light <175	1	.75	.75	.8	1	1.1	1.1	1.1
	10	1.0	1.0	1.0	10	.85	.85	.85
	≥100	1.1	1.1	1.1	100	.75	.75	.8
					1 000	.7	.7	.75
Moderate 175-425	1	.65	.7	.7	1	.95	.95	.95
	10	.85	.85	.9	10	.75	.75	.75
	≥100	.95	.95	.95	100	.65	.65	.7
					1 000	.6	.6	.65
Strong 425-700	1	.55	.6	.65	1	.8	.8	.8
	10	.75	.75	.75	10	.65	.65	.65
	≥100	.8	.8	.8	100	.55	.6	.65
					1 000	.5	.55	.6
Very strong >700	1	.5	.55	.6	1	.7	.75	.75
	10	.65	.7	.7	10	.55	.6	.65
	≥100	.7	.75	.75	100	.5	.55	.6
					1 000	.45	.5	.55

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[1] For extensive areas of bare-fallow soils and no agricultural development, reduce Kpan by 20% under hot, windy conditions; by 5-10% for moderate wind, temperature and humidity conditions.

2. SELECTION OF CROP COEFFICIENT

The four methods described in Part I.1 predict the effect of climate on reference crop evapotranspiration (ETo). To account for the effect of the crop characteristics on crop water requirements, crop coefficients (kc) are presented to relate ETo to crop evapotranspiration (ETcrop). The kc value relates to evapotranspiration of a disease-free crop grown in large fields under optimum soil water and fertility conditions and achieving full production potential under the given growing environment. ETcrop can be found by:

$$ETcrop = kc \cdot ETo$$

Each of the four methods in Part I.1 predicts ETo and only one set of crop coefficients is required. Procedures for selection of appropriate kc values are given, which take into account the crop characteristics, time of planting or sowing, and stages of crop development and general climatic conditions.

The effect of crop characteristics on the relationship between ETcrop and ETo is shown in the conceptual diagram in Figure 4. The wide variations between major groups of crops are largely due to the resistance to transpiration of different plants, such as closed stomata during the day (pineapple) and waxy leaves (citrus). Also differences in crop height, crop roughness, reflection and groundcover produce the illustrated variation in ETcrop. For high evaporative conditions, i.e. hot, strong winds and low humidity, ETo values of up to 12 to 14 mm/day and ETcrop values of up to 15 to 17 mm/day may be realistic, particularly for small fields in arid areas which are strongly affected by dry wind conditions. However, wilting of crops may occur under such conditions and, as shown in Figure 4 for sugarbeets, may result in ETcrop values well below ETo.

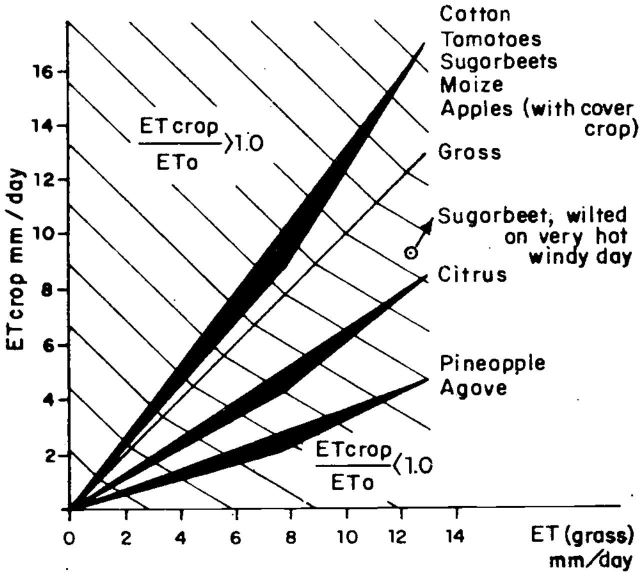

Fig. 4 ETcrop as compared to ETo

For ease of reference, approximate ranges of seasonal ETcrop for different crops are given in Table 20. The magnitudes shown will change according to the factors discussed, i.e. mainly climate, crop characteristics, length of growing season and time of planting.

Additional Considerations

Factors affecting the value of the crop coefficient (kc) are mainly the crop characteristics, crop planting or sowing data, rate of crop development, length of growing season and climatic conditions. Particularly following sowing and during the early growth stage, the frequency of rain or irrigation is important.

Table 20 Approximate Range of Seasonal ETcrop in mm

Seasonal ETcrop	mm		mm
Alfalfa	600 - 1 500	Onions	350 - 600
Avocado	650 - 1 000	Orange	600 - 950
Bananas	700 - 1 700	Potatoes	350 - 625
Beans	250 - 500	Rice	500 - 950
Cocoa	800 - 1 200	Sisal	550 - 800
Coffee	800 - 1 200	Sorghum	300 - 650
Cotton	550 - 950	Soybeans	450 - 825
Dates	900 - 1 300	Sugarbeets	450 - 850
Deciduous trees	700 - 1 050	Sugarcane	1 000 - 1 500
Flax	450 - 900	Sweet potatoes	400 - 675
Grains (small)	300 - 450	Tobacco	300 - 500
Grapefruit	650 - 1 000	Tomatoes	300 - 600
Maize	400 - 750	Vegetables	250 - 500
Oil seeds	300 - 600	Vineyards	450 - 900
		Walnuts	700 - 1 000

The crop planting or sowing date will affect the length of the growing season, the rate of crop development to full groundcover and onset of maturity. For instance, depending on climate, sugarbeets can be sown in autumn, spring and summer with a total growing season ranging from 230 to 160 days. For soybeans, the growing season ranges from 100 days in warm, low altitude areas, to 190 days at 2 500 m altitudes in Equatorial Africa and for maize 80 to 240 days respectively. Crop development will also be at a different pace; as shown in Figure 5 for sugarbeets, the time needed to reach full development or maximum water demand varies from up to 60 percent of the total growing season for an autumn sown crop to about 35 percent for an early summer sowing. In selecting the appropriate kc value for each period or month in the growing season for a given crop, the rate of crop development must be considered.

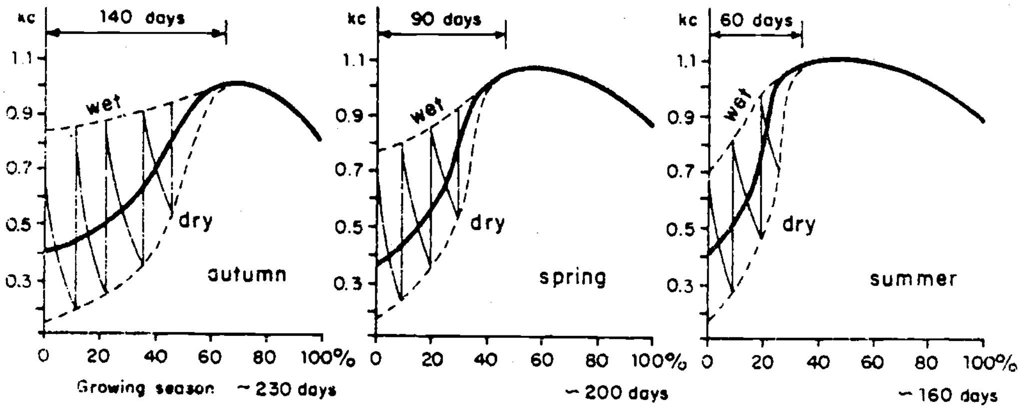

Fig. 5 Sugarbeets; kc values for different sowing dates

General climatic conditions, especially wind and humidity, are to be considered; compared with a smooth grass cover, wind will affect the rate of transpiration of taller crops more due to air turbulence above the rougher crop surface. This is more pronounced in dry than in humid climates and kc values for rougher crop surfaces are therefore greater in dry climates.

ETcrop is the sum of transpiration by the crop and evaporation from the soil surface. During full groundcover, evaporation is negligible; just following sowing and during the early growing period evaporation from the soil surface (Esoil) may be considerable, particularly when the soil surface is wet for most of the time from irrigation and rain.

Transpiration and evaporation are governed by different physical processes. However, since for the crop growing season Esoil forms part of ETcrop, and for the sake of simplicity, the coefficient relating ETo and Esoil is given herein by the appropriate 'crop' factor (kc). The great range of kc values during initial growth stage following sowing is illustrated in Figure 5. The value of kc largely depends on the level of ETo and the frequency with which the soil is wetted by rain and/or irrigation. The smooth curves in Figure 5 present average kc values rather than the actual sharp increase in kc just following rain and irrigation, with a less sharp but marked decline afterwards, until the next rain or irrigation. Some compromise in accuracy by not differentiating between various soil types has been accepted.

The presented kc values relate ETo to ETcrop. Crop coefficients published elsewhere relating to original and other methods should not be used if the methods presented in this publication are followed.

Recommended Values

(a) Field and vegetable crops

The crop growing season has been divided into four stages. Crop coefficients (kc) for given stages of crop development and different climatic conditions are presented in Table 21. The need to collect local data on growing season and rate of crop development of irrigated crops is stressed. For reference, information for selected crops and climate is given in Table 22.

The four stages of crop development are described herein as:

(1) initial stage : germination and early growth when the soil surface is not or is hardly covered by the crop (groundcover $<10\%$)

(2) crop development stage : from end of initial stage to attainment of effective full groundcover (groundcover ≅ 70-80%) [1]

(3) mid-season stage : from attainment of effective full groundcover to time of start of maturing as indicated by discolouring of leaves (beans) or leaves falling off (cotton). For some crops this may extend to very near harvest (sugarbeets) unless irrigation is not applied at late season and reduction in ETcrop is induced to increase yield and/or quality (sugarcane, cotton, some grains); normally well past the flowering stage of annual crops

(4) late season stage : from end of mid-season stage until full maturity or harvest

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[1] Start of mid-season stage can be recognized in the field when crop has attained 70 to 80% groundcover which, however, does not mean that the crop has reached its mature height. Effective full groundcover refers to cover when kc is approaching a maximum.

The steps needed to arrive at the kc values for the different stages are given below. The values of kc for the various growth stages are to be plotted as in the given example, Figure 7. For simplification the values of kc for the different periods within the growing season are represented as straight lines:

I establish planting or sowing date from local information or from practices in similar climatic zones;

II determine total growing season and length of crop development stages from local information (for approximations see Table 22);

III initial stage: predict irrigation and/or rainfall frequency; for predetermined ETo value, obtain kc from Figure 6 and plot kc value as shown in Figure 7;

IV mid-season stage: for given climate (humidity and wind), select kc value from Table 21 and plot as straight line;

V late-season stage: for time of full maturity (or harvest within a few days), select kc value from Table 21 for given climate (humidity and wind) and plot value at end of growing season or full maturity. Assume straight line between kc values at end of mid-season period and at end of growing season;

VI development stage: assume straight line between kc value at end of initial to start of mid-season stage.

For each 10 or 30 day period the kc values can be obtained from the prepared graph. A smoothed curve might first be drawn as indicated in Figure 7, although this may have little effect in terms of accuracy added.

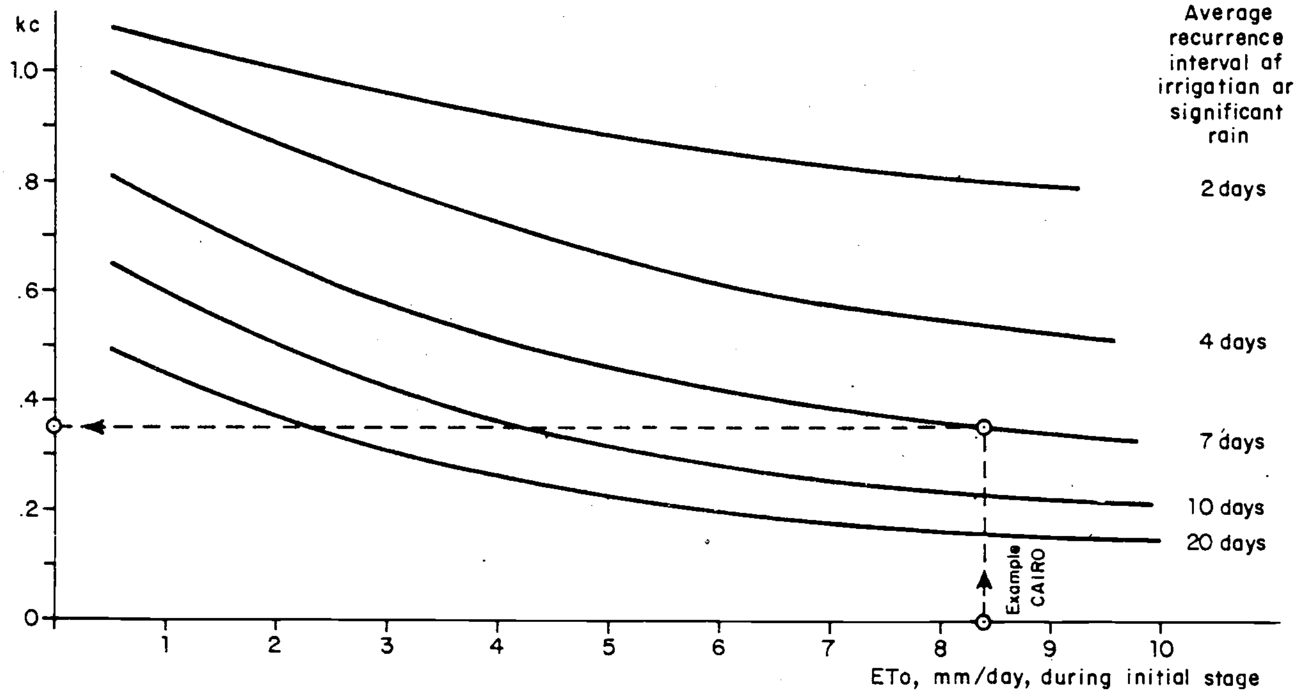


Fig. 6 Average kc value for initial crop development stage as related to level of ETo and frequency of irrigation and/or significant rain

EXAMPLE:

Given:

Cairo; corn planted mid-May; for total growing season winds are light to moderate (0-5 m/sec), and mid-summer RHmin is 30-35%; ETo initial stage is 8.4 mm/day; irrigation frequency initial period assumed to be 7 days.

I	Planting date		Late spring, early summer
II	Length of growth stages	local information (or Table 22)	
	initial		20 days
	crop development		35 days
	mid-season		40 days
	late season		30 days 125 days
III	Plot periods as indicated	Fig. 7	
IV	kc initial stage (1) ETo = 8.4 mm/day irrig. frequency = 7 days	Fig. 6	kc initial = 0.35
	kc mid-season stage (3) wind = light/moderate humidity = low	Table 21	kc mid-season = 1.14
	kc late season stage (end) (4) wind = light/moderate humidity = low	Table 21	kc end of season = 0.6
V	Plot kc value and connect values with straight lines	Fig. 7	kc development stage = 0.35-1.14 kc late season stage = 1.14-0.6
VI	Read kc value from prepared graph for each selected period at mid point of 10 to 30 day period		

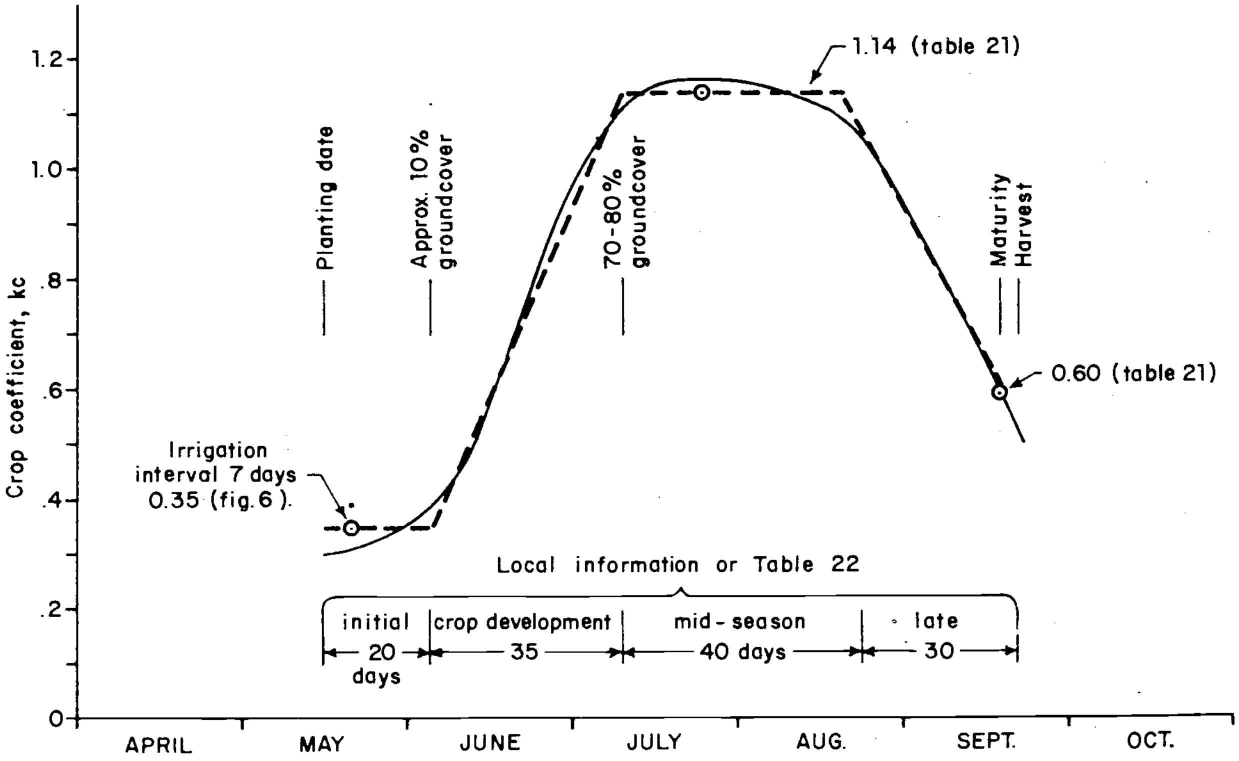


Fig. 7 Example of crop coefficient curve

Table 21 Crop Coefficient (kc) for Field and Vegetable Crops for Different Stages of Crop Growth and Prevailing Climatic Conditions

Crop	Humidity		RHmin >70%		RHmin <20%	
	Wind m/sec		0-5	5-8	0-5	5-8
	Crop stage					
All field crops	initial	1	Use Fig. 7			
"	crop dev.	2	by interpolation			
Artichokes (perennial-clean cultivated)	mid-season	3	.95	.95	1.0	1.05
	at harvest or maturity	4	.9	.9	.95	1.0
Barley		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2
Beans (green)		3	.95	.95	1.0	1.05
		4	.85	.85	.9	.9
Beans (dry) Pulses		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Beets (table)		3	1.0	1.0	1.05	1.1
		4	.9	.9	.95	1.0
Carrots		3	1.0	1.05	1.1	1.15
		4	.7	.75	.8	.85
Castorbeans		3	1.05	1.1	1.15	1.2
		4	.5	.5	.5	.5
Celery		3	1.0	1.05	1.1	1.15
		4	.9	.95	1.0	1.05
Corn (sweet) (maize)		3	1.05	1.1	1.15	1.2
		4	.95	1.0	1.05	1.1
Corn (grain) (maize)		3	1.05	1.1	1.15*	1.2
		4	.55	.55	.6 *	.6
Cotton		3	1.05	1.15	1.2	1.25
		4	.65	.65	.65	.7
Crucifers (cabbage, cauliflower, broccoli, Brussels sprout)		3	.95	1.0	1.05	1.1
		4	.80	.85	.9	.95
Cucumber		3	.9	.9	.95	1.0
Fresh market		4	.7	.7	.75	.8
Machine harvest		4	.85	.85	.95	1.0
Egg plant (aubergine)		3	.95	1.0	1.05	1.1
		4	.8	.85	.85	.9
Flax		3	1.0	1.05	1.1	1.15
		4	.25	.25	.2	.2
Grain		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Lentil		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Lettuce		3	.95	.95	1.0	1.05
		4	.9	.9	.9	1.0
Melons		3	.95	.95	1.0	1.05
		4	.65	.65	.75	.75
Millet		3	1.0	1.05	1.1	1.15
		4	.3	.3	.25	.25

Crop	Humidity	RHmin >70%		RHmin < 20%	
	Wind m/sec	0-5	5-8	0-5	5-8
Oats	mid-season 3	1.05	1.1	1.15	1.2
	harvest/maturity 4	.25	.25	.2	.2
Onion (dry)	3	.95	.95	1.05	1.1
	4	.75	.75	.8	.85
(green)	3	.95	.95	1.0	1.05
	4	.95	.95	1.0	1.05
Peanuts	3	.95	1.0	1.05	1.1
(Groundnuts)	4	.55	.55	.6	.6
Peas	3	1.05	1.1	1.15	1.2
	4	.95	1.0	1.05	1.1
Peppers (fresh)	3	.95	1.0	1.05	1.1
	4	.8	.85	.85	.9
Potato	3	1.05	1.1	1.15	1.2
	4	.7	.7	.75	.75
Radishes	3	.8	.8	.85	.9
	4	.75	.75	.8	.85
Safflower	3	1.05	1.1	1.15	1.2
	4	.25	.25	.2	.2
Sorghum	3	1.0	1.05	1.1	1.15
	4	.5	.5	.55	.55
Soybeans	3	1.0	1.05	1.1	1.15
	4	.45	.45	.45	.45
Spinach	3	.95	.95	1.0	1.05
	4	.9	.9	.95	1.0
Squash	3	.9	.9	.95	1.0
	4	.7	.7	.75	.8
Sugarbeet	3	1.05	1.1	1.15	1.2
	4	.9	.95	1.0	1.0
	no irrigation last month 4	.6	.6	.6	.6
Sunflower	3	1.05	1.1	1.15	1.2
	4	.4	.4	.35	.35
Tomato	3	1.05	1.1	1.2	1.25
	4	.6	.6	.65	.65
Wheat	3	1.05	1.1	1.15	1.2
	4	.25	.25	.2	.2

NB: Many cool season crops cannot grow in dry, hot climates. Values of kc are given for latter conditions since they may occur occasionally, and result in the need for higher kc values, especially for tall rough crops.

Table 22 Length of Growing Season and Crop Development Stages of Selected Field Crops; Some Indications

Artichokes	Perennial, replanted every 4-7 years; example Coastal California with planting in April 40/40/250/30 and (360)1/; subsequent crops with crop growth cutback to ground level in late spring each year at end of harvest or 20/40/220/30 and (310).
Barley	Also wheat and oats; varies widely with variety; wheat Central India November planting 15/25/50/30 and (120); early spring sowing, semi-arid, 35°-45° latitudes and November planting Rep. of Korea 20/25/60/30 and (135); wheat sown in July in East African highlands at 2 500 m altitude and Rep. of Korea 15/30/65/40 and (150).
Beans (green)	February and March planting California desert and Mediterranean 20/30/30/10 and (90); August-September planting California desert, Egypt, Coastal Lebanon 15/25/25/10 and (75).
Beans (dry) Pulses	Continental climates late spring planting 20/30/40/20 and (110); June planting Central California and West Pakistan 15/25/35/20 and (95); longer season varieties 15/25/50/20 and (110).
Beets (table)	Spring planting Mediterranean 15/25/20/10 and (70); early spring planting Mediterranean climates and pre-cool season in desert climates 25/30/25/10 and (90).
Carrots	Warm season of semi-arid to arid climates 20/30/30/20 and (100); for cool season up to 20/30/80/20 and (150); early spring planting Mediterranean 25/35/40/20 and (120); up to 30/40/60/20 and (150) for late winter planting.
Castorbeans	Semi-arid and arid climates, spring planting 25/40/65/50 and (180).
Celery	Pre-cool season planting semi-arid 25/40/95/20 and (180); cool season 30/55/105/20 and (210); humid Mediterranean mid-season 25/40/45/15 and (125).
Corn (maize) (sweet)	Philippines, early March planting (late dry season) 20/20/30/10 and (80); late spring planting Mediterranean 20/25/25/10 and (80); late cool season planting desert climates 20/30/30/10 and (90); early cool season planting desert climates 20/30/50/10 and (110).
Corn (maize) (grains)	Spring planting East African highlands 30/50/60/40 and (180); late cool season planting, warm desert climates 25/40/45/30 and (140); June planting sub-humid Nigeria, early October India 20/35/40/30 and (125); early April planting Southern Spain 30/40/50/30 and (150).

1/ 40/40/250/30 and (360) stand respectively for initial, crop development, mid-season and late season crop development stages in days and (360) for total growing period from planting to harvest in days.

Cotton	March planting Egypt, April-May planting Pakistan, September planting South Arabia 30/50/60/55 and (195); spring planting, machine harvested Texas 30/50/55/45 and (180).
Crucifers	Wide range in length of season due to varietal differences; spring planting Mediterranean and continental climates 20/30/20/10 and (80); late winter planting Mediterranean 25/35/25/10 and (95); autumn planting Coastal Mediterranean 30/35/90/40 and (195).
Cucumber	June planting Egypt, August-October California desert 20/30/40/15 and (105); spring planting semi-arid and cool season arid climates, low desert 25/35/50/20 and (130).
Egg plant	Warm winter desert climates 30/40/40/20 and (130); late spring-early summer planting Mediterranean 30/45/40/25 and (140).
Flax	Spring planting cold winter climates 25/35/50/40 and (150); pre-cool season planting Arizona low desert 30/40/100/50 and (220).
Grain, small	Spring planting Mediterranean 20/30/60/40 and (150); October-November planting warm winter climates; Pakistan and low deserts 25/35/65/40 and (165).
Lentil	Spring planting in cold winter climates 20/30/60/40 and (150); pre-cool season planting warm winter climates 25/35/70/40 and (170).
Lettuce	Spring planting Mediterranean climates 20/30/15/10 and (75) and late winter planting [illegible]0/40/25/10 and (105); early cool season low desert climates from 25/35/20/[illegible] and (100); late cool season planting, low deserts 35/50/45/10 and (140).
Melons	Late spring planting Mediterranean climates 25/35/40/20 and (120); mid-winter planting in low desert climates 30/45/65/20 and (160).
Millet	June planting Pakistan 15/25/40/25 and (105); central plains U.S.A. spring planting 20/30/55/35 and (140).
Oats	See Barley.
Onion (dry)	Spring planting Mediterranean climates 15/25/70/40 and (150); pre-warm winter planting semi-arid and arid desert climates 20/35/110/45 and (210).
(green)	Respectively 25/30/10/5 and (70) and 20/45/20/10 and (95).
Peanuts (groundnuts)	Dry season planting West Africa 25/35/45/25 and (130); late spring planting Coastal plains of Lebanon and Israel 35/45/35/25 and (140).
Peas	Cool maritime climates early summer planting 15/25/35/15 and (90); Mediterranean early spring and warm winter desert climates planting 20/25/35/15 and (95); late winter Mediterranean planting 25/30/30/15 and (100).

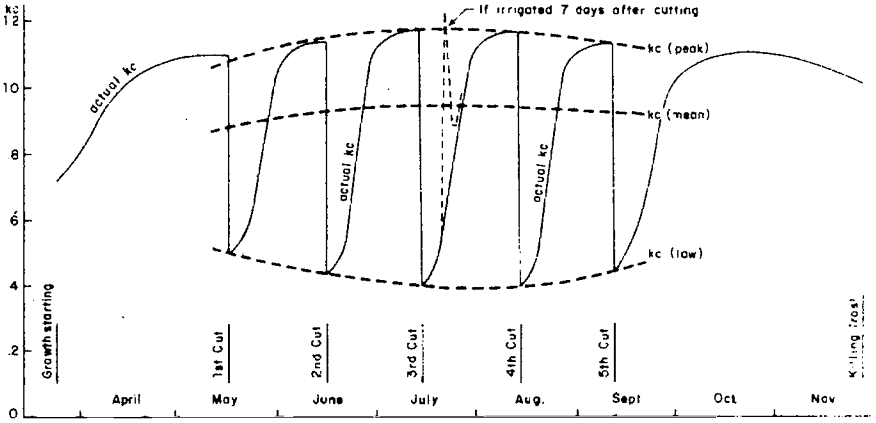
Peppers	Fresh - Mediterranean early spring and continental early summer planting 30/35/40/20 and (125); cool coastal continental climates mid-spring planting 25/35/40/20 and (120); pre-warm winter planting desert climates 30/40/110/30 and (210).
Potato (Irish)	Full planting warm winter desert climates 25/30/30/20 and (105); late winter planting arid and semi-arid climates and late spring-early summer planting continental climate 25/30/45/30 and (130); early-mid spring planting central Europe 30/35/50/30 and (145); slow emergence may increase length of initial period by 15 days during cold spring.
Radishes	Mediterranean early spring and continental summer planting 5/10/15/5 and (35); coastal Mediterranean late winter and warm winter desert climates planting 10/10/15/5 and (40).
Safflower	Central California early-mid spring planting 20/35/45/25 and (125) and late winter planting 25/35/55/30 and (145); warm winter desert climates 35/55/60/40 and (190).
Sorghum	Warm season desert climates 20/30/40/30 and (120); mid-June planting Pakistan, May in mid-West U.S.A. and Mediterranean 20/35/40/30 and (125); early spring planting warm arid climates 20/35/45/30 and (130).
Soybeans	May planting Central U.S.A. 20/35/60/25 and (140); May-June planting California desert 20/30/60/25 and (135); Philippines late December planting, early dry season - dry: 15/15/40/15 and (85); vegetables 15/15/30/- and (60); early-mid June planting in Japan 20/25/75/30 and (150).
Spinach	Spring planting Mediterranean 20/20/15/5 and (60); September-October and late winter planting Mediterranean 20/20/25/5 and (70); warm winter desert climates 20/30/40/10 and (100).
Squash (winter) pumpkin	Late winter planting Mediterranean and warm winter desert climates 20/30/30/15 and (95); August planting California desert 20/35/30/25 and (110); early June planting maritime Europe 25/35/35/25 and (120).
Squash (zucchini) crookneck	Spring planting Mediterranean 25/35/25/15 and (100+); early summer Mediterranean and maritime Europe 20/30/25/15 and (90+); winter planting warm desert 25/35/25/15 and (100).
Sugarbeet	Coastal Lebanon, mid-November planting 45/75/80/30 and (230); early summer planting 25/35/50/50 and (160); early spring planting Uruguay 30/45/60/45 and (180); late winter planting warm winter desert 35/60/70/40 and (205).
Sunflower	Spring planting Mediterranean 25/35/45/25 and (130); early summer planting California desert 20/35/45/25 and (125).
Tomato	Warm winter desert climates 30/40/40/25 and (135); and late autumn 35/45/70/30 and (180); spring planting Mediterranean climates 30/40/45/30 and (145).
Wheat	See Barley.

(b) Alfalfa, clover, grass-legumes, pastures

Alfalfa: The kc values vary similarly to those for field crops but the initial to harvest stage is repeated 2 to 8 times a year. To obtain mean ETalfalfa, values given for kc(mean) in Table 23 would generally suffice. For irrigation depth and frequency determinations the variation of kc over the cutting interval needs to be considered, that is from kc(low) just following harvesting, to kc(peak) just before harvesting. Alfalfa grown for seed production will have a kc value equal to kc(peak) during full cover until the middle of full bloom.

Fig. 8

kc values for alfalfa grown in dry climate with light to moderate wind and with cuttings every four weeks; one heavy irrigation per growth period, a week before cutting



Grasses: Grasses grown for hay reach kc(peak) values within 6 to 8 days after cutting. The kc(low) values are 10 to 20 percent higher than the kc(low) values shown for alfalfa since considerable vegetation is left on the ground after cutting.

Clover and grass-legume mixture: Due to some cover left after cutting, kc(low) will be close to that of grass, while kc(peak) will be closer to alfalfa.

Pasture (grass, grass-legumes and alfalfa): Depending on pasturing practices, kc values will show a wide variation. The values presented assume excellent plant population density, high fertility and good irrigation. For pastures kc(low) may need to be taken close to kc(low) alfalfa under poor pasturing practices when all ground cover is destroyed.

Table 23 kc Values for Alfalfa, Clover, Grass-legumes and Pasture

		Alfalfa	Grass for hay	Clover, Grass-legumes	Pasture
Humid Light to moderate wind	kc mean	0.85	0.8	1.0	0.95
	kc peak	1.05	1.05	1.05	1.05
	kc low 1/	0.5	0.6	0.55	0.55
Dry Light to moderate wind	kc mean	0.95	0.9	1.05	1.0
	kc peak	1.15	1.1	1.15	1.1
	kc low 1/	0.4	0.55	0.55	0.5
Strong wind	kc mean	1.05	1.0	1.1	1.05
	kc peak	1.25	1.15	1.2	1.15
	kc low 1/	0.3	0.5	0.55	0.5

kc(mean) represents mean value between cutting, kc(low) just after cutting, kc(peak) just before harvesting

1/ Under dry soil conditions; under wet conditions increase values by 30%.

(c) Bananas

Values of kc for bananas are given in Table 24 for Mediterranean and tropical climates. For the Mediterranean climate data are given for both first year with planting in mid-March and for second year with removal of original plants in early February. For the early stages of crop development, especially in the first year, kc values reflect little ground cover and rainfall is presumed at 5-7 day intervals. For less frequent rain, lower kc values should be used. Figure 6 can be used for estimating kc during the first 2 months after planting, taking into account rainfall frequency and level of ETo. The drop in kc in February reflects the removal of original large plants at that time. Local practices should be taken into account in timing the drop in kc, with subsequent recovery to higher values 4-5 months later, or as ground cover again approaches 70-80 percent. Months mentioned in Table 24 refer to the northern hemisphere; for the southern hemisphere add 6 months.

For tropical regions kc values for months after planting are given [illegible] take place during any month. Smaller kc values after 10 months reflect ra[illegible] decline of active [illegible] area of the mother plants. The low kc values during early months apply where heavy mulching is practised; in cases of bare soils and frequent rains, kc values are 0.8 to 1.0 and Figure 6 can be consulted.

Table 24 kc Values for Bananas

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Mediterranean climate												
First-year crop, based on March planting with crop height 3.5 m by August:												
Humid, light to mod. wind	-	-	.65	.6	.55	.6	.7	.85	.95	1.0	1.0	1.0
Humid, strong wind	-	-	.65	.6	.55	.6	.75	.9	1.0	1.05	1.05	1.05
Dry, light to mod. wind	-	-	.5	.45	.5	.6	.75	.95	1.1	1.15	1.1	1.1
Dry, strong wind	-	-	.5	.45	.5	.65	.8	1.0	1.15	1.2	1.15	1.15
Second season with removal of original plants in Feb. and 80% ground cover by August:												
Humid, light to mod. wind	1.0	.8	.75	.7	.7	.75	.9	1.05	1.05	1.05	1.0	1.0
Humid, strong wind	1.05	.8	.75	.7	.7	.8	.95	1.1	1.1	1.1	1.05	1.05
Dry, light to mod wind	1.1	.7	.75	.7	.75	.85	1.05	1.2	1.2	1.2	1.15	1.15
Dry, strong wind	1.15	.7	.75	.7	.75	.9	1.1	1.25	1.25	1.25	1.2	1.2

Tropical climates

months following planting:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	.4	.4	.45	.5	.6	.7	.85	1.0	1.1	1.1	.9	.8	.8	.95	1.05
				suckering					shooting				harvesting		

(d) Cacao

Cacao is found in climates with high humidity, high temperature and a well distributed annual rainfall of at least 1 500 mm, unless irrigation is practised. Also, due to its shallow rooting depth, cacao is sensitive to drought and growth has been observed to cease when only two thirds of the available soil water in the root zone are used and yields reduce when half the available soil water is used. For close tree spacing without cover crop and shade trees kc value suggested is 0.9 to 1.0 with shade trees and undergrowth, 1.1 to 1.15.

(e) Citrus

The kc value for citrus, large mature trees, includes different tree ground cover with clean cultivation and no weed control. Since citrus is grown primarily in dry Mediterranean-type climates, only this condition is considered. The effect of wind stronger than moderate is negligible since citrus has good transpiration control. This control or stomatal resistance varies with humidity and temperature, i.e. high resistance under dry and hot conditions and lower resistance under humid and cooler conditions. Therefore the presented kc values may need to be increased by 15 to 20 percent during mid-summer in humid and cooler climates.

For young orchards with a low percentage of tree ground cover, kc values given assume 20 percent and 50 percent tree ground cover. With frequent rain or irrigation, kc values for clean cultivation will approach those of no weed control. Some studies indicate somewhat higher kc values, up to 10-15 percent for grapefruit and lemons compared with those given. Months mentioned refer to northern hemisphere; for southern hemisphere add 6 months.

Table 25 kc Values for Citrus (Grown in Predominantly Dry Areas with Light to Moderate Wind)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Large mature trees providing ≅ 70% tree ground cover												
Clean cultivated	.75	.75	.7	.7	.7	.65	.65	.65	.65	.7	.7	.7
No weed control	.9	.9	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
Trees providing ≅ 50% tree ground cover												
Clean cultivated	.65	.65	.6	.6	.6	.55	.55	.55	.55	.55	.6	.6
No weed control	.9	.9	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
Trees providing ≅ 20% tree ground cover												
Clean cultivated	.55	.55	.5	.5	.5	.45	.45	.45	.45	.45	.5	.5
No weed control	1.0	1.0	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95

(f) Coffee

Two species of coffee provide the bulk of the world's supply. Coffea arabica and Coffea robusta. Only the former is irrigated on a limited scale; much of it is grown at higher altitudes (1 000 - 2 000 m). For mature coffee grown without shade and where cultural practices involve clean cultivation with heavy cut grass mulching, crop coefficients of around 0.9 are recommended throughout the year. If significant weed growth is allowed, coefficients close to 1.05 - 1.1 would be more appropriate.

(g) Dates

The date palm is a drought resistant plant but during prolonged drought growth will be retarded, then cease and old leaves will die. To maintain growth and high yields of good quality a regular water supply is needed throughout the year with a possible exception just prior and during harvest. Water deficiencies during spring and early summer have been shown to hasten ripening but reduce size and quality of fruits. Depending on climate suggested kc values for mature groves are 0.8 - 1.0.

(h) Deciduous fruits and nuts

Values of kc for deciduous fruit and nut crops for cover-crop conditions and clean cultivated are presented in Table 26. Coefficients given relate to full-grown trees with spacings that provide about 70 percent ground cover. Examples are given for both higher latitudes (e.g. northern Europe, northern U.S.A.) with cold winters and growing seasons extending from around 1 May (blossom) to 1 November (killing frosts) and lower latitudes with warm winter conditions (e.g. Mediterranean). In the former, and at altitudes greater than 1 200 m in lower latitude areas, trees have leaves for some 5½ to 6 months, with time of harvest varying from mid-July for cherries to mid-October for late varieties of apples. For lower latitudes near sea level, blossom occurs one month or more earlier with a wide range of harvest dates, starting and ending several weeks earlier for respective species and varieties than at the higher latitude. However, trees generally have leaves longer, e.g. well into November. Months mentioned refer to northern hemisphere; for southern hemisphere add 6 months.

Table 26

kc Values for Full Grown Deciduous Fruit and Nut Trees

	With ground cover crop [1]									Without ground cover crop [2] (clean cultivated, weed free)								
	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov
COLD WINTER WITH KILLING FROST : GROUND COVER STARTING IN APRIL																		
Apples, cherries																		
humid, light to mod. wind	-	.5	.75	1.0	1.1	1.1	1.1	.85	-	-	.45	.55	.75	.85	.85	.8	.6	-
humid, strong wind	-	.5	.75	1.1	1.2	1.2	1.15	.9	-	-	.45	.55	.8	.9	.9	.85	.65	-
dry, light to mod. wind	-	.45	.85	1.15	1.25	1.25	1.2	.95	-	-	.4	.6	.85	1.0	1.0	.95	.7	-
dry, strong wind	-	.45	.85	1.2	1.35	1.35	1.25	1.0	-	-	.4	.65	.9	1.05	1.05	1.0	.75	-
Peaches, apricots, pears, plums																		
humid, light to mod. wind	-	.5	.7	.9	1.0	1.0	.95	.75	-	-	.45	.5	.65	.75	.75	.7	.55	-
humid, strong wind	-	.5	.7	1.0	1.05	1.1	1.0	.8	-	-	.45	.55	.7	.8	.8	.75	.6	-
dry, light to mod. wind	-	.45	.8	1.05	1.15	1.15	1.1	.85	-	-	.4	.55	.75	.9	.9	.7	.65	-
dry, strong wind	-	.45	.8	1.1	1.2	1.2	1.15	.9	-	-	.4	.6	.8	.95	.95	.9	.65	-
COLD WINTER WITH LIGHT FROST : NO DORMANCY IN GRASS COVER CROPS																		
Apples, cherries, walnuts [3]																		
humid, light to mod. wind	.8	.9	1.0	1.1	1.1	1.1	1.05	.85	.8	.6	.7	.8	.85	.85	.8	.8	.75	.65
humid, strong wind	.8	.95	1.1	1.15	1.2	1.2	1.15	.9	.8	.6	.75	.85	.9	.9	.85	.8	.8	.7
dry, light to mod. wind	.85	1.0	1.15	1.25	1.25	1.25	1.2	.95	.85	.5	.75	.95	1.0	1.0	.95	.9	.85	.7
dry, strong wind	.85	1.05	1.2	1.35	1.35	1.35	1.25	1.0	.85	.5	.8	1.0	1.05	1.05	1.0	.95	.9	.75
Peaches, apricots, pears, plums, almonds, pecans																		
humid, light to mod. wind	.8	.85	.9	1.0	1.0	1.0	.95	.8	.8	.55	.7	.75	.8	.8	.7	.7	.65	.55
humid, strong wind	.8	.9	.95	1.0	1.1	1.1	1.0	.85	.8	.55	.7	.75	.8	.8	.8	.75	.7	.6
dry, light to mod. wind	.85	.95	1.05	1.15	1.15	1.15	1.1	.9	.85	.5	.7	.85	.9	.9	.9	.8	.75	.65
dry, strong wind	.85	1.0	1.1	1.2	1.2	1.2	1.15	.95	.85	.5	.75	.9	.95	.95	.95	.85	.8	.7

[1] kc values need to be increased if frequent rain occurs (see Fig. 6 for adjustment). For young orchards with tree ground cover of 20 and 50%, reduce mid-season kc values by 10 to 15% and 5 to 10% respectively.

[2] kc values assume infrequent wetting by irrigation or rain (every 2 to 4 weeks). In the case of frequent irrigation for March, April and November adjust using Fig. 6 ; for May to October use kc values of table "with ground cover crop". For young orchards with tree ground cover of 20 and 50% reduce mid-season kc values by 25 to 35% and 10 to 15% respectively.

[3] For walnuts March-May possibly 10 to 20% lower values due to slower leaf growth.

(i) Grapes

The kc values for grapes will vary considerably with cultural practices such as vine and row spacing, pruning, trellising height and span, and with extreme varietal differences in vine growth. Grapes, normally clean cultivated, use less water than many other crops due to cultural practices resulting in only 30 to 50 percent ground cover. Also there may be a somewhat greater degree of stomatal control of transpiration compared to many other crops.

In Table 27 the kc values for grapes are presented for cold winter, light winter and hot, dry summer climatic conditions. For areas with cold winters, kc values for Concord grapes are used, a variety which develops a somewhat greater degree of ground cover than that used for light winter and hot, dry summer conditions. It is, however, quite common to plant a ground cover in August to help deplete available nitrogen and to provide better winter hardiness.

In the last two cases kc values need to be reduced when ground cover is less than 35 percent. For all cases infrequent irrigation and dry soil surface during most of the time are assumed. Data refer to conditions without cover crop, e.g. clean cultivated, weed free. Months mentioned in Table 27 refer to northern hemisphere; for southern hemisphere add 6 months.

Table 27 kc Values for Grapes (Clean Cultivated, Infrequent Irrigation, Soil Surface Dry Most of the Time)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Mature grapes grown in areas with killing frost; initial leaves early May, harvest mid-September; ground cover 40-50% at mid-season												
humid, light to mod. wind	-	-	-	-	.5	.65	.75	.8	.75	.65	-	-
humid, strong wind	-	-	-	-	.5	.7	.8	.85	.8	.7	-	-
dry, light to mod. wind	-	-	-	-	.45	.7	.85	.9	.85	.7	-	-
dry, strong wind	-	-	-	-	.5	.75	.9	.95	.9	.75	-	-
Mature grapes in areas of only light frosts; initial leaves early April, harvest late August to early September; ground cover 30-35% at mid-season												
humid, light to mod. wind	-	-	-	.5	.55	.6	.6	.6	.6	.5	.4	-
humid, strong wind	-	-	-	.5	.55	.65	.65	.65	.65	.55	.4	-
dry, light to mod. wind	-	-	-	.45	.6	.7	.7	.7	.7	.6	.35	-
dry, strong wind	-	-	-	.45	.65	.75	.75	.75	.75	.65	.35	-
Mature grapes grown in hot dry areas; initial leaves late February-early March, harvest late half of July; ground cover 30-35% at mid-season												
dry, light to mod. wind	-	-	.25	.45	.6	.7	.7	.65	.55	.45	.35	-
dry, strong wind	-	-	.25	.45	.65	.75	.75	.7	.55	.45	.35	-

(j) Olives

The olive tree is particularly resistant to drought but prolonged drought negatively affects yields. Table olive production requires somewhat more water than olive production for oil. While olive orchards can be found in areas of little more than 200 mm they are most common in areas with 400 to 600 mm annual precipitation. Drought is most damaging on yields during the stone hardening and fruit swelling stage which occurs in the Mediterranean area during August-September. One or two irrigations of total 2 000 to 4 000 m^3/ha at this time have shown increase in yields considerably. Another critical period is just before fruit setting. For mature trees and depending on tree spacing and age of trees, kc values vary from 0.4 - 0.7.

(k) Rice

For paddy rice kc values are given in Table 28 for different geographical locations and seasons. Wind conditions and, during the dry season, the relative humidity may be important; where during the dry season the minimum relative humidity is more than 70 percent, the kc values given for the wet season should be used.

No difference is assumed in kc values between broadcast or sown and transplanted rice since percentage cover during first month after transplantation is little different from that of broadcast rice. There are differences in growing season according to variety; therefore the length of mid-season growth period will need adjustment. Local information on length of growing season will need to be collected.

For upland rice, the same coefficients given for paddy rice will apply since recommended practices involve the maintenance of top soil layers very close to saturation. Only during initial crop stage will kc need to be reduced by 15 to 20 percent.

Table 28 kc Values for Rice

	Planting	Harvest	First & Second month	Mid-season	Last 4 weeks
Humid Asia					
wet season (monsoon)	June-July	Nov-Dec			
light to mod. wind			1.1	1.05	.95
strong wind			1.15	1.1	1.0
dry season 1/	Dec - Jan	mid -May			
light to mod. wind			1.1	1.25	1.0
strong wind			1.15	1.35	1.05
North Australia					
wet season	Dec - Jan	Apr -May			
light to mod. wind			1.1	1.05	.95
strong wind			1.15	1.1	1.0
South Australia					
dry summer	Oct	March			
light to mod. wind			1.1	1.25	1.0
strong wind			1.15	1.35	1.05
Humid S. America					
wet season	Nov-Dec	Apr - May			
light to mod. wind			1.1	1.05	.95
strong wind			1.15	1.1	1.0
Europe (Spain, S. France and Italy)					
dry season	May-June	Sept-Oct			
light to mod. wind			1.1	1.2	.95
strong wind			1.15	1.3	1.0
U.S.A.					
wet summer (south)	May	Sept-Oct			
light to mod. wind			1.1	1.1	.95
strong wind			1.15	1.15	1.0
dry summer (Calif.)	early May	early Oct			
light to mod. wind			1.1	1.25	1.0
strong wind			1.15	1.35	1.05

1/ Only when RHmin > 70%, kc values for wet season are to be used.

(l) Sisal

Sisal requires relatively small amounts of water and excess water will negatively affect yield. The suggested kc value is perhaps 0.3 - 0.4.

(m) Sugarcane

Crop coefficients for sugarcane may vary considerably depending on climate and cane variety, particularly for initial and crop development stages. Also early crop development varies according to whether it is virgin or a ratoon crop. Total length of growing season varies with climate and according to whether the crop is virgin or ratoon. For virgin plantings this may range from 13 to 14 months in hot Iran to 16 months in Mauritius and up to 20 to 24 months in some cases in Hawaii. Ratoon crop season varies from as short as 9 months in Iran to 12 months in Mauritius and up to 14 months in other areas.

To determine kc values, use of local data or information on rate of crop development for a given cane variety is essential. Data provided refer to a 12 month ratoon crop and to a 24 month virgin cane. Irrigation application usually ceases 4 to 6 weeks before harvest.

Table 29 kc Values for Sugarcane

Crop age		Growth stages	RHmin > 70%		RHmin < 20%	
12 month	24 month		light to mod. wind	strong wind	light to mod. wind	strong wind
0 - 1	0 - 2.5	planting to 0.25 full canopy	.55	.6	.4	.45
1 - 2	2.5 - 3.5	0.25-0.5 full canopy	.8	.85	.75	.8
2 - 2.5	3.5 - 4.5	0.5-0.75 full canopy	.9	.95	.95	1.0
2.5 - 4	4.5 - 6	0.75 to full canopy	1.0	1.1	1.1	1.2
4 - 10	6 - 17	peak use	1.05	1.15	1.25	1.3
10 - 11	17 - 22	early senescence	.8	.85	.95	1.05
11 - 12	22 - 24	ripening	.6	.65	.7	.75

(n) Tea

The water requirement of tea bushes in full production can be assumed to be close to ETo. Hence, crop coefficients of around 0.95 to 1.0 are suggested for non-shaded plantations where more than 70 percent ground cover exists. Where grown under shade trees, kc values of 1.05 - 1.1 would be more appropriate for more humid periods, and perhaps 1.1 - 1.15 for dry periods.

(o) Non-cropped or bare soils

To determine the water balance, particularly after winter rains, estimation of evaporation losses from the soil surface (Esoil) is needed. This will assist, for instance, in the determination of the first irrigation application on a wheat crop sown in March-April following winter rains. Esoil will be greatly affected by the water content of the soil surface, frequency and depth of rain, type of soil and level of evaporative demand. To determine the coefficient, Figure 6 should be used; the prediction of Esoil closely follows the method shown for field crops, initial stage. Data presented in Figure 7 assume a medium textured soil. For light and heavy-textured soils kc values may need a downward adjustment by some 30 percent and upward by some 15 percent respectively.

EXAMPLE: Estimation of Esoil from fallow, essentially weed-free soil.
Given:
Cairo; ETo as given and obtained from Penman Method (1.3); fictitious rainfall data on frequency.
Calculation:
From ETo in mm/day and data on frequency of rainfall, select kc value from Figure 6.

	Nov	Dec	Jan	Feb	Mar	
ETo mm/day	3.2	2.3	2.7	3.8	5.0	Method 1.3
Frequency of rain, days	7	7	5	7	10	Data
k factor	.6	.65	.7	.55	.3	Fig. 6
Esoil mm/day = k .ETo	1.9	1.5	1.9	2.1	1.5	Calc.

(p) Aquatic weeds and open water

Evapotranspiration of floating and flat leafed aquatic weeds is very similar to that of grass. Protruding types have a slightly higher rate due to increased roughness, particularly under dry and windy conditions. Reeds such as papyrus and cattails appear to have lower values caused primarily by the plant characteristics affecting evapotranspiration. Under non-flooding conditions and in drying soils ETreeds can be expected to be considerably lower. In the case of fully submerged weeds the water loss can be taken to be equal to that of open water evaporation. In Table 30 the kc values for different aquatic weeds for various climatic conditions are given.

Water loss by evapotranspiration of aquatic weeds is frequently compared to evaporation of an open water surface (Eo). Studies carried out under natural conditions show that when the water surface is covered by aquatic weeds the water loss into the atmosphere will be lower than that from a free water surface. This is due to a combination of the sheltering of the water surface by the weeds and a higher reflectance of the green plants and their internal resistance to transpiration. The conflicting data found in literature which show ETaquatic weeds to be far greater than Eo may be related to small lysimeter and pan experiments carried out on land surfaces which are not representative of the natural conditions under which aquatic weeds grow.

Coefficients relating open water evaporation Eo to reference crop evapotranspiration (ETo) are presented in Table 30. These values apply to shallow reservoirs and lakes with depths of less than 5 m and can be used to compute monthly Eo, once monthly ETo has been determined. The presented values apply equally to deep reservoirs and lakes in equatorial zones. For areas with a change in climate during the year, the given coefficients should be used only for computing yearly evaporation losses. Deep water bodies have an appreciable heat storage which will cause a time-lag in evaporation of 4 to 8 weeks depending on the type of climate and size and depth of the water body. For reservoirs and lakes with a depth exceeding 25 m, due to heat storage the k values during spring and early summer may be 20 to 30 percent lower; due to heat release during late summer and early autumn k values may be 20 to 30 percent higher.

Table 30 kc Values for Aquatic Weeds and Coefficients for Open Water

Type of vegetation	Humid		Dry	
	light to mod. wind	strong wind	light to mod. wind	strong wind
Submerged (crassipes)	1.1	1.15	1.15	1.2
Floating (duckweed)	1.05	1.05	1.05	1.05
Flat leaf (water lilies)	1.05	1.1	1.05	1.1
Protruding (water hyacinth)	1.1	1.15	1.15	1.2
Reed swamp (papyrus, cattails)				
standing water	.85	.85	.9	.95
moist soil	.65	.65	.75	.8
Open water	1.1	1.15	1.15	1.2

3. FACTORS AFFECTING ETcrop

ETcrop obtained by the methods discussed earlier refers to evapotranspiration of a disease-free crop, grown in very large fields, not short of water and fertilizers. Actual ETcrop will depend on local factors which are not covered in the presented methods. Additional considerations are therefore given; their practical significance in determining field irrigation supply and scheduling is included in Part II.

The example used in earlier chapters on methods calculating ETcrop is applied to illustrate the effect of local conditions. As already shown, ETcrop included the effect of climate on crop water requirements as mean value of ETo in mm/day for the different months and the effect of crop characteristics as kc or ETcrop = kc . ETo.

EXAMPLE:

Given:

Cairo; maize sown in mid-May; growing season 125 days till mid-September.

Calculation:

	May	June	July	Aug	Sept	
ETo mm/month	(1/2)276	282	273	236	(1/2)183	Method 1.3
kc	0.35	0.6	1.14	1.08	0.75	Fig. 7
ETmaize mm/month	50	170	310	255	70	

3.1 CLIMATE

Variation with Time

It is common practice to use mean climatic data for determining mean ETcrop. However, due to weather changes, ETcrop will vary from year to year and for each period within the year. Annual ETcrop will vary some 10 percent for humid tropics up to some 25 percent for mid-continental climates.

From year to year, the monthly values show greater variation. For instance, in mid-latitude climates radiation for a given month can show extreme variations. In areas having distinct dry and wet seasons, the transition month shows significant differences from year to year depending on rains arriving early or late. Monthly ETcrop values can vary from one year to the next by 50 percent or more.

Daily values can vary drastically, with low values on days that are rainy, cloudy, humid and calm and with high values on dry, sunny and windy days. The range of daily, 10-day and monthly ETcrop that can occur is given in Figure 9. This variation will obviously be obscured when using mean climatic data to obtain mean ETcrop.

In selecting ETcrop for project planning and design, knowledge should be obtained on level and frequency at which high demands for water can be expected, particularly in the months of peak water use. To obtain for each month a measure of the probable range of crop water demands and to allow an assessment of the tolerable risk of meeting such demands with the selected irrigation supply, monthly ETcrop should be calculated for each year of climatic record. When sufficiently long climatic records are available (10 years or more) a frequency analysis can be made similar to

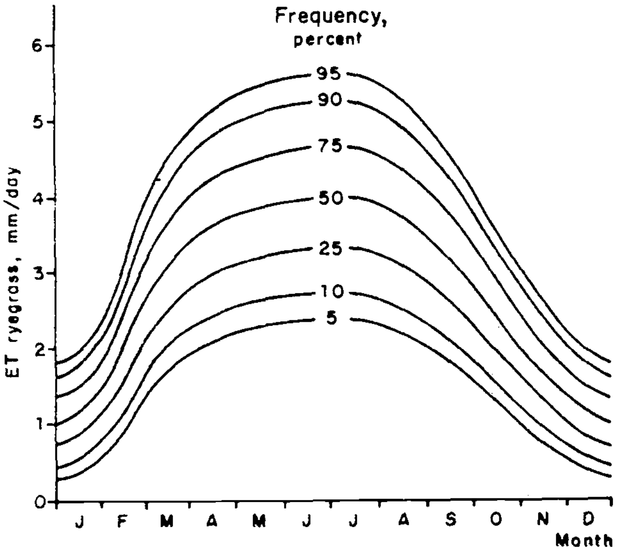
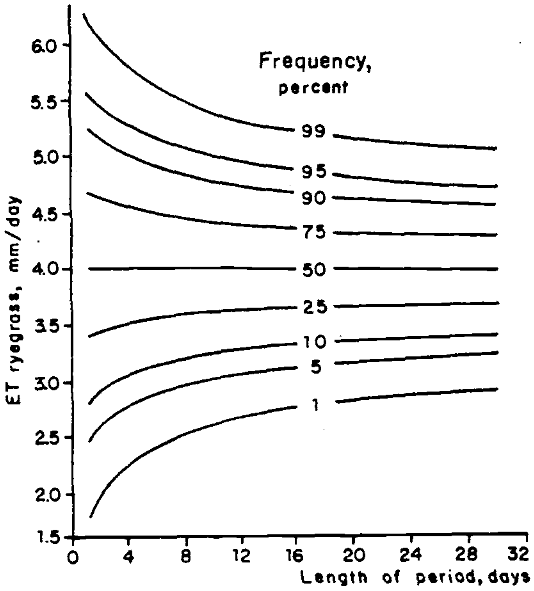


Fig. 9 Freauency distribution of mean daily ETryegrass for each month in coastal California Valley (Nixon et al., 1972)



Frequency distribution of 1 to 30 day mean ETryegrass during peak period June-July (Nixon et al., 1972)

that given for rainfall (Part II). The value of ETcrop selected for design can then be based on a probability of 75 or 80 percent or highest ETcrop value out of 4 or 5 years. Using Figure 9, rather than taking for July mean ETcrop = 4 mm/day or 124 mm/month, for planning and design purposes 4.8 mm/day (150 mm/month) would be selected, and so on for other months.

A first estimate of meeting ETcrop three out of four years but still using mean ETcrop data can also be obtained using Figure 10. Degree of weather variations for different types of climate is important. However, available soil water has a balancing effect in meeting short duration, high ETcrop values; this effect is smaller for shallow, light soils than for deep, fine textured soils. Available soil water should therefore be considered. This calculation is usually done for months of peak water use.

EXAMPLE:

Given:

Cairo; arid climate with clear weather conditions during months of peak water use. Medium soils with available soil water following irrigation of 60 mm. Crop is maize.

Calculation:

	May	June	July	Aug	Sept	
ETmaize mm/day	3.1	5.6	10.0	8.2	4.6	
correction peak ETcrop	-	-	1.1	1.1	-	Fig. 10
ETmaize mm/day	3.1	5.6	11.0	9.0	4.6	

Variation with Distance

In calculating ETcrop, by necessity climatic data are sometimes used from stations located some distance away from the area under study. This is permissible in areas where the same weather extends for long distances. Zones with rapid changes in climate over short distances frequently

1. Arid and semi-arid climates and those with predominantly clear weather conditions during month of peak ETcrop.
2. Mid-continental climates and sub-humid to humid climates with highly variable cloudiness in month of peak ETcrop.
3. and 4. Mid-continental climates with variable cloudiness and meanETcrop of 5 and 10 mm/day respectively.

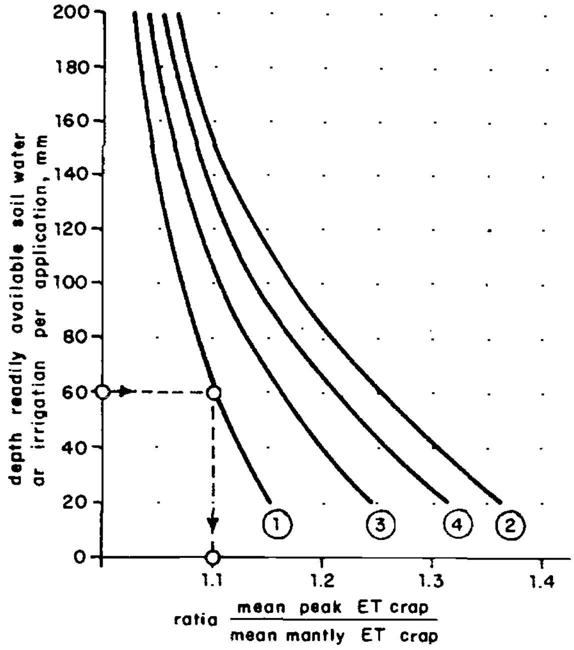


Fig. 10 Ratio peak and mean ETcrop for different climates during month of peak water use

occur, for instance in arid areas inland from large lakes (at Lake Nassar Epan only 250 m from the shore is up to double Epan at the shoreline) and where an airmass is forced upward by mountain ranges. With the change in weather over distance consequently ETcrop may change markedly over small distances, as is shown for California in Figure 11.

A check needs to be made on whether climatic data used from distant stations are representative for the area of study. No generalized guidance can be given on use of data from distant stations; where available use should be made of climatic surveys already carried out.

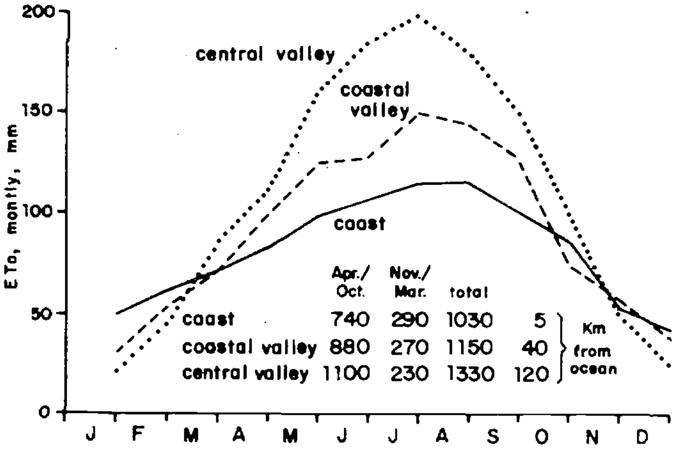


Fig. 11 Change in ETo with distance from ocean, California (State of California Bulletin 113-2, 1967)

Variation with Size of Irrigation Development, Advection

Meteorological data used are often collected prior to irrigation development in stations located in rainfed or uncultivated areas, or even on rooftops and airports. Irrigated fields will produce a different micro-climate and ETcrop may not be equal to predicted values based on these data. This is more pronounced for large schemes in arid, windy climates.

In arid and semi-arid climates, irrigated fields surrounded by extensive dry fallow areas are subject to advection. Airmass moving into the irrigated fields gives up heat as it passes over. This results in a 'clothesline' effect at the upwind edge and an 'oasis' effect inside the irrigated field. With warm, dry winds, appreciably higher ETcrop can be expected at the upwind edge of the field. With increased distance the air becomes cooler and more humid. The 'clothesline' effect

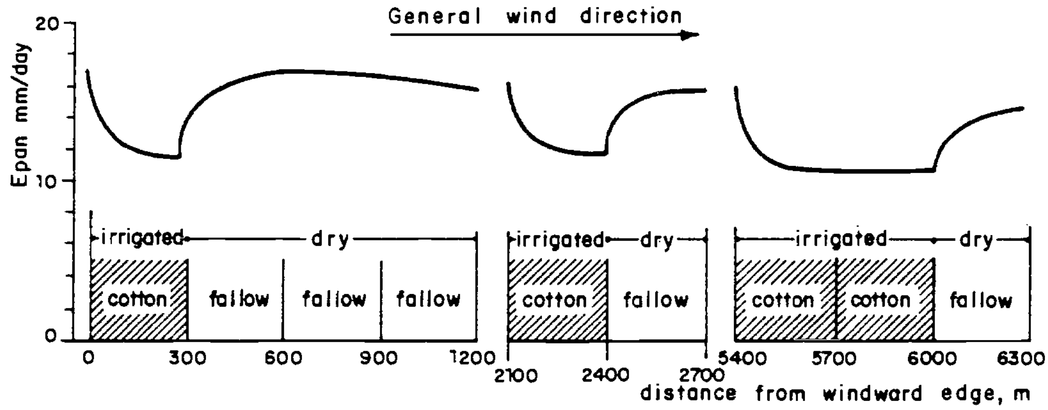


Fig. 12
Change in Epan (Hudson) for cross-section over cotton and fallow fields in Sudan (Hudson, 1964)

becomes negligible with distance from the border which may extend in hot, dry climates for 100 to 400 m for windspeed greater than 5 m/sec. It follows that due to the 'clothesline' effect results of irrigation trials conducted on a patchwork of small fields and located in dry surroundings may show up to double ETcrop as compared to that of future large schemes. Caution should be used when extrapolating such results to large future projects.

Due to the 'oasis' effect, ETcrop will be higher in fields surrounded by dry fallow land as compared to surrounded by extensive vegetated area. However, air temperature is generally lower and humidity higher inside the large irrigated schemes as compared to outside the scheme. Therefore, when ETcrop is predicted using climatic data collected outside, or prior to irrigation development, in semi-arid and arid areas, ETcrop could be over-predicted by 5 to 15 percent for fields of 5 to 20 hectares and 10 to 25 percent for large schemes with cropping density close to 100 percent. The main cause of this difference in over-prediction due to cropping density is the distribution in fallow and cropped fields; above the fallow fields the air is heated and also becomes drier before moving into the next field. This is shown in Figure 12 presenting Epan(small Hudson type) for a given cross-section over irrigated cotton and fallow fields in the Gezira scheme, Sudan.

Using climatic data collected outside or prior to irrigation development, Figure 13 suggests the correction factors needed to obtain ETcrop for irrigated fields of different sizes located in dry fallow surrounds in arid, hot conditions with moderate wind. Factors should not be applied to very small fields ($<$0.05 ha) since the correction on ETcrop could be large enough to result in wilting of the crop and stunting of growth.

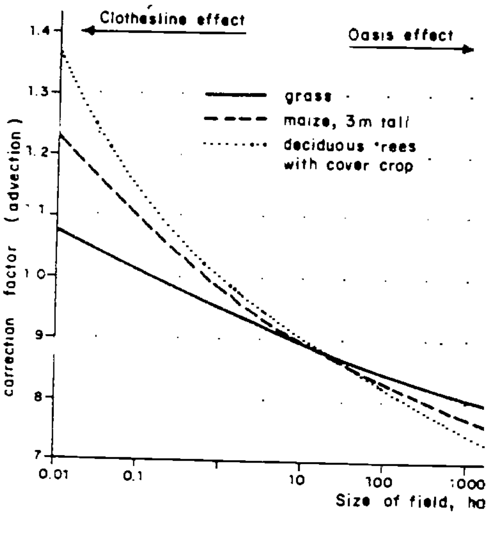


Fig. 13 Correction factor for ETcrop when determined using climatic data collected outside or prior to irrigation development, for different sizes of irrigated fields under arid and moderate wind conditions

EXAMPLE:

Given:

Maize grown in fields of 10 ha with cropping density of some 50 percent; climatic data collected prior to irrigation development.

Calculation:

	May	June	July	Aug	Sept	
ETmaize	3.1	5.6	11.0	8.2	4.6	
correction advection	-	0.9	0.9	0.9	-	Fig. 13
ETmaize mm/day	3.1	5.0	9.9	7.4	4.6	

Variation with Altitude

In a given climatic zone ETcrop will vary with altitude. This is not caused by difference in altitude as such but mainly by associated changes in temperature, humidity and wind. Also radiation at high altitudes may be different to that in low lying areas. Use of presented ETcrop methods will remain problematic for high altitude areas with possible exceptions of Penman and Pan methods with data collected at site. As given earlier, for the Blaney-Criddle method, ETo may be adjusted by 10 percent for each 1 000 m altitude change above sea level.

3.2 SOIL WATER

Published data on depth over which the crop extracts most of its water show great differences. With salt-free soil water in ample supply, water uptake for most field crops has been expressed as 40 percent of total water uptake over the first one-fourth of total rooting depth, 30 percent over the second one-fourth, 20 percent over the third and 10 percent over the last. However, movement of soil water will take place inside and to the rootzone when portions become dry. Also water can be supplied to the roots from shallow groundwater. If plants are sufficiently anchored and there are proper growing conditions, including available water and nutrient, soil aeration, soil temperature and soil structure, the crop is not affected even when rooting depth is severely restricted. Water management practices should be adjusted accordingly.

Level of Available Soil Water

The methods presented on ETcrop assume soil water in ample supply. After irrigation or rain, the soil water content will be reduced primarily by evapotranspiration. As the soil dries, the rate of water transmitted through the soil will reduce. When at some stage the rate of flow falls below the rate needed to meet ETcrop, ETcrop will fall below its predicted level. The effect of soil water content on evapotranspiration varies with crop and is conditioned primarily by type of soils and water holding characteristics, crop rooting characteristics and the meteorological factors determining the level of transpiration. With moderate evaporative conditions whereby ETcrop does not exceed 5 mm/day, for most field crops ETcrop is likely to be little affected at soil water tensions up to one atmosphere (corresponding approximately to 30 volume percentage of available soil water for clay, 40 for loam, 50 for sandy loam and 60 for loamy sand). When evaporative conditions are lower the crop may transpire at the predicted ET rate even though available soil water depletion is greater; when higher, ETcrop will be reduced if the rate of water supply to the roots is unable to cope with transpiration losses. This will be more pronounced in heavy textured than in light textured soils.

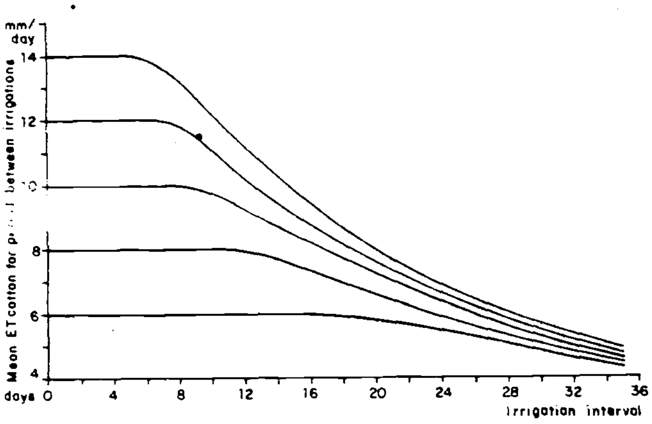


Fig. 14 Mean actual ETcotton over the irrigation interval for different durations of irrigation interval and for different ETcotton levels (Rijtema and Aboukhaled, 1975)

Since reduction in evapotranspiration affects crop growth and/or crop yields, timing and magnitude of reduction in ETcrop are important criteria for irrigation practices. Following an irrigation the crop will transpire at the predicted rate during the days immediately following irrigation. With time the soils become drier and the rate will decrease, more so under high as compared to low evaporative conditions. This is shown in Figure 14 for cotton grown in Egypt on a fine textured soil. Whether or not the reduction in ETcrop is permissible during part or whole growing season can be determined only when the effect of soil water stress on yield during various stages of growth is known.

In planning and design, the predicted ETcrop values should be applied unless specific objectives are pursued such as assuring that the greatest number of farmers benefit from irrigation or maximising yield per unit of water when available water supply is the limiting factor.

Groundwater

For most crops, growth and consequently ETcrop will be affected when groundwater is shallow or the soil is waterlogged. In spring in cooler climates, wet soils warm up slowly, causing delay in seed germination and plant development; land preparation may be delayed, resulting in later planting. Consequently, different ETcrop values apply during the remainder of the season. The tolerance of some crops to shallow groundwater tables and waterlogging is given in Table 31.

Table 31 Tolerance Levels of Crops to High Groundwater Tables and Waterlogging

	Groundwater at 50 cm	Waterlogging
High tolerance	sugarcane, potatoes, broad beans	rice, willow, strawberries, various grasses, plums
Medium tolerance	sugarbeet, wheat, barley, oats, peas, cotton	citrus, bananas, apples, pears, blackberries, onions
Sensitive	maize, tobacco	peaches, cherries, date palms, olives, peas, beans

Source: Irrigation, Drainage and Salinity. An International Source Book. FAO/Unesco, 1973.

Higher groundwater tables are generally permitted in sandy rather than loam and clay soils due to the difference in capillary fringe above the groundwater table. For most crops minimum depth of groundwater table required for maximum yield has been expressed as: for sand, rooting depth + 20 cm; for clay, rooting depth + 40 cm; for loam, rooting depth + 80 cm. No correction on ETcrop will be required.

Salinity

ETcrop can be affected by soil salinity since the soil water uptake by the plant can be drastically reduced due to higher osmotic potential of the saline groundwater. Poor crop growth may be due to adverse physical characteristics of some saline soils. Some salts cause toxicity and affect growth. The relative extent to which each of these factors affect ETcrop cannot be distinguished. [1]

Reduced water uptake under saline conditions is shown by symptoms similar to those caused by drought, such as early wilting, leaf burning, a bluish-green colour in some plants, reduced growth and small leaves. The same level of soil salinity can cause more damage under high than under low evaporative conditions. The negative effect of soil salinity can be partly offset by maintaining a high soil water level in the rootzone, and unless crop growth is impeded, predicted ETcrop values will apply. (For leaching requirements, see Part II, 1.2.3.)

Water and Crop Yields

For many crops ETcrop has shown a direct relationship with dry matter production when, except for water, the growth factors such as fertility, temperature, sunshine and soil are not limiting. Different relationships apply to crop species; under similar conditions to obtain the same dry matter yield ETalfalfa may need four times the amount of water than that for sorghum, and twice that for wheat. Also climate has a pronounced effect, as is shown in Figure 15 for dry matter yield of grass.

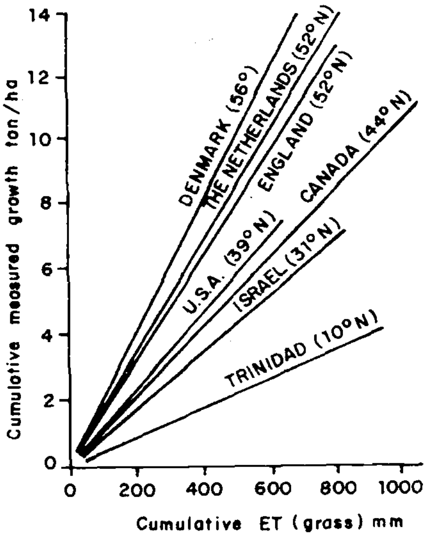


Fig. 15 Relation between ETgrass and dry matter production from pastures at different latitudes (Stanhill, 1960)

Where yields are either the chemical product (sugar, oil) or the reproductive part (grain, apples) of the plant, varietal characteristics are pronounced. With the same ETcrop, yield of high yielding rice varieties can be four times that of the traditional varieties under good water management and timely supply of inputs. However, for adaptive varieties recent concepts show that the ratio of relative harvested yield to relative ETcrop may be nearly constant when growth factors other than water are not limiting (Stewart and Hagan, 1973, 1974). This is shown in Figure 16 for 14 non-forage crops where the envelope curve represents some 90 percent of data drawn from various sources. The scatter found in Figure 16 is caused by many factors including timing and duration of soil water shortages.

The effect of timing and duration of water shortage on some crops is very pronounced during certain periods of growth; Figure 16(2) shows that for maize yields are negligible when ET is severely restricted during the tasselling stage; Figure 16(3) shows that prolonged reduction in

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[1] Westcot, D.W. and Ayers, R.S. Water quality for agriculture. Irrigation and Drainage Paper No. 29. FAO Rome, Italy. 1976.

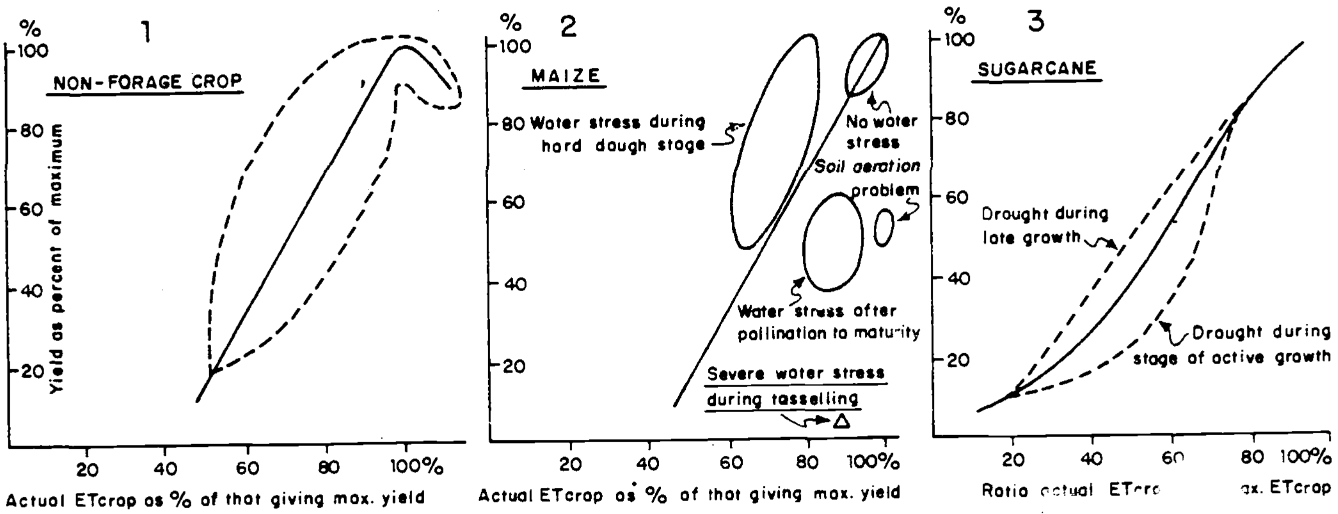


Fig. 16 Relationships between relative yield and relative ETcrop for non-for nd virgin cane (Downey, 1972; Chang, 1963)

ETsugarcane during the period of active growth has a much greater negative effect on yield than when experienced during late growth. Reduction in ETcrop is particularly critical when the crop i sensitive to soil water stress and could drastically affect yields. Sensitive stages for some crops are given in Table 32. However, slight, timely ET reduction by withholding water may have a positive effect on yields such as improved quality in apples, peaches and plums, aromatic quality of tobacco, oil content of olives and sugar content in sugarcane. Without a scheduled water shortage for cotton vegetative growth will continue while yield of fibre will be greatly reduced. A comprehensive review of yield response to water during different stages of crop growth is given in the references quoted. 1/

3.3 METHOD OF IRRIGATION

ETcrop is affected little by the method of irrigation if the system is properly designed, installed and operated. The advantages of one method over another are therefore not determined by differences in total irrigation water supplied but by the adequacy and effectiveness with which crop requirements can be met.

Different methods imply different rates of water application. When comparing the various methods in terms of water efficiency in meeting crop demand such differences should be recognized; the apparent superiority of one method over another may be merely the result of too much or too little water being applied. There may be no fault in the actual method of irrigation, only in the management.

1/ Slatyer, R.O. Plant-water relationships. Academic Press, 1967.
Hagan, R.M., Haise, H.R. and Edminster, T.W. Irrigation of Agricultural Lands, ASA No. 11.
Kozlowski, T.T. Water Deficits and Plant Growth I, II and III. Academic Press, 1968.
Salter, P.J. and Goode, J.E. Crop Responses to Water at Different Stages of Growth. Commonwealth Agricultural Bureau, 1967.
Vaadia, Y.F. et al. Plant Water Deficits and Physiological Processes. American Review of Plant Physiology. 12:265-292, 1961.
de Wit, C.T. Transpiration and crop yields, Verslagen Lanbk. Onderz. 64.6. 1958.

Table 32 Critical Periods for Soil Water Stress for Different Crops

Alfalfa	just after cutting for hay and at the start of flowering for seed production
Apricots	period of flower and bud development
Barley	early boot stage > soft dough stage > onset of tillering or ripening stage
Beans	flowering and pod setting period > earlier > ripening period. However, ripening period > earlier if not prior water stress.
Broccoli	during head formation and enlargement
Cabbage	during head formation and enlargement
Castor bean	requires relatively high soil water level during full growing period
Cauliflower	requires frequent irrigation from planting to harvesting
Cherries	period of rapid growth of fruit prior to maturing
Citrus	flowering and fruit setting stages; heavy flowering may be induced by withholding irrigation just before flowering stage (lemon); "June drop" of weaker fruits may be controlled by high soil water levels
Cotton	flowering and boll formation > early stages of growth > after boll formation
Groundnuts	flowering and seed development stages > between germination and flowering and end of growing season
Lettuce	requires wet soil particularly before harvest
Maize	pollination period from tasselling to blister kernel stages > prior to tasselling > grain filling periods; pollination period very critical if no prior water stress
Oats	beginning of ear emergence possibly up to heading
Olives	just before flowering and during fruit enlargement
Peaches	period of rapid fruit growth prior to maturity
Peas	at start of flowering and when pods are swelling
Potatoes	high soil water levels; after formation of tubers, blossom to harvest
Radish	during period of root enlargement
Sunflower	possibly during seeding and flowering - seed development stage
Small grains	boot to heading stage
Sorghum	secondary rooting and tillering to boot stage > heading, flowering and grain formation > grain filling period
Soybeans	flowering and fruiting stage and possibly period of maximum vegetative growth
Strawberries	fruit development to ripening
Sugarbeet	3 to 4 weeks after emergence
Sugarcane	period of maximum vegetative growth
Tobacco	knee high to blossoming
Tomatoes	when flowers are formed and fruits are rapidly enlarging
Turnips	when size of edible root increases rapidly up to harvesting
Water melon	blossom to harvesting
Wheat	possibly during booting and heading and two weeks before pollination

A number of practices thought to affect ETcrop are mentioned briefly below:

Surface Irrigation

Reducing the area wetted by alternate furrow irrigation generally has little effect on ETcrop. The positive effect on crop growth sometimes noticed should be ascribed to other factors such as better soil aeration. Reduction in evaporation from the soil surface is obtained in the case of incomplete crop cover (less than 60 percent) and/or by wetting only a relatively small area (less than 30 percent). This latter is practised in orchards and vineyards by irrigating near the trunks; the net reduction in seasonal ETcrop will in general not be more than 5 percent.

Sprinkler Irrigation

Transpiration by the crop may be greatly reduced during application but will be compensated by increased evaporation from the wet leaves and soil surface. The combined effects do not greatly exceed predicted ETcrop. The effects of under-tree sprinkling on water savings are unlikely to be very great. With above-tree canopy sprinkling the micro-climate can change considerably but is, however, relatively short lived and little effect on ETcrop will be observed except possibly for centre-pivot systems with daily water application.

Evaporation losses from the spray are small and generally below 2 percent. Losses due to wind drift may be considerable at higher wind speeds and can reach 15 percent at 5 m/sec. Strong winds also result in a poor water distribution pattern. Sprinkler irrigation should not normally be used when windspeeds are over 5 m/sec.

Drip or Trickle Irrigation

A well operated drip system allowing frequent application of small quantities of water can provide a nearly constant low tension soil water condition in the major portion of the rootzone. The high water use efficiency can be attributed to improved water conveyance and water distribution to the rootzone. ETcrop with near or full ground cover is not affected unless under-irrigation is practised. Only with widely spaced crops and young orchards will ETcrop be reduced since evaporation will be restricted to the area kept moist. For young orchards with 30 percent ground cover on light, sandy soils and under high evaporation conditions requiring very frequent irrigations, a reduction in ETcrop of up to possibly 60 percent has been observed. This reduction would be considerably lower for medium to heavy textured soils under low evaporative conditions requiring much less frequent irrigation. For closely spaced crops under drip irrigation the crop water requirements can be predicted using the methods described.

Subsurface Irrigation

With a subsurface water distribution system, depending on the adequacy of the water supply through upward water movement to the rootzone, ETcrop should be little affected except for the early stage of growth of some crops when frequent irrigation is required.

3.4 CULTURAL PRACTICES

Fertilizers

The use of fertilizers has only a slight effect on ETcrop, unless crop growth was previously adversely affected by low soil nutrition delaying full crop cover. Irrigation imposes a greater demand on fertilizer nutrients; adequately fertilized soils produce much higher yields per unit of irrigation water than do poor soils, provided the fertilizer is at the level in the soil profile where soil water is extracted by the plant. The movement of soluble nutrients and their availability to the crop is highly dependent on method and frequency of irrigation.

Plant Population

The effect of plant population or plant density on ETcrop is similar to that of percentage of ground cover. When top soils are kept relatively dry, evaporation from the soil surface is sharply reduced and ETcrop will be less for low population crops than for high population crops. During the early stages of the crop a high population planting would normally require somewhat more water than low density planting due to quicker development of full ground cover. In irrigated agriculture plant population has been considered of little importance in terms of total water needs.

Tillage

Tillage produces little if any effect on ETcrop unless a significant quantity of weed is eliminated. Rough tillage will accelerate evaporation from the plough layer; deep tillage may increase water losses when the land is fallow or when the crop cover is sparse. After the surface has dried, evaporation from the dry surface might be less than from an untilled soil. Other factors such as breaking up sealed furrow surfaces and improving infiltration may decide in favour of tillage. With soil ripping between crop rows the crop could be slightly set back due to root pruning.

Mulching

In irrigated agriculture the use of a mulch of crop residues to reduce ETcrop is often considered of little net benefit, except for specific purposes such as reducing erosion, preventing soil sealing and increasing infiltration. Crop residues may even be a disadvantage where soils are intermittently wetted; the water-absorbing organic matter remains wet much longer thus increasing evaporation. As a barrier to evaporation it is rather ineffective. The lower temperature of the covered soil and the higher reflected capacity of the organic matter are easily outweighed by evaporation of the often rewetted crop residue layer. There may be additional disadvantages such as the increased danger of pests and diseases, slower crop development due to lower soil temperatures, and problematic water distribution from surface irrigation. Polyethylene and perhaps also asphalt mulches are effective in reducing ETcrop, when it covers more than 80 percent of the soil surface and crop cover is less than 50 percent of the total cultivated area. Weed control adds to the succesful use of plastic.

Windbreaks

Reduced wind velocities produced by artificial and vegetative windbreaks may reduce ETcrop by about 5 percent under windy, warm, dry conditions at a horizontal distance equal to 25 times the height of the barrier downwind from it, increasing to 10 and sometimes up to 30 percent at a distance of 10 times this height. ETcrop as determined by the overall climatic conditions and using the reduced wind speed data is not altered. In most cases shrubs and trees are used and, due to the transpiration of the vegetative windbreak, overall ET may be more.

Anti-transpirants

The use of anti-transpirants, natural or artificially induced variations in plant foliage properties and soil conditioners to reduce ETcrop continue to interest many investigators, but is still in the experimental stage.

Part II - APPLICATION OF CROP WATER REQUIREMENT DATA IN IDENTIFICATION, DESIGN AND OPERATION OF IRRIGATION PROJECTS

A number of approaches are available for planning optimum use of water resources in agricultural production. For irrigation projects they are based on translating production objectives into adequate technical planning criteria. This comprises the collection of needed information on water, soils and crops, the preparation of a tentative plan and the search for the optimal plan by analysing modifications of the tentative plan through a staged and step by step procedure. Several stages of planning can be identified which can be broadly divided into the project identification and preliminary planning stage (II.1), the project design stage (II.2) and project implementation and operation stage (II.3).

Discussions are centred here around the development of basic data on crop water requirements and irrigation supply. In terms of irrigation supply, each planning stage requires a certain type of data; those normally used are given in Table 33.

Table 33 Project Planning Stages and Irrigation Supply Data

Planning Stage	Data Application	Data Required
Production objectives		
Project identification	- inventory of resources - present hydrological budget - water resources potential - identification of irrigable areas - choice of production system - preliminary project location and size - irrigation supply requirements - method of water delivery - preliminary size and cost of main works - engineering alternatives - technical, managerial and financial	average monthly supply and monthly peak supply
Project design	- project size - layout of distribution system - hydraulic criteria - cropping pattern - supply scheduling - method of water delivery - irrigation methods and practices - capacity of engineering works - phasing of project works - optimization of water use	supply schedules (size, duration and interval of supplies)
Project operation	- review supply schedules - evaluate water use efficiency - evaluate technical and managerial supply control - monitor field water balance - improve and adjust system operation - establish data collection routines on water, climate, soil, crop - prepare supply schedules on daily basis	supply schedules on daily basis, daily field water budgets

1. PROJECT IDENTIFICATION AND PRELIMINARY PLANNING

1.1 INTRODUCTION

At the project identification and preliminary planning stage a comprehensive inventory of available resources is made. On physical resources, this would include surface and groundwater potential, water quality, existing water uses and certainty of supply. For promising areas, soil surveys (scale 1:10 000) are undertaken to delineate the extent and distribution of soil types, together with their chemical and physical characteristics particularly water-related properties such as soil depth, water holding capacity, infiltration rate, permeability and drainage, erosion and salinity hazards. Evaluation of climate would include temperature, humidity, wind, sunshine duration or radiation, evaporation, rainfall, occurrence of night frost, and others, on which crop selection and crop water needs will be based. Criteria on production potential under irrigation must justify development not only from an agronomic, technical and economic, but also from a sociological point of view. Knowledge of present farming systems, including among others farm equipment use, social amenities, credit facilities and farming incentives, will therefore be required in selecting a development plan. Infrastructure and human resources must be evaluated including communications, markets, population, labour and employment.

Based on the knowledge of available resources, the choice of the production system under irrigation must be made. Important parameters are:

Crop selection: Here, in addition to water available, climate and soils, the preference of the farmer, labour requirements and markets among others must be considered. These are often site-specific such as limited water available restricting high water-consuming crops, unsuitable soils for some crops, limited labour for highly-intensified production and processing, and areawide marketing constraints. The cropping pattern may need to be adjusted to the available water supply over time.

Cropping intensity: At the field level, frequently cropping intensity does not correspond to that of the project as a whole. Cropping intensity may also vary with time. Early assumptions must be made since this largely governs the acreage that can be irrigated from the available water and the design and operation of the distribution network. This also greatly affects the level of investment.

Water supply level: An acceptable level of supply, or irrigation norm, must be selected based on a certain probability that water needs for a selected cropping pattern and cropping intensity will be met for each portion of the growing season. For instance, available water supply may be expressed as: (i) seasonal irrigation shortage not to exceed 50 percent of the needed supply in any one year and (ii) sum of irrigation shortages not to exceed 150 percent of the needed supply in a 25-year period. Of particular importance are periods when water shortages have a pronounced effect on yields or germination (Table 32). A detailed evaluation of water supply available and water demands over time is therefore required.

Given a certain supply, in turn cropping patterns may need to be adjusted to avoid peak irrigation requirements at periods of high evaporative demand and peak requirements of various crops occurring simultaneously. This must include consideration of dormancy periods, shifting of sowing dates, transplantation practices, shortening of growing seasons, and others. Knowledge of the crop response to water during the different growth stages will greatly assist in reducing the risk of possible crop failure or yield depression due to periods of limited water supply.

Method of irrigation: Selection of the method of irrigation needs to be made at an early date by evaluating the required investments, water use efficiency, simplicity of use and adaptability to local conditions, erodability of soils, infiltration rates, water salinity and others. The advantage of one method over another is not so much determined by difference in irrigation supply needed or its efficiency but by the adequacy with which the crop requirements are met.

Efficiency of the system: The efficiency of the system in terms of meeting water demands at field level in quantity and time is determined by both water losses by canal seepage and the way the system is managed and operated. Size of the project, method of delivery (either continuous, rotation or demand), the physical control facilities in the system, type of management and communications all become important factors. Additional water losses are incurred during field distribution and application, and farm layout, land levelling and irrigation practices greatly affect water use efficiency at field level.

Drainage and leaching: Drainage is essential for successful irrigation; without proper drainage rapidly rising groundwater levels and soil salinization can result. To avoid salt accumulation in the root zone and related crop damage, the leaching requirement must be determined. Leaching during off-peak water use periods or non-cropping periods will reduce peak water demand and design capacity of the distribution system. Timing and depth of leaching will depend mainly on type of crop, soil, climate, irrigation practices and irrigation water quality.

In formulating the project, a thorough study of the engineering alternatives is required in order that the most appropriate technical, managerial and economical solution is achieved. Alternative preliminary layouts of the scheme are generally prepared, including size and shape of commanded areas, water level and flow control, and location and size of required engineering works. Land ownership, natural boundaries, land slope and land preparation including land levelling must be reviewed in relation to this scheme layout. Feasibility of land consolidation, where needed, should be considered from the legal, technical, economic and particularly sociological point of view.

Accurate evaluation of future project operation and water scheduling cannot be made unless pilot projects are operational at or before the planning stage. No scheme functions perfectly the day it becomes operational. Allowance should be made in the planning and design to account for changes in cropping pattern and intensity, at the same time avoiding any excesses. Refinements of irrigation scheduling to match crop irrigation needs should be made after the project has been in operation for some years. The type of data normally used at the project identification and preliminary planning stage is average monthly supply and monthly peak supply.

1.2 SEASONAL AND PEAK PROJECT SUPPLY REQUIREMENTS

The calculation of seasonal and peak project supply required for a given cropping pattern and intensity includes the net irrigation requirements and other water needs including leaching of salts and efficiency of the distribution system. These are calculated on a monthly basis. Using average supply (m^3/ha/month), the total project acreage can then be determined from the available water resources.

The water requirements of each crop are calculated on the basis of meeting the evapotranspiration rate (ETcrop) of a disease-free crop, growing in large fields under optimal soil conditions including sufficient water and fertility and achieving full production potential under the given growing environment. This depends mainly on climate, growing season, crop development, and agricultural and irrigation practices.

The net irrigation requirements of the crops (In) are calculated using the field water balance. The variables include crop evapotranspiration (ETcrop), rainfall (Pe), groundwater contribution (Ge) and stored soil water at the beginning of each period (Wb), or:

$$\mathrm{In} = \underset{\text{losses}}{\mathrm{ETcrop}} \; \underset{-}{-} \; \underset{\text{gains}}{(\mathrm{Pe} + \mathrm{Ge} + \mathrm{Wb})}$$

All variables are expressed in units of depth of water (mm) and, depending on accuracy required, In can be determined for seasonal, monthly or 10-day periods. For preliminary planning monthly data are frequently used. The sum of In for the different crops over the entire irrigated area forms the basis for determining the necessary supply.

To determine the irrigation requirements, in addition to meeting the net irrigation requirements, water may be required for leaching of accumulated salts from the root zone and for cultural practices. In the calculations of irrigation requirements, water for leaching should be included. The leaching requirement (LR) is the portion of the irrigation water applied that must drain through the active root zone to remove accumulated salts. Since irrigation is never 100 percent efficient, allowance must be made for losses during conveyance and application of water. Project efficiency (Ep) is expressed in fraction of the net irrigation requirements (In).

The project irrigation supply requirements (V) can be obtained from:

$$V_i = \frac{10}{\mathrm{Ep}} \sum_i \left[\frac{\mathrm{A.In}}{1 - \mathrm{LR}}\right]_i \quad \mathrm{m}^3/\mathrm{month}$$

where: Ep = project irrigation efficiency, fraction (II.1.2.3)
A = acreage under a given crop, ha
In = net water requirements of given crop, mm/month (II, 1.2.1)
LR = leaching requirements, fraction (II, 1.2.2)

The factor 10 appears due to conversion of In in mm/month to V in m^3/month.

For preliminary planning, the capacity of the engineering works can be obtained from the supply needed during the month of peak water use (Vmax). Normally a flexibility and safety factor is included.

The discussion here is centred on a step by step calculation procedure requiring a number of assumptions. The sensitivity of the assumptions made should, however, be tested for alternative project plans.

CALCULATION PROCEDURES

1.2.1 Crop Water Requirements (ETcrop): see Part I

Collect available climatic data and select ETo prediction method.
Calculate reference crop evapotranspiration (ETo) in mm/day for each month (I. 1).
For each crop, determine growing season, duration of crop development stages and select crop coefficient (kc) (I.2).
Calculate for each month (or part thereof) the crop evapotranspiration:
ETcrop = kc.ETo in mm/day.
Consider factors affecting ETcrop (extreme values, advection, project size, agricultural and irrigation practices). Correct ETcrop for peak water use month.

1.2.2 Net Irrigation Requirements (In)

Rainfall (Pe): analyse rainfall records and prepare rainfall probabilities; consider effectiveness of rain; select level of dependable rainfall, mm/month.
Groundwater (Ge): estimate groundwater contribution to the crop water needs, mm/month.
Stored soil water (Wb): from water balance or pre-season rainfall or snow determine contribution of Wb to the crop water needs, mm/month.

1.2.3 Irrigation Requirements

Leaching requirements (LR): evaluate quality of irrigation water and drainage conditions of area; select salinity tolerance level for each crop and determine LR; obtain leaching efficiency (Le) from field experiments.
Irrigation efficiency (E): select conveyance efficiency (Ec), field canal efficiency (Eb) and application efficiency (Ea) considering technical and managerial control, delivery and application methods.

1.2.4 Summarize calculation to find irrigation supply requirements (Vi and Vmax).

1.2.1 Crop Water Requirements (ETcrop)

The water requirements are based on ETcrop, for which the calculation procedures given in Part I can be followed. The water requirements as determined permit optimum production under the given growing environment. Unless included as a specific project objective, no allowance is usually made to reduce crop water requirements, even when water use/yield relationships are available for the area.

EXAMPLE:

Given:

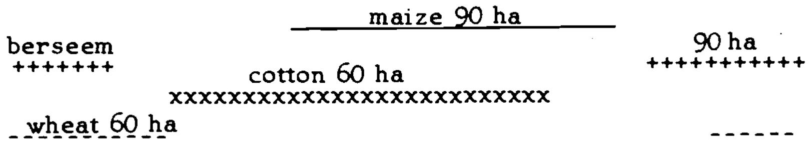
Semi-arid, hot and moderate windy climate; climatic data collected outside irrigated area. Cotton, sown early March, harvested end August. Size of project 150 ha; cropping intensity 100%; surrounds are dry, fallow land.

Calculation:

	J	F	M	A	M	J	J	A	S	O	N	D
ETo mm/day	2.4	3.3	4.8	6.0	8.1	8.6	7.8	6.6	5.1	4.3	2.8	2.1
kc cotton			0.3	0.6	1.0	1.12	1.15	0.6				
advection correction					0.9	0.9	0.9					
peak month correction						1.1	1.1					
ETcotton mm/day			1.5	3.6	8.1	9.5	9.0	4.0				
ETcotton mm/month			45	110	225	285	280	120				

Once the cropping pattern and intensity have been selected, water requirements for the different months are computed similarly for fields under different crops. They are computed for each crop and can then be weighted and totalled for each month.

EXAMPLE:
<u>Given</u>:
Semi-arid, hot and moderate windy climate. Project size 150 ha; cropping intensity 200%. Cropping pattern: maize (90 ha) from May through September followed by berseem (90 ha) from October through February; cotton (60 ha) from March through August followed by wheat (60 ha) from November through March.
<u>Calculation</u>:



	J	F	M	A	M	J	J	A	S	O	N	D	T
ETmaize					85	140	275	225	115				840
ETberseem	80	95								65	90	70	400
ETcotton			45	110	225	285	280	120					1065
ETwheat	80	100	95								40	60	375
ETcrop	80	100	55	45	140	200	280	185	70	40	70	70	1325

mm/month weighted for acreage, or 90/150.ETmaize + 90/150.ETberseem + 60/150.ETcotton + 60/150.ETwheat, rounded of to nearest 5 mm

1.2.2 Net Irrigation Requirements (In)

Part of the crop water requirements is met by rainfall (Pe), groundwater (Ge) and stored soil water (Wb); or In = ETcrop - Pe - Ge - Wb, and is determined on a monthly basis.

(i) Effective rainfall (Pe)

Dependable rainfall:

Crop water needs can be fully or partly met by rainfall. Rainfall for each period will vary from year to year and therefore, rather than using mean rainfall data (saying roughly one year is drier, the next is wetter), a dependable level of rainfall should be selected (saying the depth of rainfall that can be expected 3 out of 4 years or 4 out of 5 years). Also the degree of shortage below the dependable level during the dry years should be given, since loss in crop yields during the dry years may significantly affect the project's economic viability. A higher level of dependable rainfall (say 9 out of 10 years) may need to be selected during the period that crops are germinating or are most sensitive to water stress and yields are severely affected. Methods of computing rainfall probability are given below, using yearly data. Monthly data are normally used for preliminary planning purposes.

For large schemes, where mountains or other features influence rainfall or the occurrence of storms, the distribution of rainfall over area must be evaluated. Methods are described in textbooks on hydrology (see Footnote 1/on next page).

EXAMPLE:
A simple method is by grouping the rainfall data; a rough indication of rainfall probability is obtained by the number of times the yearly amount falls within a group divided by the number of years of record.

Year	1956	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
mm/month	75	85	50	65	45	30	20	65	35	80	45	25	60	75	40	55

Highest value is 85 and lowest 20 mm. Using a 10 mm grouping:

0 - 9	0	50 - 59	2x
10 - 19	0	60 - 69	3x
20 - 29	2x	70 - 79	2x
30 - 39	2x	80 - 89	2x
40 - 49	3x	90 - 99	0
			16

Rainfall will equal or exceed 40 mm for 3 out of 4 years (or 12/16).

An improved estimate can be obtained computing and plotting rainfall probabilities. The steps involved are:

- tabulate rainfall totals for given period (line 2)
- arrange data in descending magnitude and give rank number m (lines 3 and 4)
- tabulate plotting position (Fa) using 100m/(N + 1). N is total data number, m is rank number with m = 1 for the highest value (line 5)
- prepare vertical scale and plot rainfall according to Fa position on log-normal probability paper (Fig. 17)

Line	1956	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
1 Year	1956	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
2 mm/given month	75	85	50	65	45	30	20	65	35	80	45	25	60	75	40	55
3 sequence	85	80	75	75	65	65	60	55	50	45	45	40	35	30	25	20
4 number m	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
5 plotting position (Fa)	6	12	18	24	29	35	41	47	53	59	65	71	76	82	88	94

From Fig. 17: dependable rainfall 3 out of 4 years, or 75% probability, for given month is 36 mm; 4 out of 5 years, or 80% probability, 32 mm etc.

A skewed frequency distribution, where points on the probability paper do not fall in a reasonable alignment, may mean either too few data are available, data are affected by some physical occurrence causing consistent bias, or, more often, rainfall is not normally distributed to allow simple statistical analysis. The last can be partly overcome by:

- plotting on probability paper the square root or logarithm of the same rainfall data; or
- for periods with little or no rainfall, use Ga = p + (1 - p). Fa, where Ga is probability of occurrence and p is the portion in which no rainfall occurred. Sample: if no rainfall is recorded in 6 out of 30 years in the period considered then p = 0.20. Then Fa is determined on a 24-year basis following the step method given above.

Drought duration frequency:
The lowest values of total rainfall for a given number of consecutive days, say 15, 30 and 40 days, are selected. The drought duration frequency is obtained by plotting values for each selected period of consecutive days according to the given method.
For additional details see references.[1/]

[1/] Ven Te Chow, Handbook of Applied Hydrology. McGraw-Hill, 1964.
Linsley, Kohler and Paulus, Hydrology for Engineers. McGraw-Hill, 1958.
WHO, Guide to Hydrometeorological Practices, 1965.
USDA (SCS), Engineering Handbook Hydrology, Section 4, suppl.A., 1957.
Ramirez, L.E., Development of a procedure for determining spacial and time variations of precipitation in Venezuela, PRWG 69-3. Utah, 1971.

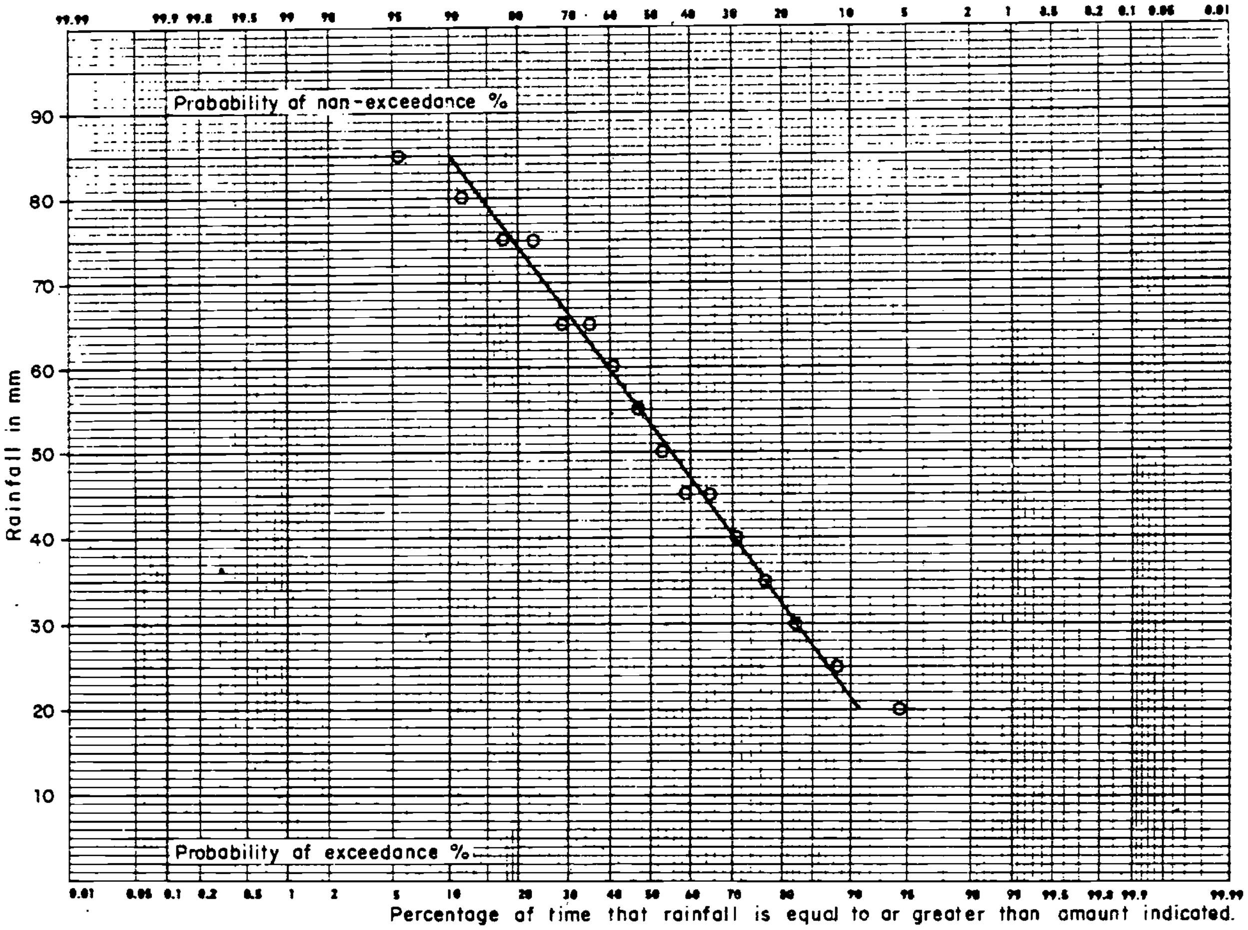


Fig. 17 Example of rainfall·probability calculation

Effective rainfall:

Not all rainfall is effective and part may be lost by surface runoff, deep percolation or evaporation. Only a portion of heavy and high intensity rains can enter and be stored in the root zone and the effectiveness is consequently low. Frequent light rains intercepted by plant foliage with full ground cover are close to 100 percent effective. With a dry soil surface and little or no vegetative cover, rainfall up to 8 mm/day may all be lost by evaporation; rains of 25 to 30 mm may be only 60 percent effective with a low percentage of vegetative cover.

Effective rainfall can be estimated by the evapotranspiration/precipitation ratio method, Table 34 (USDA, 1969). The relationship between average monthly effective rainfall and mean monthly rainfall is shown for different values of average monthly ETcrop. At the time of irrigation the net depth of irrigation water that can be stored effectively over the root zone is assumed equal to 75 mm; correction factors are presented for different depths that can be effectively stored. Data in Table 34 do not account for infiltration rate of the soil and rainfall intensity; where infiltration is low and rainfall intensities are high, considerable water may be lost by runoff which is not accounted for in this method.[1]

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[1] A more detailed prediction of effective rainfall is available in FAO Irrigation and Drainage Paper No. 25, Effective Rainfall. N.G. Dastane, 1975.

Table 34 Average Monthly Effective Rainfall as Related to Average Monthly ETcrop and Mean Monthly Rainfall

(USDA (SCS), 1969)

Monthly mean rainfall mm		12.5	25	37.5	50	62.5	75	87.5	100	112.5	125	137.5	150	162.5	175	187.5	200
		Average monthly effective rainfall in mm*															
Average	25	8	16	24													
monthly	50	8	17	25	32	39	46										
ETcrop	75	9	18	27	34	41	48	56	62	69							
mm	100	9	19	28	35	43	52	59	66	73	80	87	94	100			
	125	10	20	30	37	46	54	62	70	76	85	92	98	107	116	120	
	150	10	21	31	39	49	57	66	74*	81	89	97	104	112	119	127	133
	175	11	23	32	42	52	61	69	78	86	95	103	111	118	126	134	141
	200	11	24	33	44	54	64	73	82	91	100	109	117	125	134	142	150
	225	12	25	35	47	57	68	78	87	96	106	115	124	132	141	150	159
	250	13	25	38	50	61	72	84	92	102	112	121	132	140	150	158	167

* Where net depth of water that can be stored in the soil at time of irrigation is greater or smaller than 75 mm, the correction factor to be used is:

Effective storage	20	25	37.5	50	62.5	75	100	125	150	175	200
Storage factor	.73	.77	.86	.93	.97	1.00	1.02	1.04	1.06	1.07*	1.08

EXAMPLE:

Given:

Monthly mean rainfall = 100 mm; ETcrop = 150 mm; effective storage = 175 mm

Calculation:

Correction factor for effective storage = 1.07

Effective rainfall 1.07 x 74 = 79 mm

Dew:

The contribution of dew to crop water requirements is usually very small, consisting of condensation on cooler surfaces, the re-condensation on leaves of water evaporated from the soil, and trapping of fog or cloud droplets by vegetation. For irrigated crops much of the moisture condensed on crops by early morning comes from the water evaporated from the soil. Measured data from India and Israel show annual measured dew accumulation below 30 mm, with a monthly maximum of 3 to 7 mm; California monthly maximum is only 0.5 mm. Data from Australia show that about 3 percent of monthly ETcrop is met by dew during summer. In arid and semi-arid regions dew deposition is often too small to make any contribution. On high mountain ranges (Canary Islands) crop water requirements can be fully met by the interception of fog, but this is very rare. There has been a strong tendency to over-estimate dew accumulation; impossible amounts have been claimed as researchers overlook absolute physical limitations involved in the process.

Snow:

Snow on the soil surface contains approximately 1 cm of water per 10 cm snow. The contribution of melting snow towards meeting future crop water requirements should be seen as a contribution to the soil-water reservoir similar to winter rains.

(ii) Groundwater contribution (Ge)

The contribution from the groundwater table is determined by its depth below the root zone, the capillary properties of the soil and the soil water content in the root zone. For heavy soils, distance of movement is high and the rate low; for coarse textured soils the distance of movement is small and the rate high. Very detailed experiments will be required to determine the groundwater contribution under field conditions. In Figure 18 examples of groundwater contribution are given in mm/day for different depths of groundwater below the root zone and various soil types assuming the root zone is relatively moist.

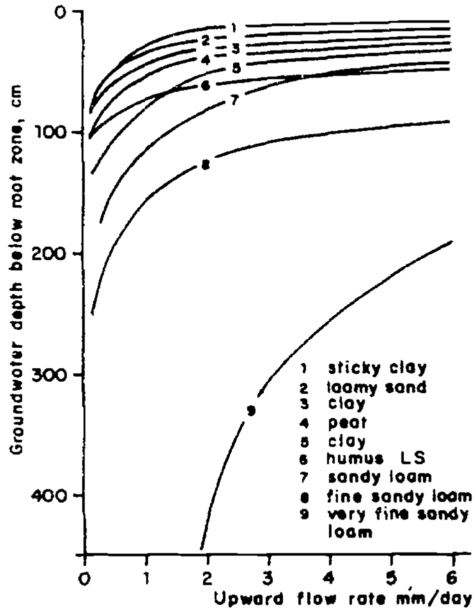

Fig. 18 Contribution of groundwater to moist root zone in mm/day

EXAMPLE:

Given:

Sandy loam soil; groundwater depth below root zone in December and January is 80 cm.

Calculation:

Using Fig. 18 a first estimate of groundwater contribution to ETcrop is some 1.5 mm/day.

(iii) Stored soil water (Wb)

Winter rains, melting snow or flooding may cause the soil profile to be near or at field capacity at the start of the growing season, which may be equivalent to one full irrigation. Also some water may be left from the previous irrigation season. It can be deducted when determining seasonal irrigation requirements. Excess winter rain will leach salts accumulated in the root zone in the summer season and as such can be assumed effective.

Water stored in the root zone is not 100 percent effective. Evaporation from the wet soil surface is equal to open-water evaporation, but this rate decreases as the soil dries. Evaporation losses may remain fairly high due to the movement of soil water by capillary action towards the soil surface. Water is lost from the root zone by deep percolation where groundwater tables are deep. Deep percolation can still persist after attaining field capacity. Depending on weather, type of soil and time span considered, effectiveness of stored soil water may be as high as 90 percent or as low as 40 percent.

1.2.3 Irrigation Requirements

Other than for meeting the net irrigation requirements (In), water is needed for leaching accumulated salts from the root zone and to compensate for water losses during conveyance and application. This should be accounted for in the irrigation requirements. Leaching requirements (LR) and irrigation efficiency (E) are included as a fraction of the net irrigation requirements.

Water needed for land preparation may need to be considered in the case of rice. At the planning stage normally no allowance is made for such needs for other crops; this applies similarly to water needs for cultural practices and aid to germination and quality control of the harvested yield. They are usually covered by adjusting irrigation schedules.

(i) Leaching requirements (LR)

Soil salinity is mainly affected by water quality, irrigation methods and practices, soil conditions and rainfall. Salinity levels in the soil generally increase as the growing season advances. Leaching can be practised during, before or after the crop season depending on available water supply, but provided that salt accumulation in the soil does not exceed the crop tolerance level. Table 35 can be used to evaluate the effect of the quality of the irrigation water on soil salinity, permeability and toxicity.[1]

The crop tolerance levels given in Table 36 can be used to determine the leaching requirements for a given quality of irrigation water.[1] Crop tolerance levels are given as electrical conductivity of the soil saturation extract (ECe) in mmhos/cm. With poor quality water, frequent irrigation and excessive leaching water may be required to obtain acceptable yields. In Table 36 values of quality of irrigation water are also given which relate to commonly experienced yield levels. Irrigation water quality (ECw) is expressed as electrical conductivity in mmhos/cm.

Table 35 Effect of Irrigation Water Quality on Soil Salinity, Permeability and Toxicity

	none	moderate	severe
Salinity			
ECw (mmhos/cm)	< 0.75	0.75 - 3.0	> 3.0
Permeability			
ECw (mmhos/cm)	> 0.5	0.5 - 0.2	< 0.2
adj. SAR			
Montmorillonite	< 6	6 - 9	> 9
Illite	< 8	8 - 16	> 16
Kaolinite	< 16	16 - 24	> 24
Toxicity (most tree crops)			
sodium (adj. SAR)*	< 3	3 - 9	> 9
chloride (meq/l)* 1/	< 4	4 - 10	> 10
boron (mg/l)	< 0.75	0.75 - 2	> 2

* For most field crops use Table 36.

1/ Sprinkler irrigation may cause leaf burn when > 3 meq/l. (Ayers and Westcot, 1976)

Leaching requirement (LR) is the minimum amount of irrigation water supplied that must be drained through the root zone to control soil salinity at the given specific level. For sandy loam to clay loam soils with good drainage and where rainfall is low the leaching requirement can be obtained from:

for surface irrigation methods (including sprinklers) $LR = \frac{ECw}{5ECe - ECw}$

for drip and high frequency sprinkler (near daily) $LR = \frac{ECw}{2Max\ ECe}$

where: ECw = electrical conductivity of the irrigation water, mmhos/cm
ECe = electrical conductivity of the soil saturation extract for a given crop appropriate to the tolerable degree of yield reduction (Table 36)
MaxECe = maximum tolerable electrical conductivity of the soil saturation extract for a given crop (Table 36)

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[1] Ayers, R.S. and Westcot, D.W. Water quality for agriculture. Irrigation and Drainage Paper No. 29. FAO Rome, Italy. 1976.

Table 36 Crop Salt Tolerance Levels for Different Crops (Ayers and Westcot, 1976)

Crop	Yield potential 100% ECe	100% ECw	90% ECe	90% ECw	75% ECe	75% ECw	50% ECe	50% ECw	Max. ECe
Field crops									
Barley 1/	8.0	5.3	10.0	6.7	13.0	8.7	18.0	12.0	28
Beans (field)	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	7
Broad beans	1.6	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12
Corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Cotton	7.7	5.1	9.6	6.4	13.0	8.4	17.0	12.0	27
Cowpeas	1.3	0.9	2.0	1.3	3.1	2.1	4.9	3.2	9
Flax	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Groundnut	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	7
Rice (paddy)	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	12
Safflower	5.3	3.5	6.2	4.1	7.6	5.0	9.9	6.6	15
Sesbania	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	17
Sorghum	4.0	2.7	5.1	3.4	7.2	4.8	11.0	7.2	18
Soybean	5.0	3.3	5.5	3.7	6.2	4.2	7.5	5.0	10
Sugarbeet	7.0	4.7	8.7	5.8	11.0	7.5	15.0	10.0	
Wheat 1/	6.0	4.0	7.4	4.9	9.5	6.4	13.0		
Vegetable crops									
Beans	1.0	0.7	1.5	1.0	2.3	1.5	[illegible]	2.4	[illegible]
Beets2/	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15
Broccoli	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	14
Cabbage	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12
Cantaloupe	2.2	1.5	3.6	2.4	5.7	3.8	9.1	6.1	16
Carrot	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.1	8
Cucumber	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10
Lettuce	1.3	0.9	2.1	1.4	3.2	2.1	5.2	3.4	9
Onion	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	8
Pepper	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	9
Potato	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Radish	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	9
Spinach	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15
Sweet corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Sweet potato	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	11
Tomato	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13
Forage crops									
Alfalfa	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16
Barley hay1/	6.0	4.0	7.4	4.9	9.5	6.3	13.0	8.7	20
Bermuda grass	6.9	4.6	8.5	5.7	10.8	7.2	14.7	9.8	23
Clover, berseem	1.5	1.0	3.2	2.1	5.9	3.9	10.3	6.8	19
Corn (forage)	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	16
Harding grass	4.6	3.1	5.9	3.9	7.9	5.3	11.1	7.4	18
Orchard grass	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	18
Perennial rye	5.6	3.7	6.9	4.6	8.9	5.9	12.2	8.1	19
Soudan grass	2.8	1.9	5.1	3.4	8.6	5.7	14.4	9.6	26
Tall fescue	3.9	2.6	5.8	3.9	8.6	5.7	13.3	8.9	23
Tall wheat grass	7.5	5.0	9.9	6.6	13.3	9.0	19.4	13.0	32
Trefoil, big	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	8
Trefoil, small	5.0	3.3	6.0	4.0	7.5	5.0	10.0	6.7	15
Wheat grass	7.5	5.0	9.0	6.0	11.0	7.4	15.0	9.8	22
Fruit crops									
Almond	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.7	7
Apple, pear	1.7	1.0	2.3	1.6	3.3	2.2	4.8	3.2	8
Apricot	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	6
Avocado	1.3	0.9	1.8	1.2	2.5	1.7	3.7	2.4	6
Date palm	4.0	2.7	6.8	4.5	10.9	7.3	17.9	12.0	32
Fig, olive, pomegranate	2.7	1.8	3.8	2.6	5.5	3.7	8.4	5.6	14
Grape	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12
Grapefruit	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8
Lemon	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8
Orange	1.7	1.1	2.3	1.6	3.2	2.2	4.8	3.2	8
Peach	1.7	1.1	2.2	1.4	2.9	1.9	4.1	2.7	7
Plum	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.8	7
Strawberry	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4
Walnut	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8

1/ During germination and seedling stage ECe should not exceed 4 or 5 mmhos/cm. Data may not apply to new semi-dwarf varieties of wheat.

2/ During germination ECe should not exceed 3 mmhos/cm.

When the leaching efficiency (Le) is 100 percent the water needed to satisfy both ETcrop and LR is equal to (ETcrop - Pe)/(1 - LR). The leaching efficiency (Le) has been shown to vary with the soil type, and particularly with the internal drainage properties of the soil and the field. Since Le can be as low as 30 percent for cracking and swelling heavy clays and go to 100 percent for sandy soils, it must be measured at a most early date for the area under investigation.

EXAMPLE:

Given:

Cotton; ETcrop = 1065 mm/season; effective rainfall during growing season = 160 mm. From water analyses ECw = 7 mmhos/cm. Irrigation by a surface method. Soil is slightly layered, medium textured with measured Le = 0.7.

Calculation:

$$LR = \frac{7}{5 \times 7.7 - 7} \times \frac{1}{0.7} = 0.32 \qquad 100\% \text{ yield}$$

$$LR = \frac{7}{5 \times 9.6 - 7} \times \frac{1}{0.7} = 0.24 \qquad 90\% \text{ yield}$$

$$LR = \frac{7}{5 \times 13 - 7} \times \frac{1}{0.7} = 0.17 \qquad 75\% \text{ yield}$$

To meet seasonal ETcrop and LR depth of water required is respectively (1065 - 160)/(1 - LR) = 1330, 1190 and 1090 mm/season. Level of leaching requirement to be adopted must be based on available water at headworks, yields required and economic criteria. Timing of leachings must also be determined by available water supply at peak water demand periods.

The prediction of annual leaching requirements does not fully account for effect of type of salts, restrictive drainage conditions and excess rainfall. It does not cover waste water, trace metals and pesticides. Also, field water management practices when using saline water will affect yields. For detailed evaluation, references given should be consulted.[1/]

(ii) Irrigation efficiency (E)

To account for losses of water incurred during conveyance and application to the field, an efficiency factor should be included when calculating the project irrigation requirements. Project efficiency is normally subdivided into three stages, each of which is affected by a different set of conditions:

Conveyance efficiency (Ec): ratio between water received at inlet to a block of fields and that released at the project headworks.

Field canal efficiency (Eb): ratio between water received at the field inlet and that received at the inlet of the block of fields.

Field application efficiency (Ea): ratio between water directly available to the crop and that received at the field inlet.

Project efficiency (Ep): ratio between water made directly available to the crop and that released at headworks, or Ep = Ea.Eb.Ec.

[1/] Ayers, R.S. and Westcot, D.W. Water quality for agriculture. Irrigation and Drainage Paper Paper No. 29. FAO Rome, Italy. 1976.
FAO/Unesco. Irrigation, Drainage and Salinity. An Intern. Source Book. Unesco, Paris. 1973.
Salinity Lab. Handbook No. 60. Diagnosis and Improvement of Saline and Alkali Soils. USDA, 1954.
FAO, Irrigation and Drainage Paper No. 7. Salinity seminar Baghdad. FAO Rome, Italy. 1972.
Unesco. Final report on the Gruesi Project, Tunisia. 1971.

Conveyance and field canal efficiency are sometimes combined as distribution efficiency (Ed), where Ed = Ec.Eb; field canal and application efficiency are sometimes combined as farm efficiency where Ef = Eb.Ea.

Factors affecting conveyance efficiency (Ec) are, amongst others, size of the irrigated acreage, size of rotational unit, number and types of crops requiring adjustments in the supply, canal lining and the technical and managerial facilities of water control. The field canal efficiency (Eb) is affected primarily by the method and control of operation, the type of soils in respect of seepage losses, length of field canals, size of the irrigation block and the fields. As can be expected, the distribution efficiency (Ed) has been shown to be particularly sensitive to quality of technical as well as organizational operation procedures (Ed = Ec.Eb). Farm efficiency (Ef) is much dictated by the operation of the main supply system in meeting the actual field supply requirements as well as by the irrigation skill of the farmers.

Table 37 Conveyance (Ec), Field Canal (Eb), Distribution (Ed) and Field Application Efficiency (Ea)

				ICID/ILRI
Conveyance Efficiency (Ec)				
Continuous supply with no substantial change in flow				0.9
Rotational supply in projects of 3 000 - 7 000 ha and rotation areas of 70 - 300 ha, with effective management				0.8
Rotational supply in large schemes (> 10 000 ha) and small schemes (< 1 000 ha) with respective problematic communication and less effective management:				
	based on predetermined schedule			0.7
	based on advance request			0.65
Field Canal Efficiency (Eb)				
Blocks larger than 20 ha:	unlined			0.8
	lined or piped			0.9
Blocks up to 20 ha:	unlined			0.7
	lined or piped			0.8
Distribution Efficiency (Ed = Ec.Eb)				
Average for rotational supply with management and communication	adequate			0.65
	sufficient			0.55
	insufficient			0.40
	poor			0.30
Field Application Efficiency (Ea)		USDA	US(SCS)	
Surface methods				
	light soils	0.55		
	medium soils	0.70		
	heavy soils	0.60		
	graded border		0.60 - 0.75	0.53
	basin and level border		0.60 - 0.80	0.58
	contour ditch		0.50 - 0.55	
	furrow		0.55 - 0.70	0.57
	corrugation		0.50 - 0.70	
Subsurface			up to 0.80	
Sprinkler,	hot dry climate		0.60	
	moderate climate		0.70	0.67
	humid and cool		0.80	
Rice				0.32

Water losses can be high during field application. Low application efficiency (Ea) will occur when rate of water applied exceeds the infiltration rate and excess is lost by runoff; when depth of water applied exceeds the storage capacity of the root zone excess is lost by deep drainage. With surface irrigation, field layout and land grading is most essential; uneven distribution of water will cause drainage losses in one part and possibly under-irrigation in the other part of the field resulting in very low efficiency. Ea may vary during the growing season with highest efficiencies during peak water use periods.

In the planning stage, efficiency values for the various stages of water distribution and application are estimated on the basis of experience. When estimated too high water deficiencies will occur and either selective irrigation and/or improvement in operational and technical control (lining, additional structures, etc.) will be required. When estimated too low the irrigation area is reduced, and the system is therefore over-designed and probably wasteful irrigation is practised. However, the former is commonly the case. Some indicative data are given in Table 37 which are applicable to well designed schemes in operation for some years and based mainly on a recent comprehensive ICID/ILRI survey and USDA and US(SCS) sources.[1/]

EXAMPLE:
<u>Given</u>:
150 ha scheme, irrigation blocks of 10 ha with unlined canals, furrow irrigation, adequate management.
<u>Calculation</u>:
$Ep = Ed \times Ea = 0.65 \times 0.65 \cong 0.4$

1.2.4 Summary of Calculation of Seasonal and Peak Project Supply Requirements (V)

Once cropping pattern and intensity have been selected, irrigation requirements and water needs for leaching have been calculated and efficiency of the system estimated, the monthly, seasonal and yearly supply requirements for a given project acreage can be determined by:

$$V_i = \frac{10}{Ep} \sum_i \left[\frac{A(ETcrop - Pe - Ge - Wb)}{1 - LR} \right]_i \quad m^3/\text{period}$$

EXAMPLE:
<u>Given</u>: From previous examples:

crop	acreage A ha	ETcrop mm/year	Pe mm	Ge mm	Wb mm	LR fraction	Ep fraction
maize	90	840	20	-	-	0.44	0.4
berseem	90	400	150	90	-	0.22	0.4
cotton	60	1065	160	-	-	0.24	0.4
wheat	60	375	240	90	-	0.25	0.4

Project acreage 150 ha; cropping intensity 200%.
<u>Calculation</u>:

$$V = \frac{10}{0.4}\left[\left[\frac{840 - 20}{1 - 0.44} \times 90\right] + \left[\frac{400 - 150 - 90}{1 - 0.22} \times 90\right] + \left[\frac{1065 - 160}{1 - 0.24} \times 60\right] + \left[\frac{375 - 240 - 90}{1 - 0.25} \times 60\right]\right] \cong \underline{5.4\ 10^6}\ m^3/\text{year}$$

Similarly the monthly supply requirements can be determined.

[1/] Bos M.G. and Nugteren J. On Irrigation Efficiencies. Publication 19. International Institute for Land Reclamation and Improvement, 89p. 1974.

For a first estimate on capacity of engineering works, the peak supply (Vmax) can be based on project supply of the month of highest irrigation demands (In peak). Leaching is normally practised outside this month, but when saline water is used, this may need to be considered in the peak supply.

$$\text{Vmax} = C\,\frac{10}{\text{Ep}}\,\sum(\text{A.In peak})$$

To incorporate flexibility in the delivery capacity of the supply system as well as to allow for future intensification and diversification of crop production, a flexibility factor (C) is frequently added. This factor varies with the type of project and is generally higher for small schemes as compared to large schemes. For projects based on supplemental irrigation this factor is high. With monocultures such as rice, orchards and permanent pastures the factor is small. The C factor should not be confused with the design factor α which indicates rotation of supply within the scheme. For the design of structures, in addition a safety factor which depends on the type and size is normally added.

EXAMPLE:

Given:

Data from previous example. Peak irrigation month is July, with ETcotton = 280 and ETmaize = 275 mm/month. For 150 ha scheme with project efficiency 0.4, flexibility factor selected is 1.2

Calculation:

$$\text{Vmax} = 1.2\,\frac{10}{0.4}\left[280 \times 60 + 275 \times 90\right] = \underline{1.25\ 10^{6}}\ \text{m}^3/\text{peak month}$$

or some 480 l/sec with flexibility factor

or some 400 l/sec without flexibility factor

2. PROJECT DESIGN

2.1 INTRODUCTION

Based on a comprehensive resources inventory and following the selection of the production system, the procedure generally followed in deriving the design data for the distribution system is first to prepare a preliminary layout of the scheme and to determine the area distribution of crops to be grown and the cropping intensity. This will also include size and shape of commanded areas, water level and flow control and provisions to be made such as location and size of main canals and number, type and capacity of structures needed. Preliminary estimates on design capacity can be based on irrigation supply requirements during the months of peak water use. The classic method of deriving supply over area and time for projects greater than 2 000 ha is to consider each area served by the main canals. For a given cropping pattern and intensity, the irrigation requirements (mm/month/ha) can be determined and from this the average supply of the area served (V in m^3/day). A fixed supply is thus assumed to the area served by each main canal; the water supply is then rotated among the different fields composing the area served. The graphical presentation, where supply is plotted against each area served by the lateral canals and totalled for the main canal, is called the supply or capacity line. Sometimes empirically-derived capacity lines are available but their use for projects other than that for which they were developed is often not justified.

A detailed layout of the system is prepared next, considering field size, field layout, topography, land slope, natural boundaries, land ownership, and land preparation including need for land grading. The operation criteria of the system are based on the field irrigation supply schedules, i.e. size, duration and interval of supply, and method of supply (continuous, rotation or demand). Supply schedules are determined for individual fields and subsequently for field blocks, the area served by laterals and main canals. Because of differences in crops and areas served the supply may become irregular over the total project area; peak supply for parts of the project area can occur at different times. The supply schedules thus determined can show large and frequent differences with the supply requirements using weighted monthly supply data (II.1.2.4). Based on the supply schedules, canal capacities and need for regulating and check structures can then be determined together with the organizational framework for operating and maintaining the system.

In future, changes can be expected in supply requirements due, for instance, to crop intensification and diversification. An extra allowance can be made in the scheduling criteria. However, at the planning stage normally conservative estimates are applied on irrigation efficiencies, since it may take many years to operate the project in an efficient manner. Any increase in the supply requirements may then be met by the savings in water due to the improvements in project operation and field irrigation practices.

2.2 FIELD AND PROJECT SUPPLY SCHEDULES

To derive the data for design and operation of the irrigation distribution system, a detailed evaluation is made of the supply schedules. This should preferably start at the lowest irrigation unit, and subsequently include the block of fields, area served by lateral canals and project areas served by main canals.

The supply requirements at the field level are determined by the depth and interval of irrigation. These data can be obtained from the soil water balance andare primarily determined by (i) the total available soil water ($Sa = Sfc - Sw$ where Sfc and Sw are the soil water content in mm/m soil depth at field capacity and wilting point respectively); (ii) the fraction of available soil water permitting unrestricted evapotranspiration and/or optimal crop growth; and (iii) the rooting depth (D). The depth of irrigation application (d) including application losses is:

$$d = \frac{(p.Sa).D}{Ea} \quad mm$$

and frequency of irrigation expressed as irrigation interval of the individual field (i) is:

$$i = \frac{(p.Sa).D}{ETcrop} \quad days$$

where: p = fraction of available soil water permitting unrestricted evapotranspiration, fraction
Sa = total available soil water, mm/m soil depth
D = rooting depth, m
Ea = application efficiency, fraction

Since p, D and ETcrop will vary over the growing season, the depth in mm and interval of irrigation in days will vary.

For design and operation of the water distribution system, the supply requirements of the individual fields will need to be expressed in flow rates or stream size (q in m^3/sec) and supply duration (t in seconds, hours or days). The field supply (q.t) is:

$$q.t = \frac{10}{Ea} (p.Sa).D.A \qquad m^3$$

where: q = stream size, m^3/sec
t = supply duration, seconds
Ea = application efficiency, fraction
p = fraction of available soil water permitting unrestricted evapotranspiration, fraction
Sa = total available soil water, mm/m soil depth
D = rooting depth, m
A = acreage, ha

In determining the relative values of q and t, the soil intake rate and method of irrigation must be taken into account. For instance, t will be greater for heavy as compared to light soils and also for sprinkler and furrow irrigation as compared to basin irrigation. Furthermore, the stream size (q) must be handled easily by the irrigator.

The capacity and operation of the distribution system are based on the supply requirements during the peak water use month. However, the function of the system is to satisfy, as far as possible, the momentary irrigation requirements of each crop and each area in terms of size (Q), duration (T) and interval of supply (I).[1] Field irrigation requirements will vary for each crop during the growing season and the supply must follow those changes over area and time. Analysis of the

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[1] Miniscules are used here to denote supply requirements at the field level (d, q, t, i) and capital letters are used to denote capacity and operation variables of the supply system (V, Q, T, I).

system and selection of the method of supply (continuous, rotation or demand) should therefore start with an evaluation of the field variables. The following indicators can therefore be used:

- supply requirement factor fi = Vi/Vmax which for a given period is the ratio between the average daily supply requirements (m^3/day) and the average maximum daily supply requirements during the peak water use period (m^3/day).
- design factor α = 86 400 Qmax/Vmax which is the ratio between the canal capacity or maximum possible discharge (m^3/sec) and the maximum average daily supply requirement during the peak water use period (m^3/day).
- supply duration factor ft = T/I which is the ratio between supply duration T (day) and the supply interval 1 (day).
- supply factor fs = Qi/Qmax which is the ratio between actual required and maximum possible supply (m^3/sec).

The design and operation criteria must furthermore consider the degree to which the variation in supply requirements can be met, the technical facilities to regulate and convey the required supply, and the construction, operation and maintenance costs. Adequate control of the water source at headworks must be secured to permit the variation in project and field supply over time.

CALCULATION PROCEDURES

2.2.1 Field Irrigation Schedules:

Determine field water balance for each crop over the growing season on monthly or shorter basis without considering irrigation.
Select for each crop the level to which the available soil water can be depleted for given soil and climate.
Determine for each crop the depth and interval of irrigation application over the growing season.

2.2.2 Field Irrigation Supply Schedules:

Determine criteria on field size, method of irrigation and field water management practices.
Select stream size based on method of irrigation, irrigation practices and water handling at the farm level.
Determine for selected stream size the duration and interval of field supply for given crop, soil and climatic conditions.

2.2.3 Design and Operation of Supply System:

Prepare detailed field layout and water distribution plan.
Select for given scheme layout and production pattern the method of delivery.
Quantify supply schedules for the different crops and acreages over the growing season.
Determine capacity and operation requirements of the distribution system.

2.2.1 Field Irrigation Schedules

Field irrigation schedules are based on the field water balance and are expressed in depth (d in mm) and interval of irrigation (i in days).

(i) Depth of irrigation application (d)

Depth of irrigation application is the depth of water that can be stored within the root zone between the so-called field capacity (Sfc) and the allowable level the soil water can be depleted for a given crop, soil and climate. Data on type of soil and its water holding characteristics should be collected at site; approximate data on available soil water for different soil types are given in Table 38. Available soil water is expressed in mm/m soil depth. The total available amount of water stored in the soil (Sa) one or two days after irrigation is given by the soil water content at field capacity (soil water tension of 0.1 to 0.3 atmospheres) minus that at wilting point (Sw) (soil water tension of 15 atmospheres).

Table 38 Relation between Soil Water Tension in bars (atmospheres) and Available Soil Water in mm/m soil depth
(after Rijtema, 1969)

Soil water tension (atmospheres)	0.2	0.5	2.5	15
	Available soil water in mm/m			
	(Sa)			
Heavy clay	180	150	80	0
Silty clay	190	170	100	0
Loam	200	150	70	0
Silt loam	250	190	50	0
Silty clay loam	160	120	70	0
Fine textured soils	200	150	70	0
Sandy clay loam	140	110	60	0
Sandy loam	130	80	30	0
Loamy fine sand	140	110	50	0
Medium textured soils	140	100	50	0
Medium fine sand	60	30	20	0
Coarse textured soils	60	30	20	0

Not all water in the root zone held between Sfc and Sw is readily available to the crop. The level of maximum soil water tension or maximum soil water depletion tolerated to maintain potential crop growth varies with type of crop. The depth of water readily available to the crop is defined as p.Sa where Sa is the total available soil water (Sfc - Sw) and p is the fraction of the total available soil water which can be used by the crop without affecting its evapotranspiration and/or growth. The value of p depends mainly on type of crop and evaporative demand. Some crops, such as vegetables, potatoes, onions and strawberries, require relatively wet soils to produce acceptable yields; others such as cotton, wheat and safflower will tolerate higher soil water depletion levels. However, the tolerated depletion level varies greatly with crop development stage; for most crops a reduced level of depletion should be allowed during changes from vegetative to reproductive growth or during heading and flowering to fruit setting. Some crops do not have such water specific stages. Periods when crops are sensitive to soil water shortages are given in Table 32.

The depth of soil water readily available to the crop (p.Sa) will also vary with the level of evaporative demand. When ETcrop is low ($\geqslant$ 3 mm/day), the crop can transpire at its maximum rate to a soil water depletion greater than that when ETcrop is high ($\geqslant 8$ mm/day). This is somewhat more pronounced in heavy soils as compared to coarse textured soils.

Depth of irrigation application (d) is equal to the readily available soil water (p. Sa) over the root zone (D). An application efficiency factor (Ea) is always added to account for the uneven application over the field or:

$$d = (p.Sa).D/Ea \quad \text{mm}$$

General information is given in Table 39 for different crops on rooting depth (D) on fraction of total available soil water allowing optimal crop growth (p) and on readily available soil water (p. Sa) for different soil types. Data presented in Table 39 consider ETcrop to be 5 to 6 mm/day and rooting depth refers to full grown crops. When ETcrop is 3 mm/day or smaller, the readily available soil water (p. Sa) can be increased by some 30 percent; when ETcrop is 8 or more mm/day it should be reduced by some 30 percent. Depth of rooting will depend on many factors and should be determined locally. When the project is operational, refinements will be required and local information should be collected; this particularly applies to the soil water depletion levels for each crop during the different growing stages. Reference should also be made to the comprehensive reviews available on crop response to soil water deficits at different stages of crop growth. [1]

EXAMPLE:
Given:
Cotton; medium textured soil, ET cotton is 9.5 mm/day; rooting depth is 1.5m; application efficiency is 0.65.
Calculation:
Available soil water (Sa) (Table 38) = 140 mm/m
Fraction of available soil water (p) (Table 39) = 0.65
Readily available soil water (p. Sa) = 91 mm/m
Correction for ETcrop = 0.7
Rooting depth (D) = 1.5 m
Readily available soil water (p. Sa). D = 95 mm
Depth of irrigation 95/Ea = 150 mm

(ii) Irrigation application interval (i)

Correct timing of irrigation applications is of over-riding importance. Delayed irrigations, particularly when the crop is sensitive to water stress, could affect yields, which cannot be compensated for by subsequent over-watering. Timing of irrigation should conform to soil water depletion requirements of the crop which are shown to vary considerably with evaporative demand, rooting depth and soil type as well as with stages of crop growth. Therefore, rather than basing irrigation interval on calendar or fixed schedules, considerable flexibility in time and depth of irrigation should be maintained to accommodate distinct differences in crop water needs during the crop's growing cycle. These detailed considerations are often not covered at the design stage. General information on field scheduling, however, should be available before selecting the method of canal operation and undertaking

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[1] Slatyer, R.O. Plant-water Relationships. Academic Press, 1967.
Hagan, R.M., Haise, H.R. and Edminster T.W. Irrigation for agricultural lands. ASA No. 11, 1967.
Kozlowski, T.T. Water Deficits and Plant Growth I, II and III. Academic Press, 1968.
Salter P.J. and Goode, J.E. Crop responses to water at different stages of growth. Commonwealth Agricultural Bureau, 1967.
Vaadia Y.F. et al. Plant water deficits and physiological processes. American Review of Plant Physiology. 12:265-292, 1961.

Table 39 Generalized Data on Rooting Depth of Full Grown Crops, Fraction of Available Soil Water (p) and Readily Available Soil Water (p.Sa) for Different Soil Types (in mm/m soil depth) when ETcrop is 5 - 6 mm/day

Crop	Rooting depth (D) m	Fraction (p) of available soil water[1]	Readily available soil water (p.Sa) mm/m[1] fine	medium	coarse
Alfalfa	1.0 - 2.0	0.55	110	75	35
Banana	0.5 - 0.9	0.35	70	50	20
Barley[2]	1.0 - 1.5	0.55	110	75	35
Beans[2]	0.5 - 0.7	0.45	90	65	30
Beets	0.6 - 1.0	0.5	100	70	35
Cabbage	0.4 - 0.5	0.45	90	65	30
Carrots	0.5 - 1.0	0.35	70	50	20
Celery	0.3 - 0.5	0.2	40	25	10
Citrus	1.2 - 1.5	0.5	100	70	30
Clover	0.6 - 0.9	0.35	70	50	20
Cacao		0.2	40	30	15
Cotton	1.0 - 1.7	0.65*	130	90*	40
Cucumber	0.7 - 1.2	0.5	100	70	30
Dates	1.5 - 2.5	0.5	100	70	30
Dec. orchards	1.0 - 2.0	0.5	100	70	30
Flax[2]	1.0 - 1.5	0.5	100	70	30
Grains small[2]	0.9 - 1.5	0.6	120	80	40
winter[2]	1.5 - 2.0	0.6	120	80	40
Grapes	1.0 - 2.0	0.35	70	50	20
Grass	0.5 - 1.5	0.5	100	70	30
Groundnuts	0.5 - 1.0	0.4	80	55	25
Lettuce	0.3 - 0.5	0.3	60	40	20
Maize[2]	1.0 - 1.7	0.6	120	80	40
silage		0.5	100	70	30
Melons	1.0 - 1.5	0.35	70	50	25
Olives	1.2 - 1.7	0.65	130	95	45
Onions	0.3 - 0.5	0.25	50	35	15
Palm trees	0.7 - 1.1	0.65	130	90	40
Peas	0.6 - 1.0	0.35	70	50	25
Peppers	0.5 - 1.0	0.25	50	35	15
Pineapple	0.3 - 0.6	0.5	100	65	30
Potatoes	0.4 - 0.6	0.25	50	30	15
Safflower[2]	1.0 - 2.0	0.6	120	80	40
Sisal	0.5 - 1.0	0.8	155	110	50
Sorghum[2]	1.0 - 2.0	0.55	110	75	35
Soybeans	0.6 - 1.3	0.5	100	75	35
Spinach	0.3 - 0.5	0.2	40	30	15
Strawberries	0.2 - 0.3	0.15	30	20	10
Sugarbeet	0.7 - 1.2	0.5	100	70	30
Sugarcane[2]	1.2 - 2.0	0.65	130	90	40
Sunflower[2]	0.8 - 1.5	0.45	90	60	30
Sweet potatoes	1.0 - 1.5	0.65	130	90	40
Tobacco early	0.5 - 1.0	0.35	70	50	25
late		0.65	130	90	40
Tomatoes	0.7 - 1.5	0.4	180	60	25
Vegetables	0.3 - 0.6	0.2	40	30	15
Wheat	1.0 - 1.5	0.55	105	70	35
ripening		0.9	180	130	55
Total available soil water (Sa)			200	140	60

[1] When ETcrop is 3 mm/day or smaller increase values by some 30%; when ETcrop is 8 mm/day or more reduce values by some 30%, assuming non-saline conditions (ECe < 2 mmhos/cm).

[2] Higher values than those shown apply during ripening.

Sources: Taylor (1965), Stuart and Hagan (1972), Salter and Goode (1967), Rijtema (1965) and others.

detailed field design. The irrigation interval can be obtained from:

$$i = \frac{(p.Sa).D}{ETcrop}$$

The efficiency of irrigation application is not considered when determining i.

EXAMPLE:
Given:
Cotton; ETcotton is 9.5 mm/day; readily available soil water over the root zone during full growth corrected for ETcotton (p.Sa).D = 95 mm.
Calculation:
Irrigation application interval (i) is 95/9.5 = 10 days

(iii) Calculation of field irrigation schedules

A first evaluation of depth (d) and interval (i) of irrigation application for the whole growing season can be made using the monthly soil water balance and soil water depletion data. The steps needed are shown together with a hypothetical example:

1 - 5 Determine running soil water balance for the growing season without irrigation on monthly (or shorter)basis or soil water available at end of each month (We) is We = Wb + Ge + Pe - ETcrop (mm/month)

6 Plot We in mm at end of each month and draw curve (6).

7 Determine for given soil and crop the depth of total available soil water stored in the root zone (Sa.D) using Table 38 and plot values; make adjustment for beginning of growing season during which the roots develop.

8 Determine from Table 39 fraction (p) of total available soil water and correct for ETcrop. Calculate (1 - p)Sa.D for each month and plot; make adjustment for first part of growing season.

9 When soil water balance curve (6) meets soil water depletion curve (8), replenish soil water with (p.Sa).D by drawing vertical line between (8) and (7).

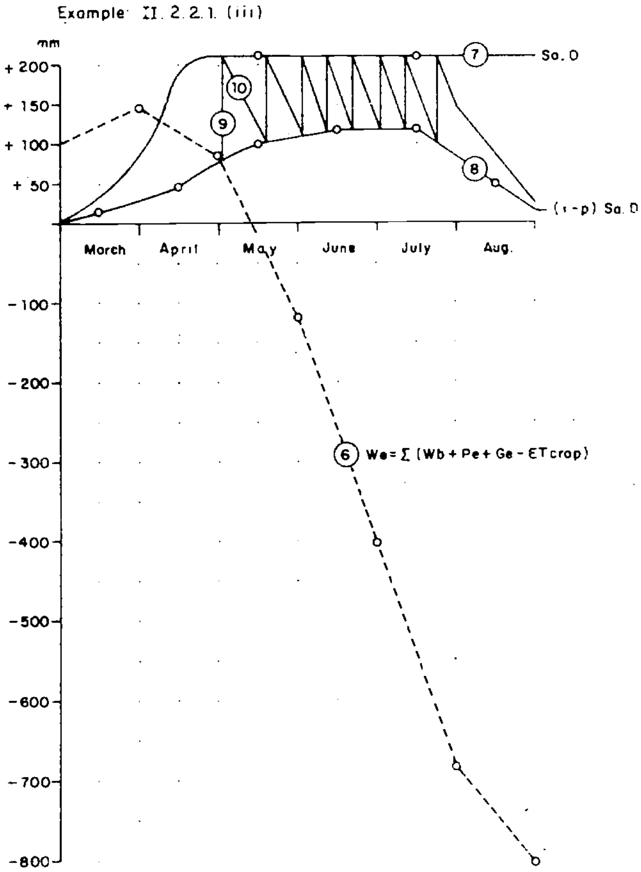
10 Plot new soil water balance curve (10) starting from line (7) and parallel to line (6) for that period until line (8); repeat step (9).

11 Determine number of irrigations for each month.

12 Determine net depth of irrigation for each month.

13 Determine interval of irrigation for each month.

14 Add application losses and leaching water to determine supply requirements.



EXAMPLE:

Given:

Cotton; growing season March through August. Crop, soil and climatic data as given below; rooting depth end April is 1.5 m; soil is medium textured.

Calculation:

	M	A	M	J	J	A
			all in mm			
(1) Wb begin. of month	+100	+145	+ 85	-120	-405	-685
(2) Pe rainfall	+ 90	+ 50	+ 20			
(3) Ge groundwater						
(4) ETcotton	- 45	-110	-225	-285	-280	-120
(5) We end of month	+145	+ 85	-120	-405	-685	-805

(6) Plot We at end of months as given.

(7) Total available soil water (Sa) is 140 mm/m soil (Table 38) or at full crop growth (Sa.D) = 140 x 1.5 = 210 mm; plot values and correct for early growing season.

(8) For medium textured soil and given ETcotton determine fraction (p) of available soil water and (1 - p)Sa.D in mm.

	M	A	M	J	J	A
fraction (p)	0.65	0.65	0.65	0.65	0.65	0.65
ETcrop mm/day	1.5	3.5	7.5	9.5	9.0	4.0
corrected p	0.9	0.8	0.5	0.45	0.45	0.75
(1 - p)Sa.D mm	(20)	(45)	105	115	115	50

(9) and (10) Give graphical interpretation as indicated.

	M	A	M	J	J	A
(11) No of irrigations per month	0	0	2	3	3	0
(12) Net depths of irrigation mm			125 105	100 95 95	95 95 110	
(13) Irrigation interval day			- 17	14 10 10	10 10 12	

(14) Add leaching requirement and application efficiency.

2.2.2 Field Irrigation Supply Schedules

Field supply is primarily determined by the field irrigation schedules (depth and interval of irrigation) and by the method the water is distributed to and applied over the fields. The method of irrigation application (surface, sprinkler, drip) is in turn determined by factors such as type of crop, soil type, need for land grading, water use efficiency, erosion hazards, salinity of the irrigation water, cost and others. Field irrigation supply at the time of irrigation for a given soil, crop and level of evaporative demand is:

$$q.t = \frac{10}{Ea} (p.Sa).D.A \quad m^3$$

where:
q = stream size in l/sec
t = supply duration in seconds
Ea = application efficiency, fraction
Sa = total available soil water, mm/m soil depth
p = fraction of total available soil water permitting unrestricted evapotranspiration and/or crop growth, fraction
D = rooting depth, m
A = acreage, ha

EXAMPLE:

Given:

Cotton, June, medium textured soil, ET crop is 9.5 mm/day; readily available soil water is 0.7 x 90 = 65 mm/m soil depth, rooting depth is 1.5 m, application efficiency is 0.65, field size is 3 ha.

Calculation:

$$q.t = \frac{10}{0.65} \cdot 65 \cdot 1.5 \cdot 3 = 4\ 500\ m^3$$

To obtain a first estimate of q and t, by converting the depth of water to be applied into stream size and supply duration, Table 40 or monograph Fig. 19 can be used. The Table and monograph do not take into account the irrigation application rate, irrigation method and practices, and the stream size that can be handled by the irrigator, and as such may give unrealistic estimates. Estimates of q and t must be evaluated on the basis of the different irrigation methods and practices.

Table 40 Average Intake Rates of Water in mm/hr for Different Soils and Corresponding Stream Size l/sec/ha

Soil Texture	Intake Rate mm/hr	Stream size q l/sec/ha
Sand	50 (25 to 250)	140
Sandy loam	25 (15 to 75)	70
Loam	12.5 (8 to 20)	35
Clay loam	8 (2.5 to 15)	22
Silty clay	2.5 (0.03 to 5)	7
Clay	5 (1 to 15)	14

Fig. 19 Monograph showing Relation between Depth of Irrigation, Area Irrigated, Volume of Irrigation Water, Supply Duration and Stream Size
(after Israelson and Hansen)

se:

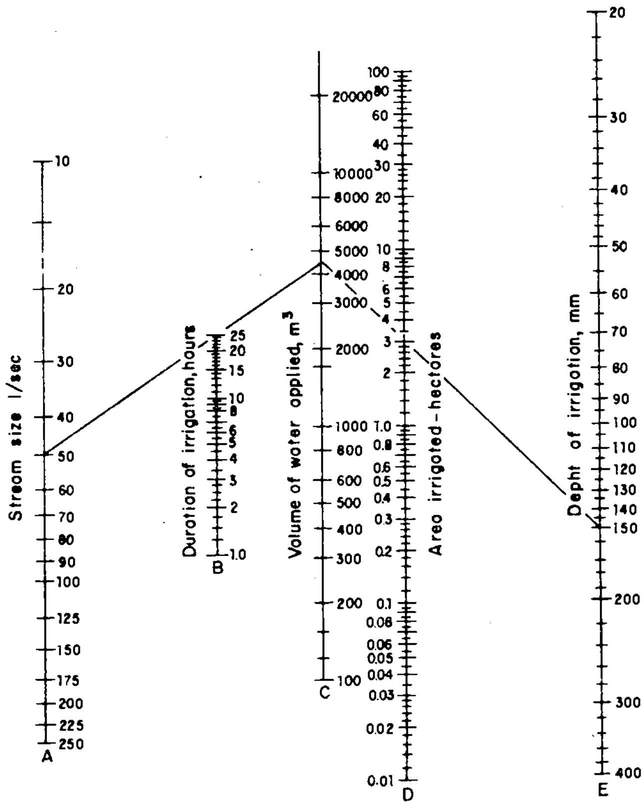
1 Select appropriate vales on scales A, D and E.

Lay ruler from the point on scale E through the point on scale to scale C.

3. Place the point of a sharp pencil against the ruler on scale C.

4. Slide the ruler on the pencil to the point on scale A.

5. The answer appears where the ruler intersects scale B.



EXAMPLE:
Given:
Depth of irrigation is 150 mm, acreage is 3 ha, available stream size q is 50 l/sec
Calculation:
Using monograph Fig. 19, t = 25 hrs.

(i) Surface irrigation

For a given field, the stream size (q in l/sec or m^3/sec) will depend mainly on the type of soil or infiltration rate, on the method of surface irrigation and the number and size of furrows, borders or basins that can be irrigated simultaneously.

In the case of the basin (or level border) method, to attain uniform water distribution the flow of water to each basin should be at least two times or more that required for the average soil intake rate, i.e. the water should be applied between 0.2 and 0.4 of the time necessary for the required depth of water to enter the soil. In the case of furrow and border irrigation, the flow of water per furrow or border should be large enough to reach the end of the run, and small enough not to cause erosion, flooding and tail losses. The size of the flow must be adjusted to the infiltration rate of the soil, the length of run, land slope, erosion hazard, shape of the flow channel and the water depth to be applied. The stream size (q) that can be handled by an irrigator is 20 to 40 l/sec.

Information on irrigation methods must be available at the design stage of the project, and field trials on irrigation methods and practices are required. For reference, the flow in l/sec for a suggested size or length of field under basin, border and furrow irrigation is given for different soil types and land slopes in Tables 41, 42 and 43. These data apply to well graded fields.[1]

EXAMPLE:
Given:
Cotton, with water application of 150 mm including application losses.
Soil is medium textured; land slope is 0.5%. Furrow irrigation with spacing 0.8 m; 20 furrows can be operated simultaneously.
Calculation:
Table 42: length of furrow = 470 m
Table 42: average flow per furrow = 1.25 l/sec
q is number of furrows x average flow = 20 x 1.25 = 25 l/sec
t is area x depth of application divided by q or
(20 x 0.8 x 470) x 0.15/0.025 = 45 000 sec or = 12.5 hrs
With day and night irrigation, the area irrigated per
day is (24/12.5) x 20 x 0.8 x 470/1 000 ≅ 1.5 ha

(ii) Sprinkler irrigation

The determination of the field irrigation supply for sprinkler irrigation is similar to that for surface irrigation, the main difference being the detail of information required to operate the system so as to minimize the equipment required.

The stream size is determined by the application rate which in turn is governed by the basic intake of the soil and by the number of sprinklers operating simultaneously. This latter is determined by the system layout, which in turn is largely dictated by size and shape of the field, irrigation interval and the farmer's preference on number of hours per day and number of days per week the system will operate. These factors have a distinct effect on stream size and supply duration.

---

[1] For the evaluation of irrigation methods, reference is made to Merriam (1968), Slabbers (1971) and Booher (1973).

Table 41 Size of Basins and Stream Size for Different Soils※

Size of basin (ha)				flow (l/sec)
Sand	Sandy Loam	Clay Loam	Clay	
.02	.06	.12	.2	30
.05	.16	.30	.5	75
.10	.30	.60	1.0	150
.15	.45	.90	1.5	225
.20	.60	1.20	2.0	300

Table 42 Length of Furrows and Stream Size for Different Soil Type, Land Slope and Depth of Water Application ※

Slope (%)	Length of furrow (m)												average flow (l/sec)
	heavy texture				medium texture				light texture				
0.05	300	400	400	400	120	270	400	400	60	90	150	190	12
.1	340	440	470	500	180	340	440	470	90	120	190	220	6
.2	370	470	530	620	220	370	470	530	120	190	250	300	3
.3	400	500	620	800	280	400	500	600	150	220	280	400	2
.5	400	500	560	750	280	370	470*	530	120	190	250	300	1.25
1.0	280	400	500	600	250	300	370	470	90	150	220	250	.6
1.5	250	340	430	500	220	280	340	400	80	120	190	220	.4
2.0	220	270	340	400	180	250	300	340	60	90	150	190	.3
Application depth (mm)	75	150	225	300	50	100	150	200	50	75	100	125	

Table 43 Size of Borders and Stream Size for Different Soil Type and Land Slope (Deep Rooted Crops)※

Soil type	Slope (%)	Width (m)	Length (m)	Average flow (l/sec)
Sand	.2 - .4	12 - 30	60 - 90	10 - 15
	.4 - .6	9 - 12	60 - 90	8 - 10
	.6 - 1.0	6 - 9	75	5 - 8
Loamy sand	.2 - .4	12 - 30	75 - 150	7 - 10
	.4 - .6	9 - 12	75 - 150	5 - 8
	.6 - 1.0	6 - 9	75	3 - 6
Sandy loam	.2 - .4	12 - 30	90 - 250	5 - 7
	.4 - .6	6 - 12	90 - 180	4 - 6
	.6 - 1.0	6	90	2 - 4
Clay loam	.2 - .4	12 - 30	180 - 300	3 - 4
	.4 - .6	6 - 12	90 - 180	2 - 3
	.6 - 1.0	6	90	1 - 2
Clay	.2 - .3	12 - 30	350+	2 - 4

※Under conditions of perfect land grading.

For a given system, the depth and interval of irrigation can be changed by varying the application duration and number of days between irrigations. Any alteration in the number of laterals and sprinklers operating at any time, other than that laid down in the design, may negatively affect the operation and uniformity of water application, unless flow and pressure regulators are used. The total stream size should therefore as far as possible conform to the discharge rate used in the design.

EXAMPLE:
<u>Given</u>:
Cotton; ETpeak is 9.5 mm/day; basic intake rate is 10 mm/hr; depth per application net is 95 mm; application efficiency is 0.75.
<u>Calculation</u>:
Application time (t) is (95/0.75)/10 = 12 hours
For 10 mm/hr, spacing 18 x 18, required stream size per sprinkler is 10 x 18 x 18/1 000 = 3.25 m^3/hr
From Table 44, nozzle size 5.0/5.5 mm, pressure 2.5 atm.
For given field size and shape, with no off hours of application per day and per week and irrigation interval, the system layout including number of sprinklers per lateral (usually maximum 15) and number of laterals operating simultaneously can be found. Stream size (q) is found by the number of sprinklers and number of laterals operating at one time multiplied by sprinkler discharge.
Total pressure required at the pump can be determined from pipe friction losses, sprinkler height over the pump, and pressure at sprinkler nozzle. Water lift to pump and pump efficiency is to be added when selecting type and size of pump.

Table 44 Operating Figures for Some Sprinklers (Square Pattern)

Nozzle mm	Pressure kg/cm^2	Wetted Diameter m	Discharge m^3/hr	Spacing m	Area Irrigated m^2	Precipitation mm/hr
4.5	2.0	13.5	1.1	12 x 18	215	5.0
	2.5	14.0	1.2	12 x 18	215	5.5
	3.0	14.5	1.3	18 x 18	325	4.1
5.0	2.0	13.5	1.3	12 x 18	215	6.2
	2.5	14.5	1.5	18 x 18	325	4.6
	3.0	15.0	1.6	18 x 18	325	5.0
6.0	2.0	14.5	1.9	18 x 18	325	6.0
	2.5	16.3	2.2	18 x 24	430	5.0
	3.0	16.5	2.8	18 x 24	430	5.5
4.5/4.8	2.0	14.0	2.3	12 x 18	215	10.8
	2.5	14.8	2.6	18 x 18	325	8.0
	3.0	15.5	2.8	18 x 18	325	8.8
5.0/5.5	2.5	16.0	3.3	18 x 18	325	10.2*
	3.0	16.3	3.6	18 x 24	430	8.4
	3.5	16.6	3.9	18 x 24	430	9.1
5.0/7.5	3.0	19.0	5.3	24 x 24	575	9.3
	3.5	19.3	5.8	24 x 24	575	10.7
	4.0	20.0	6.2	24 x 24	575	10.7
6.0/7.5	3.0	17.7	6.1	18 x 24	430	14.0
	3.5	18.5	6.6	24 x 24	575	11.3
	4.0	19.0	7.0	24 x 24	575	12.2

(iii) Drip irrigation

With a drip system, irrigation water is supplied to individual trees, groups of plants or plant rows by emitters placed on laterals delivering a flow (qe) of 2 to 10 l/hr each. The stream size is determined by the number and type of emitters, soil type, crop and allowable soil water depletion. In a well-operated system a nearly constant low soil water tension can be maintained in the root zone. For a selected level of soil water depletion and knowing ETcrop and soil infiltration rate, the frequency and duration of application can be determined. Information on flow rates is given in Tables 45, 46 and 47.

EXAMPLE:

Given:

Tomatoes; acreage (A) is 40 ha; ETpeak is 7 mm/day; soil intake rate is 5 mm/hr; total available soil water (Sa) is 140 mm/m soil depth, at time of irrigation (1 - p)Sa is 90 mm/m soil depth; rooting depth (D) is 1 m. Row spacing (l_1) is 1.2 m with emitter spacing (l_2) of 0.6 m; emission uniformity (Eu) is 0.95; application losses including evaporation 0.90; emitter flow (qe) selected is 2 l/hr.

Calculation:

Fraction of surface area wetted (P) using Table 47 is w/(l_1 x l_2) = 0.4/(1.2 x 0.6) = 0.55
Depth of application (d) = (p.Sa)D.P/(Eu.Ea) = 32 mm
Irrigation interval (i) is (p.Sa)D.P/ETcrop = 4 days
Flow duration (t) is d x l_1 x l_2/qe = 11.5 hours
Operation unit (N) is (i x 24)/t = 8
Stream size required assuming continuous operation of the system 2.8A/N x qe/(l_1 x l_2) = 39 l/sec

Table 45 Flow Rate per Drip Emitter (qe) in l/hr, Continuous Flow, for Different ETcrops and Number of Emitters per ha

ETcrop mm/day	Emitters per ha							
	250	500	750	1000	1500	2000	2500	5000
1.25	2.08	1.04	0.69	0.52	0.35	0.26	0.21	0.10
2.50	4.16	2.08	1.38	1.04	0.69	0.52	0.42	0.21
3.75	6.25	3.12	2.08	1.56	1.04	0.78	0.62	0.31
5.00	8.33	4.16	2.77	2.08	1.39*	1.04	0.83	0.42
6.25	10.41	5.12	3.47	2.60	1.74	1.30	1.04	0.52
7.50	12.50	6.25	4.17	3.13	2.08	1.56	1.25	0.63

Table 46 Flow Rate per Tree, Continuous Flow, for Different ETcrop and Tree Spacing, l/hr

Tree spacing m	ETorchard mm/day		
	5	6.25	7.5
6 x 6	7.5	9.5	11
9 x 9	17	21	25
12 x 12	30	37	45
15 x 15	47	59	70
18 x 18	67	84	101

Table 47 Surface Area Wetted (w) in m^2 for Different Emitter Flow and Soil Infiltration Rate

Emitter flow l/hr cont.	Soil infiltration rate mm/hr		
	2.5	5	7.5
2	0.8	0.4*	0.25
4	1.6	0.8	0.50
6	2.4	1.2	0.75
8	3.2	1.6	1.00

2.2.3 Design and Operation of Supply System

Following the preparation of detailed field and canal layout the criteria on which the canal system will operate need to be developed. The method of operating the supply system can be broadly delineated as continuous, rotational and supply on demand. With the continuous method of supply the system is constantly in operation with supply adjusted to the changing irrigation requirements over the season. The method is mainly used for the main canals supplying acreages of 50 ha or more. Only in the case of some monocultures such as rice, pastures and orchards is the continuous supply sometimes maintained up to the field level.

Rotation is most commonly used for surface irrigation; a fixed supply is normally selected and changes in irrigation requirements are met by adjusting the duration and interval of supply. Supply schedules should be prepared in advance. The method is not well adapted to a diversified cropping pattern or sudden large changes in supply requirements.

For optimal operation, the free demand or random supply method requires high investments in canal structures and a high level of management. It is primarily restricted to closed conduit pressure systems such as sprinkler irrigation or small projects (smaller than 50 ha), with adequate control of the water source such as pump irrigation from streams or wells. Within certain limitations the method allows the user of water to take irrigation water when desired.[1]

To develop the operation of the supply system the following indicators can be used:

- supply requirement factor fi = Vi/Vmax which for a given period i is the ratio between the average daily supply requirements during the period i (Vi in m^3/day) and the average maximum daily supply requirements during the peak water use period (Vmax in m^3/day)
- supply factor fs = Qi/Qmax which for a given period i is the ratio between the required stream size during the period i (Qi in m^3/sec) and the maximum possible stream size or canal capacity (Qmax in m^3/sec)
- supply duration factor ft = T/I which is the ratio between supply duration (T in days) and the supply interval (I in days)
- design factor α = 86 400 Qmax/Vmax which is the ratio between the maximum possible stream size or canal capacity (Qmax in m^3/sec) and the average maximum daily supply requirement during the peak water use period (Vmax in m^3/day) on which the design is based

For the different methods of supply the values of the indicators can be summarized as follows:

	fi	fs	ft	α	
continuous	0 - 1	0 - 1	1	1	> 50 ha except possibly for rice (fi = fs)
rotational	0 - 1	1	0 - 1	1 - 5	50 - 250 ha
				> 5	< 50 ha
demand	0 - 1	0 - 1	0 - 1	> 1	all acreages

---

[1] I. Nugteren. Technical aspects of water conveyance and distribution systems. In: Water Use Seminar, Damascus. Irrigation and Drainage Paper 13, FAO Rome. p.170-185.
Fukuda H. and Tsutsui H. Rice irrigation in Japan. OTCA, Tokyo. 88p.

(i) Continuous supply

With continuous supply the system is constantly in operation. The discharge in the canal system is adjusted to the daily irrigation requirements; the supply is distributed within the system proportionally to the acreages served. The design is based on:

$$Q_{max} = \alpha V_{max}/86\,400\ E$$

where: Q_{max} = canal capacity, m^3/sec
V_{max} = maximum average daily supply requirements in peak water use period for given crop acreage, m^3/day
α = design factor
E = efficiency factor of conveyance and/or field canal, fraction

Disregarding efficiency and any over-capacity, the design factor α is equal to one. Since the supply during any part of the irrigation season needs to follow the daily irrigation supply requirements, the supply factor (fs) is equal to the supply requirement factor (fi). The supply duration factor (ft) is equal to one.

With the continuous supply method, construction costs are minimal since the design factor α is approximately equal to one. The supply is regulated mainly by simple diversion structures which are easy to operate. Accurate adjustments in the supply proportional to actual field requirements are difficult to handle particularly when stream sizes become small, resulting in low efficiency (see Ep for rice, Table 37,equal to 0.32, ICID/ILRI). However, except possibly for some rice schemes, the fields need to be irrigated at given intervals, and at the field level an interrupted or rotational delivery will be required. Continuous supply is in general limited to canals serving 50 ha or more, and within the 50 ha block the supply is rotated among the individual fields.

(ii) Rotational supply

With rotational supply the capacity and operation of the distribution system is based on a constant or fixed supply to each field or farm (q) while the supply duration (T) and supply interval (I) is varied according to the changing field irrigation requirements over the growing season. When in operation each canal section carries the maximum discharge (Qmax in m^3/sec). With a fixed supply delivered to each farm, usually for 1 or 2 days during the supply interval of some 10 to 20 days, rotations must be introduced between farm inlets and/or distributory canals. Since the distribution system always carries the maximum discharge, the whole system is closed for part of the time when irrigation requirements are low.

Rotational supply, with rotation blocks of 50 to 250 ha, is well adapted to schemes with a single crop or simple cropping pattern. An advantage is the relatively high conveyance efficiency since canals are either fully filled or empty. Supply can be regulated from headworks and few check structures are required. Large variations in discharges are avoided reducing sedimentation problems. An equitable distribution of available water among farmers can be achieved. A main disadvantage can be that water supply to a diversified cropping pattern with distinct, different irrigation requirements over area and time is very problematic. The supply interval to each farm does vary over the season but is the same for all crops unless different crops are grown over large acreages or special provisions are provided such as introduction of double rotations. While the operation of the system, i.e. the supply schedules, must meet the changing field requirements over the season, the design criteria are based on supply requirements for the peak water use month.

The evaluation of the design and operation criteria of the system should start with an analysis of the field irrigation requirements. Starting at the field level, a constant or fixed stream size (q) should preferably be selected. This is not an absolute requirement but the use of a fixed stream size throughout the system simplifies the setting up of supply schedules and a certain degree of standardization of the capacity of canals and water control structures is achieved. The capacity of each canal section is then a multiple of q; to this an allowance must be added for the irrigation efficiency (E). The stream size selected is based on the method of irrigation and the way the water is distributed over the field or farm. It should easily be handled by one irrigator or between 20 and 40 l/sec. For large farms q can be increased 2 or 3 times.

The operation of the distributary canal supplying the individual field or farm is expressed in supply duration (T) and supply interval (I), which in turn are based on the supply that is required at the field level (q.t) and the field application interval (i) (2.2.2). The operation of the supply system is subsequently worked out for the tertiary, secondary and primary canals, taking into account the rotational system selected. However, with a fixed stream size (q) to each farm, the supply duration (T) to each field or farm at any time is in relation to the farm acreage. When possible, the farms as well as groups of farms or irrigation blocks should have approximately the same acreage since irrigation schedules can thus be more easily adjusted to the changing irrigation supply requirements over the growing season.

The capacity of the canal system is determined by the design factor α, which depends on the ratio 86 400 Qmax/Vmax, as well as on the duration (T) the canal is in operation during the interval (I) during the peak water use period, or:

$$\mathrm{Qmax} = \alpha\,\mathrm{Vmax}/86\,400\,E$$

and $$\alpha = I/T = 1/ft$$

where:
Qmax = maximum stream size or canal capacity, m^3/sec
Vmax = average maximum daily supply requirements during the peak water use period, m^3/day
α = design factor
E = efficiency, fraction
I = supply interval, during peak water use period, days
T = supply duration during peak water use period, days
ft = supply duration factor during peak water use period, fraction

For the main canals serving acreages of 50 to 250 ha, the value of α will be approximately equal to one as this simplifies canal operations and requires the least construction costs. For the distributary canals within the 50 to 250 ha, the canal will be operated on rotation and values of α will be greater than one. The part of the distribution system operating on rotation can be seen by the transition of small α values and large ft values of the main canals into small ft values and large α values of the distributary canals and/or farm inlets. The selection of rotation system will have to be made at an early stage. It will depend amongst others on the farm and farm block acreage and layout, flow control, ease of operation of the system and cost of construction.

A number of examples are mentioned on possible rotation systems. Note that the purely hypothetical examples are meant to show calculation procedures only.

A common type of rotation system is where the supply of the distributary canal is rotated among the farm inlets situated along the distributary canal. Except for the farm inlet, the design factor α is equal to one for all canals. Each farm inlet will receive the fixed stream size (q) with duration depending on irrigation requirements but proportional to the farm acreage. (Also stream size can vary but this requires localized arrangements.)

EXAMPLE:

(1) Rotation amongst 10 farms of equal size situated along a distributary canal; field supply interval (i) is 10 days; supply duration (t) is 1 day.
For each farm inlet ft = 0.1 and α = 10
For distributary and upstream canal sections ft = 1 and $\alpha \cong 1$

(2) Rotation amongst 4 farms of 1, 2, 2 and 5 ha each located along one distributary canal; field supply interval (i) is 10 days.
Farm inlet ft = 0.1, 0.2, 0.2 and 0.5 and $\alpha \cong$ 10, 5, 5 and 2.
For distributary and upstream canal sections ft = 1 and $\alpha \cong 1$

A more accurate supply can usually be obtained by simultaneously supplying all farms situated along the distributary canals and rotation of the fixed stream size among distributary canals.

EXAMPLE:
Rotation among 10 distributary canals each supplying 10 farms of approximately equal acreages; i is 10 days.
For each farm inlet ft = 0.1 and $\alpha \cong 10$
For each distributary ft = 0.1 and $\alpha \cong 10$
For upstream canal sections ft = 1 and $\alpha \cong 1$

With large design factors the operation of the distribution system may become rather complicated and expensive. To simplify operations a second rotation may, when needed, be applied, one between tertiary and one between distributary canals.

EXAMPLE:
<u>Given</u>:
Cotton on 150 ha; from example 2.2.2 Surface irrigation stream size (q) is 25 l/sec and during peak water use periods delivery time (t) is 25 hours, irrigating 1.5 ha; delivery interval (i) is 10 days; supply requirement in peak season is 15 mm/day or Vmax is 150 m3/day/ha.
Water is supplied by one secondary canal serving 150 ha; the supply is rotated among 2 tertiary canals each supplying 75 ha; tertiary canal supply is rotated among 5 distributary canals each supplying 15 ha; on each distributary canal 5 farms each of 3 ha are supplied simultaneously.
<u>Calculation</u>:
Supply duration (t) to each 3 ha farm in peak period is 1 day out of 10 days with stream size 2 x q = 50 l/sec. α = 86 400 Qmax/Vmax.
farm inlet : α = 86 400 x 0.050/450 $\cong$ 10 ft = 0.1
distributary : α = 86 400 x 0.250/2 250 $\cong$ 10 ft = 0.1
tertiary : α = 86 400 x 0.250/11 250 $\cong$ 2 ft = 0.5
secondary : α = 86 400 x 0.250/22 500 $\cong$ 1 ft = 1
upstream sections : $\alpha \cong$ 1 ft = 1
Note: If the tertiary canal would supply simultaneously the 5 distributary canals which are in turn supplying 1 farm per day, the capacity of the distributary can be reduced from 250 to 50 l/sec which may be a simpler and cheaper solution. In this latter case:
farm inlet : α = 86 400 x 0.050/450 $\cong$ 10 ft = 0.1
distributary : α = 86 400 x 0.050/2 250 $\cong$ 2 ft = 0.5
tertiary : α = 86 400 x 0.250/11 250 $\cong$ 2 ft = 0.5
secondary : α = 86 400 x 0.250/22 500 $\cong$ 1 ft = 1

At the design stage, an accurate evaluation of the operation of the supply system can only be made when pilot projects have previously been started. However, as shown, a number of criteria in the operation of the system should and can be used, using pre-arranged schedules. These schedules can be either rigid (fixed supply with fixed duration and fixed interval) or, preferably, flexible and adjusted to changes in cropping patterns and field irrigation requirements. The canal system, however, remains to be operated at the maximum discharge (Qmax), while duration (T) and interval (I) of supply is varied. The delivery schedule to each farm is, however, based on the irrigation requirements of the main crop and the other crops are supplied on the same schedule. Only in the case of extensive acreage of shallow rooted crops, requiring more frequent irrigation as compared to the main crop, can an extra or double rotation be included during the supply interval based on the main crop. During periods of low irrigation requirements the supply is interrupted for longer periods. The period (T) out of the supply interval (I) that each canal is operating is $T = (fi/\alpha)I$; each canal is closed $(1 - fi/\alpha)I$.

EXAMPLE:

Given:

Cotton on 150 ha. Water distribution system same as previous example. Average daily supply requirement (Vi) during May is 115 m^3/day/ha and irrigation interval (i) is 17 days (see example 2.2.2 Surface irrigation); as previously given maximum daily supply requirement (Vmax) is 450 m^3/day/ha and design factor (α) for farm inlet is 10, for distributary canal is 10, for tertiary canal is 2 and for secondary and upstream canal is 1.

Calculation:

Supply requirement factor $fi = Vi/Vmax = 115/150 \cong 0.75$
Supply duration farm inlet $T = (fi/\alpha)I = (0.75/10)17 = 1.2$ days
distributary $T = (0.75/10)17 = 1.2$ days
tertiary $T = (0.75/\ 2)17 = 6.5$ days
secondary $T = (0.75/\ 1)17 = 13$ days

(iii) Supply on demand

Supply on demand allows the user(s) to take irrigation water as desired. The capacity of the supply system (canals or pipes) with free demand is based on a selected probability of the number of fields supplied simultaneously during the peak water use period.[1] A free demand supply is difficult to achieve in open canal systems. More common is the demand system with advance scheduling; requests for water are made 2 or 3 days in advance and the distribution of water is programmed accordingly. To operate the system efficiently water users should be acquainted with proper irrigation scheduling. A well-trained staff must be available to operate the system. It requires full control of water level and discharge of each part of the distribution system. Remodelling of schemes based on rotational supply is feasible provided basic data on irrigation scheduling are available and conditions mentioned can be met. High capital investment and a high level of management is required.

2.2.4 Summary Calculation of Project Design and Operation

The calculation procedure can be summarized for each month from the field irrigation schedules (2.2.1), the field irrigation supply schedules (2.2.2) and the design and operation of the supply system (2.2.3). At the design stage a number of assumptions have to be made; several alternatives in the operation of the supply system and field irrigation schedules should be considered. Enough flexibility should be built into the design to allow for future changes and refinements in meeting the field irrigation requirements. Supply schedules need to be adjusted once the project is in operation, which would include refinement of information on field variables (crop, soil and climate) as well as on conveyance and operation characteristics of the supply system. In a system operated on a continuous or rotational basis, subsequent improvements can be made to achieve a supply on demand, provided requests for supply are made 2 or 3 days in advance.

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[1] R. Clement. Calcul des débits dans les réseaux d'irrigation fonctionnant à la demands. La Houille Blanche No. 5. 1966.

An example is given summarizing the calculations required for a simplified flexible rotation supply:

EXAMPLE:

Field irrigation schedules:

1. Prepare for given crop and climate the running soil water balance, over the growing season according to $We = \sum (Wb + Pe + Ge - ETcrop)$ in mm/month.
2. Determine for given crop and soil the total available soil water over the rooting depth (D) or Sa.D; determine fraction (p) of total available soil water (Sa.D) allowing optimal growth and correct for ETcrop. Calculate (1 - p)Sa.D in mm for each month.
3. Plot running soil balance (We), total available soil water over rooting depth (Sa.D) and allowable soil depletion (1 - p)Sa.D in mm for each month; determine irrigation application timing and interval according to method given in 2.2.2.

Field supply schedules:

4. Determine criteria on method of irrigation and farm irrigation practices and select stream size (q) to field and farm in m^3/sec.
5. Determine maximum daily supply requirements during the peak water use period (Vmax) and average daily supply requirements (Vi) for each part of the growing season from $Vi = 10\ ETcrop/Ea$ (disregarding rainfall).

Design and operation:

6. Determine supply requirement factor $fi = Vi/Vmax$ for the growing season.
7. Select the method of supply for the selected canal system layout and give the design factor $\alpha = 86\,400\ Qmax/Vmax$ for the different canal sections; determine the supply duration $T = (fi/\alpha)i$ for the different canal sections over the irrigation season, in days.
8. Determine supply interruption of main canals during supply interval (i) in days.

The calculation example below is based on an irrigation section of 150 ha with cotton from March through August and supplied by rotation as described in previous examples under 2.2.1 and 2.2.3.

		M	A	M	J	J	A
1.	Wb beginning of month	+100	+145	+85	-120	-405	-685
	Pe rainfall	+ 90	+ 50	+20			
	Ge groundwater						
	ETcotton	- 45	-110	-225	-285	-280	-120
	We end of month, mm	+145	+ 85	-120	-405	-685	-805
2.	Rooting depth, m	0.20	1.25	1.50	1.50	1.50	1.50
	Sa medium texture, mm/m	140	140	140	140	140	140
	Sa.D, mm	30	175	210	210	210	210
	at ET cotton	1.5	3.5	7.5	9.5	9.0	4.0
	p corrected	0.9	0.8	0.5	0.45	0.45	0.75
	(1 - p)Sa.D, mm	(25)	(45)	105	115	115	50

3.	Date of irrigation			2/5	19/5	2/6	12/6	22/6	2/7	12/7	22/7
	Irrigation interval, days			17	14	10	10	10	10	12	
4.	Stream size (q), m^3/sec										
	to field		0.025								
	to farm		0.050								
5.	Daily supply Vi, m^3/day			115	115	150	150	150	140	140	
6.	Supply requirement factor, fi			0.75	0.75	1	1	1	0.95	0.95	
7.	Supply duration factor t, days										
	for farm inlet	($\alpha \cong 10$)		1.3	1.05	1	1	1	0.95	1.15	
	for distributary	($\alpha \cong 10$)		1.3	1.05	1	1	1	0.95	1.15	
	for tertiary	($\alpha \cong 2$)		6.5	5.25	5	5	5	4.75	5.75	
	for secondary	($\alpha \cong 1$)		13	10.5	10	10	10	9.5	11.5	
8.	Supply interruption in secondary canals, days			4	3.5	0	0	0	0.5	0.5	

3. PROJECT OPERATION

3.1 REFINEMENT OF FIELD SUPPLY SCHEDULES

To achieve high water use efficiencies and high production, the irrigation schedules should follow the variation in crop water needs during the growing season. Irrigation schedules prepared at the design stage should be continuously revised and updated once the project is in operation. This applies equally to most traditional irrigation schemes where field supply is still based on fixed quantities and fixed periods. In addition to refinement of supply criteria, this also concerns the hydraulic properties of the distribution system as well as the operation and management of such systems.

Adaptive Research

In order to develop the criteria for scheduling the supply and to obtain acceptable irrigation efficiencies, adaptive research should be carried out on representative soils typical of the project area. Field trials should be as large as possible and placed within the irrigated area to avoid the effect known as "clothesline" which can grossly affect the result obtained from a patchwork of small experimental plots. The research programmes should be continuous. The type and detail of adaptive research programmes will depend greatly on their purpose, but also on available financial resources, existing governmental organizations and institutes, and the experience of the staff. Adaptive research should start as early as possible, and, if possible, well before the stages of detailed project design and project execution. Institutions to provide the necessary information and to carry out the programme should be associated with the project, and for large schemes should be part of project administration.

To make optimum use of knowledge and experience available in the country the adaptive research programmes should be carried out in close collaboration with established national research institutes. Studies should reflect the most critical problems met in project design and operation. Field sub-stations should be established at the project site and be equipped to apply, on a practical scale, the results from research stations to local conditions. Apart from agronomic and fertilizer trials, their types of activity should include:

- evaluation of all water components in the field under selected irrigation treatments for various stages of crop growth and evaporative demand
- irrigation practices (frequency and amount studies); in the case of salinity hazard, leaching and cultural practices should be developed
- water/yield relationship as affected by water scheduling and seasonal and periodic water deficits on yield
- irrigation methods including field trials on layout, length of run, permissible stream size for irrigation method selected
- irrigation/fertilizer interactions.

The outcome of field experiments on irrigation practices and water/yield relationships for the project should allow the formulation of recommendations on depth and frequency of irrigation over the growing season for the different crops and soil types. Such recommendations must in turn be expressed in irrigation supply schedules and the operation of the distribution system should be adjusted accordingly.

To obtain usuable results the water-related experiments should preferably be conducted with adaptive high yielding varieties, a high fertility level and adequate pest control, with water remaining as the main variable. To obtain water/yield data from irrigation depth and frequency studies the type of experiments visualized are (i) with non-soil water stress conditions throughout the growing season, (ii) with fixed levels of soil water stress throughout the growing season, and (iii) with soil water stress during certain physiological stages of crop growth. Experiments under (i) would be based on calculated data on crop water needs (ETcrop) and on water holding characteristics for the main soil types (Table 38). Soil water depletion needs to be checked, for instance by use of tensiometers. With treatment (ii) the irrigation application is based on soil water depletion levels in the root zone which, for non-sensitive field crops could be for fine textured soils 80, 140 and 200 mm per m soil depth, for medium textured soils 60, 100 and 140 mm/m and for coarse textured soils 30, 45 and 60 mm/m. For water sensitive crops much lower values would apply (Table 39). Treatment (iii) is applied during certain stages of crop growth to save water without substantially reducing yields. Stress condition irrigating at for instance 60 and 80 percent depletion of available water should be applied outside the crop critical stages for water stress (Table 32). Frequently little factual data can be obtained and results of experiments are so-called "statistically insignificant" when irrigation treatments are based on fixed irrigation intervals throughout the growing season or are based on applying depths of irrigation water according to replenishing the root zone to field capacity and to fractions above and below field capacity.[1] Whenever salinity problems are involved, the available soil water must in addition to soil water potential also include the osmotic potential. Leaching requirements must be based on salt tolerance levels for the different crops (Table 36).

Practical field studies can be carried out in the irrigated fields and provide results the value of which is often greatly underestimated. They can also be used for demonstration and training purposes. The survival rate of such experiments may be low because of uncontrollable factors, the difficulty of maintaining the farmers' interest and keeping appropriate records. Close collaboration with the local extension service should be maintained.

The need to set up pilot projects before embarking on large-scale project development is evident. The pilot area should cover between 100 and 500 ha to allow analysis of future project operations. Apart from water requirement and application experiments, problems concerning water scheduling and the distribution of water, use of surface and/or groundwater, water and salt balance, and water use efficiency can be studied. The pilot scheme should be designed with an eye to its inclusion in the anticipated large project.

Data Collection

In addition to information on cropping patterns and practices including anticipated production plans, data on water availability, climate and soils should be collected on a continuous basis. On water availability this would include gauging of rivers and groundwater level fluctuations and

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[1] Rijtema P.E. and Aboukhaled, A. Crop water use. In: Research on Crop Water Use, Salt Affected Soils and Drainage in the Arab Republic of Egypt. FAO Near East Regional Office, Cairo. p. 72. 1975.

reservoir operations, together with periodic measurement of water quality and sediments.

An agro-meteorological station should be established at an early date. The station should be placed inside the project area and be surrounded by an irrigated field, minimum size 100 x 100 m. The station should be at least 10 x 10 m with short grass as ground cover. Observations at a field station should include (i) temperature, maximum and minimum; (ii) relative humidity (wet and dry bulb thermometers); (iii) precipitation (raingauge); (iv) wind (totalizers); (v) sunshine (Campbell Stokes sunshine recorder); and (vi) evaporation (Class A pan).[1/] The station should be established in collaboration with national meteorological services. For selection of instruments the national, accepted standards are normally followed. Properly trained meteorological observers should be employed. The services of an agro-meteorologist will be required to select the equipment and sites, to train personnel, to advise on observation programmes and for the analyses of the data obtained.[1/]

A detailed soil survey (scale 1:5 000 to 10 000) should have been completed before the design of the project. Additional investigations will be required, in particular on physical and chemical properties of the soil and their changes under prolonged irrigation.[2/] Soil salinity and groundwater table observations should be made at regular intervals.

Project Monitoring

Project monitoring should be executed on a permanent basis and include evaluation of method of supply and scheduling of irrigation water as well as water use efficiency studies by direct measurements of the separate components. Water use studies in the farmer's field are required. Particular attention may be given to land preparation, land grading and irrigation methods and practices for traditional and new cropping patterns. Scheme management including institutional aspects, personnel, communication facilities and improvement and maintenance schedules should be periodically reviewed. The closely related agricultural services often found complementary to the activities of the scheme management such as agricultural supplies, farm machinery, credit and extension will need to meet the changing demands for such services. Modification and renovation of systems should be considered as an integral part of the long-range planning of irrigation development.

3.2 APPLICATION OF FIELD IRRIGATION DATA

Once the irrigation data for a given crop, soil and climate are available, various ways can be used to put these data into practice. The supply to individual fields can be scheduled using soil water indicators, plant indicators or evaporation measuring devices such as pans. Numerous technical publications, manuals and irrigation guides provide instructions on the application of direct measurements and the use of soil water indicators for irrigation scheduling.[3/] However, the use of these devices by farmers is often disappointing.

[1/] Agro-meteorological field stations. Irrigation and Drainage Paper No. 27. FAO Rome. 1976

[2/] Soil survey in irrigation investigations. Soils Bulletin (draft). Land and Water Development Division. FAO Rome. 1974.

[3/] Hagan, R.M., Haise, T. and T. Edminster. Irrigation of agricultural lands. 1967
Irrigation, Drainage and Salinity. An Intern. Source Book. Unesco, Paris. 1073.
Stanhill, G. Practical soil moisture problems in agriculture. WMO. 1968.

EXAMPLE: Irrigation scheduling by soil water accounting procedure using Class A evaporation pan.

Required: Standard raingauge and Class A pan on grassed site surrounded by short crop; daily observation (08.00 hours).
Estimated or measured wind and humidity levels of previous day.
Soil data on water holding characteristics; crop rooting depth and level of maximum soil water depletion.
Crop coefficient (kc) for different stages of crop growth.

Procedure: At 08.00 hours pan evaporation is measured. For humidity and wind values of previous day and for given upwind distance of green crop, kpan is determined (Table 18). For given stage of crop growth kc is selected (Tables 21 and following) ETcrop = kpan x kc x Epan.

From soil water balance, subtract ETcrop, add daily rainfall and irrigation application.

Irrigation is applied when allowable soil water depletion has been reached (Table 39).

SOIL WATER BALANCE SHEET

Scheme: .Ralinku...... Soil type: Silty loam... Total available soil water 25. v% 0- 30 cm
Field: ..14....
25. v% 30- 60 cm
Farmer: .Lokoto.......
25. v% 60- 90 cm
Months: .April-Sept..........
... v% 90-120 cm
Pan location: 100m upwind cropped field........ Crop: .potatoes... Rooting depth ..60......... cm
Irrigate when balance is: ..115......... mm

Date	Days after planting	Epan mm	Wind	Humidity	kpan	kcrop	ETcrop mm	Rain mm	Irr. mm	Balance mm	Remarks
27/4	0	6.3	light	med	·8	·9	4.5	—	80	150	pre-irr.
28/4	1	7.2	mod	low	.65	·7	3.5	—		146.5	
29/4	2	6.9	mod	med	·75	·5	2.5	4		148	
											Weeding
											full cover
										128.5	first flower
9/7	73	8.7	light	low	·7	1.1	6.5			122	
10/7	74	9.8	mod	low	·65	1.1	7.0			115	
									45	160	Irrigation
										142	
30/8	95	11.7	mod	med	·75	·8	7.0			135	
31/8	96	10.6	light	med	·8	·8	7.0	16		144	

It is preferable that advice and assistance be given by central irrigation authorities or extension services. The necessary data can be collected from small experimental field plots which mirror the local agricultural practices (Philippines). When extensive research has already been carried out, evaporation pans (Class A) can be used for scheduling irrigation (Israel, Hawaii). Other methods are based on meteorological data combined with known soil and crop data, supplemented by sufficient field checks (U.S.A.).[1] For development and testing of such prediction methods, adequate experimental data must be locally available. Communications must be simple and direct. To formulate recommendations on irrigation scheduling the following is required:

Action	Requirements
	Cropping plans including type of crop, location, acreages, date of planting, soils, water supply.
1. Estimate ET for reference crop (grass, alfalfa).	Adequately tested crop water prediction method.
2. Apply crop coefficient for given crop depending on stage of growth and soil water level.	Adequate experimental and field data on given crop, soil and production potential.
3. Determine soil water depletion level in irrigated fields (calculated, and by making field checks).	Date of last irrigation, water retention capacity of soil, soil survey.
4. Predict future rainfall contribution.	Rainfall frequency distribution analysis of long-term daily data.
5. Predict with computed ETcrop when day of maximum allowable soil water will be reached.	Detailed soil and crop data, water use/production function.
6. Calculate total amount of water to be delivered to the field at predicted time.	Irrigation efficiency, groundwater contributed to root zone, leaching requirements.
	Information centre; extension service.

Correct timing of irrigation is even more essential when water is in short supply. Early decisions must be made regarding the times at which water can be saved and when its allocation is most essential. Savings in irrigation water may be made by optimum utilization of soil water stored from winter rains or pre-irrigation. Additional savings may be made by allowing the soil to dry to the maximum permissible degree at the end of the growing season, rather than by leaving a high level of available soil water at harvest time; possibly one or two irrigations may be saved by this practice. Also, total depth of water and the number of irrigations can be minimized on the basis of a good understanding of water-crop yield relationships. During periods of water shortages, irrigation supplies can be programmed on pre-selected ETcrop deficits, with the least deficit allowed during the most sensitive growth stage; for most crops this is from flowering and early fruit development onward. However, such refinements in field application scheduling can only be of value if the design and operation and management of irrigation systems are geared to meeting actual field requirements by providing the correct supply to the farm at the right time.

Time is required for the introduction of modern irrigated farming technology and for the eventual acceptance of new practices by the farmers. For the adoption of efficient irrigation practices in the farming system a range of long-term activities will be required such as the setting up of adequate scheme management, provision of extension services, establishment of demonstration plots, and availability of training facilities. It is only when this framework has been established and is functioning that carefully developed criteria can be tested and applied, once their validity has been proved.

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[1] See for instance: Jensen M.E. Scheduling irrigations using climate-crop-soil data. ASCE, J. Irrigation and Drainage. 96:25-38. 1970.

APPENDIX I

PERSONS AND INSTITUTES CONSULTED

Denmark : Hydrotechn. Lab. and Climate Stat., Royal Veterinary and Agric. Univ. Copenhagen; S.E. Jensen, K.J. Kristensen, H.C. Aslyng

Ethiopia : Inst. Agr. Res., Holletta, Addis Ababa; A. Retta, C.R.K. Prashar

France : Station de Bioclimatologie, Sta. de Rech. Agron. du Sud-est, Inst. Nat. de la Rech. Agron., Cantarel-84, Montfavet; J. Damagnez, C. Samie, O. de Villele

Haiti : Service Meteorologique National, Port au Prince, D.A.R.N.D.R.; A. Goutier, M. Frère

India : Indian Agric. Res. Inst., New Delhi 12; N.G. Dastane, A.M. Michael

Israel : Dept. of Soil Science, Hebrew Univ., Rehovet; D. Hillel, E. Rawitz
Min. Agric., Agric. Res. Org., The Volcani Center, Bet Dagan; Y. Vaadia, G. Stanhill, M. Fuchs, F. Schmueli, J.D. Kalma
Dept. of Irrig., Hebrew Univ., Rehovet; S.D. Goldberg

Kenya : East African Agric. and Forestry Res. Org., Nairobi; C.W.O. Eeles, F.J. Wangati

Lebanon : Dept. of Irrig. Agron., Tal Amara; S. Sarraf, A. Aboukhaled, S. Chebli
UNDP(SF) LEB/13 Project; A. Marasovic

Nigeria : Inst. for Agric. Res., Ahmadu Bello Univ., Samaru, Zaria; J.M. Kowal, A.H. Kassan

Netherlands : Inst. for Land and Water Management Res., Wageningen; C. van den Berg, P.E. Rijtema, R.A. Feddes

Philippines : Intern. Rice Research Inst., Los Banos; T. Wickham, S.K. de Datta

Senegal : Projet pour le développement de la recherche agronomique et de ses applications, Saint-Louis; D.A. Rijks

South Africa : South African Sugar Association Exp. Stat., Mount Edgecombe, Natal; G. Thompson, J.G. Lover

Sudan : Dept. of Agron., Fac. of Agr., Khartoum Univ.; A.M.H. El Nadi

Syrian Arab Rep. : Res. Stat. Billaneh, Min. Agr. UNDP Project SYR/22, Aleppo; Salah Samsam, J. Petrasovic. Univ. of Aleppo, Fac. Agr.; A.N. Zein El-Abdin, A. Farra, Y. Kattan

Thailand : Asian Inst. of Technology, Bangkok; A. Hossain, E.F. Schulz

Tunisia : UNDP/SF Project TUN/70/529, Tunis; B. Said, R.R. Combremont

Uganda : Dept. of Soil Science, Makerere Univ., Kampala; P. Nkedi-Kizza

United Kingdom : Inst. of Hydrology, Wallingford, Berks.; J.S.G. McCulloch

U.S.A. : US Water Cons. Lab. USDA (ARS), Phoenix, Arizona; C.H.M. van Bavel
Imperial Valley Cons. Res. Center, USDA (ARS), Brawley, California; R. Le Mert, L. Willardson, A.J. MacKenzie
North Appalachian Exp. Watershed, USDA (ARS), Coshocton, Ohio; L.L. Harrold, J.L. McGuiness
Irrig. Agric. Res. and Ext. Center, Prosser, Washington; J.E. Middleton, M.C. Jensen, E.S. Degman
Agric. Res. Serv. USDA Lompoc, California; P.R. Nixon, G.P. Lawless
State of California, The Resources Agency, Dept. of Water Resources, Sacramento; J.W. Shannon, N.A. MacGillivray, R.E. Merrill, J. Lawrence, C. Muir
Agric. Res. Serv. USDA, Colorado State Univ., Fort Collins, Colorado; G. Kruse, H.R. Haise
Univ. of California, Davis, California; F.J. Lourence, S. von Oettingen, R.M. Hagan, J. Ian Stewart, D.W. Henderson, F.J. Veihmeyer, W.L. Sims, V.E. Rubatzky, R.B. Duffin, R.E. Voss
Dept. of Geography, Univ. of Hawaii, Honolulu; Jen-hu Chang
Soils Dept., Univ. of Hawaii and Hawaiian Sugar Planters Experiment Station, Honolulu; P. Ekern
Snake River Conserv. Lab. USDA (ARS), Kimberley, Idaho; M.E. Jensen, J. Wright, R.D. Burman
C. Brewer and Company Ltd., Honolulu, Hawaii; K. Shoji
Dept. of Agric. and Irr. Eng., Utah State Univ., Logan, Utah; J.E. Christainsen, G. Hargreaves

Zaïre : Institut National pour l'Etude Agronomique; E.A. Bernard, M. Frère

Venezuela : Servicio Shell para el Agricultor, en collaboración conjunta con la Facultad de Agronomía de la Univ. Central de Venezuela, Cagua-Aragua; J.E. López, K. Mathisen, O. Padilla

Joint FAO/IAEA Div. of Atomic Energy in Food and Agriculture, Vienna; Y. Barrada
FAO Regional Office for Asia and the Far East, Bangkok, Thailand; O. van't Woudt
FAO Regional Office for the Near East, Cairo, Arab Republic of Egypt; A. Aboukhaled, A. Arar

APPENDIX II

BACKGROUND AND DEVELOPMENT OF METHODS TO PREDICT REFERENCE CROP EVAPOTRANSPIRATION (ETo)

by

W.O. Pruitt and J. Doorenbos

The approach presented in this publication defines the use of available methods to predict evapotranspiration for different climatic conditions. After consideration of many methods and based on climatic data needed to apply these and the accuracy required, four methods were selected for detailed analysis and calibration. Three are based on methods proposed earlier by H.F. Blaney and W.D. Criddle (1950), G.F. Makkink (1957), and H.L. Penman (1948). The fourth, pan evaporation, has been found by many to be reliable when local pan environment is standardized and adjustments are made for major climatic differences. The methods were calibrated against potential evapotranspiration as defined at the Conference on Physics in Agriculture (Wageningen, Netherlands, 1955), herein defined as reference crop evapotranspiration (ETo) (Part I.1).

There were, as expected, difficulties and obstacles experienced in carrying out the FAO study. The great variety of experimental procedures and type and accuracy of data collected made adaptation of published research results to a common data base very problematic. Contradictions in the published research results were noted, whereby anomalies in predicting water use from available prediction methods faded into insignificance. The terminology used easily led to misinterpretation, while in many instances the minimum data set permitting even a crude evaluation of research results was not available. Observations on crop development were seldom made and environmental and site conditions were frequently not reported in published literature. The format for presenting research results in most instances required further personal contact with the researcher. This meant that after a review of numerous research results the final evaluation was in fact based on a selected few research sites with recognized excellence in type and accuracy of basic input data which adequately represented a wide range of climatic conditions. The results of analyses were subsequently tested on experimental results from locations found in different climatic zones (Branscheid, 1976).

Based on comments received and following a re-analysis of available data, modifications to an earlier draft edition (1975) are herein made, particularly Figures 1 and 2 and Table 16 (Part I.1).

1 DATA AVAILABLE

1.1 Blaney-Criddle Method

Complete weather data were available for some twenty locations representing a very wide range of climates, along with measured ET for either grass, clover, alfalfa or grass-legume mixes. For alfalfa, data 10-14 days following cutting were eliminated. To relate ETo to actual ET data, the data were adjusted downwards by 7 to 20 percent, depending on stage of growth and climate (with the exception of grass). In addition to weekly and monthly data, daily ET and climatic data at six locations were used to encompass the wide range of conditions. The results of the analyses were subsequently compared to data of many other stations.

1.2/1.3 Radiation and Penman Methods

Data from ten research sites provided the main input for calibration of the methods. Together with complete weather data, ET data determined from lysimeters were available for grass at seven sites, for alfalfa at two sites, and for alfalfa-timothy at one site. Corrections as explained above were made for the alfalfa and alfalfa-timothy data. The lysimeters ranged from highly sensitive weighing units providing data for hourly periods or longer to drainage type lysimeters for which only 10-day to monthly data could be considered accurate. The lysimeters were in fields at least one hectare in size (2-5 ha for most fields), except for those at Tal Amara and Phoenix which were less than one hectare, but for much of the season the upwind fields were in irrigated crops. Direct measurements of net radiation were available at five of the ten sites. Solar radiation data were available for all ten sites, along with temperature, humidity and wind. Data for the distribution of wind, day and night, were available from Tal Amara, Lebanon; Montfavet, France (near Avignon); Copenhagen, Denmark; Davis and Brawley, California, USA. Subsequently the presented methodology was used to compare calculated and measured data for many other locations.

1.4 Pan Evaporation Method

The pan coefficients which relate pan evaporation (Epan) to ETo for pans surrounded by green crop (Case A, Part I.1.4) with 100 m or more upwind distance of irrigated grass, medium to high RHmean and light to moderate wind, were obtained from a wide range of sites. Coefficients for pan surrounded by dry fallow land (Case B, Part I.1.4) were based on studies in India by Ramdas (1957), in USA by Pruitt (1960, 1966) and Nixon (1966), and in Israel by Stanhill (1961). The significant reduction in recommended Kp values with strong wind and low RH conditions is based largely on daily data over a 15-year period in California. Many literature references were used for interpolation purposes.

2 DEVELOPMENT OF METHODS

2.1 Blaney-Criddle Method

A strong correlation exists for a given climate between ETo and the Blaney-Criddle "f" factor (Pruitt, 1960, 1964; Tanner, 1967). The initial approach in this study was to present the ETo and f relationship in a similar manner for different locations representing a wide range of climates. Use was made of relationships already established for different crops in many areas, which were presented in the original Blaney-Criddle formula as the "K" value. For a given site the user could then select the relationship of a similar climate (Figure 1).

The K values reported in literature relate to crops other than grass and are therefore highly dependent on stage of growth, cover and maturity. Also, K values may be similar for similar climates but the effect of different lengths of growing season and the nature of the ETo/f relationship will present problems of interpolation.1/ The latter is shown in Figures 2a and 2b. Since the range of climatic conditions is similar in Davis, Prosser and Soledad, the same relationship given in Figure 2a between ETo and f would apply. However, climatic conditions during January and December in Davis are comparable with conditions during March and November in Prosser; the range of climatic conditions is less pronounced in Soledad particularly during summer. Distinct monthly differences can be noted plotting the same monthly K values from Figure 2a for each month of occurrence in Figure 2b. More pronounced differences can be expected for other climates. A definite identification of relationships between ETo and f values together with a specific climatic description is therefore required.

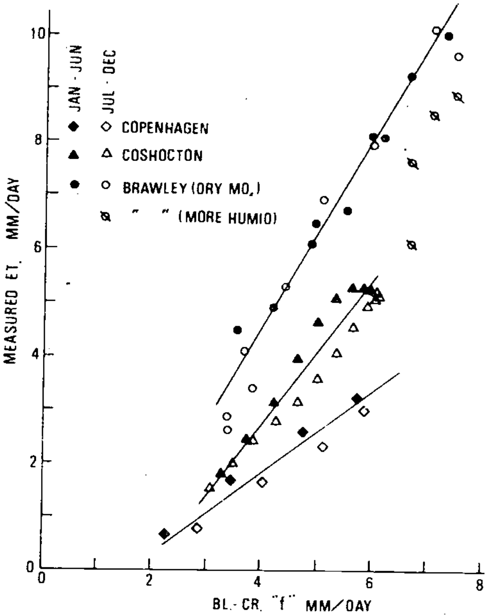
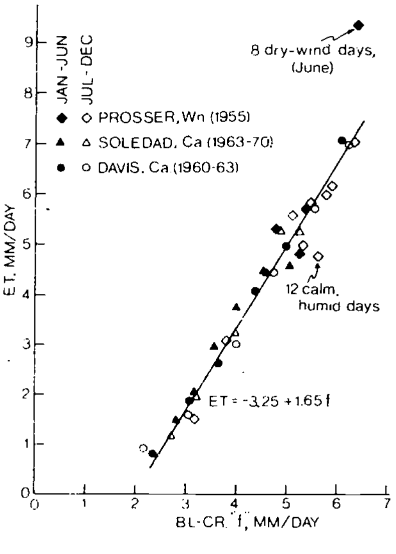


Fig. 1 Reference evapotranspiration and Blaney-Criddle f values in mm/day for different climates (Aslyng, 1965; McGuiness et al., 1972; LeMert, personal communication)

Using daily, weekly and 10-day data from (amongst others) Brawley, Copenhagen, Davis, Montfavet, Tal Amara and Wageningen, the relationships between ETo and f were classified according to ranges of RHmin, n/N and Uday. Figure 3 gives an example of the analysis carried out and presents three of the 27 relationships used (Figure 1 of Part 1.1.1). Figure 3 also shows that the presented relationships will slightly overpredict ETo for some climatic conditions (represented by Line 1 of Block 1 and Line 1 of Block IV of Figure 1, Part 1.1.1). The relationships are in good agreement for conditions found in Brawley, Phoenix, Wageningen and Yangambi.



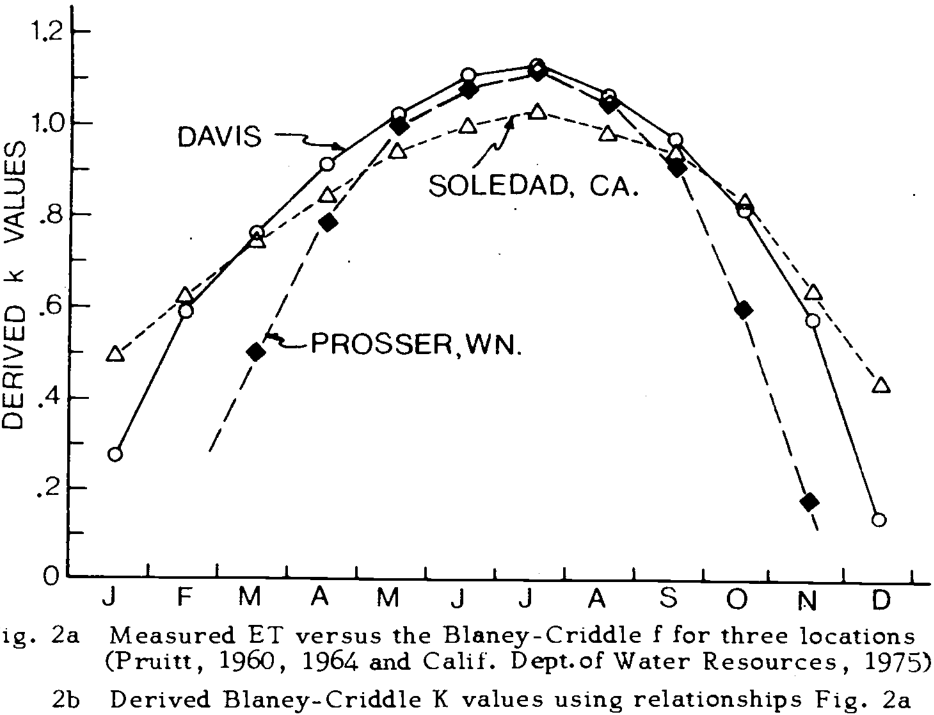


Fig. 2a Measured ET versus the Blaney-Criddle f for three locations (Pruitt, 1960, 1964 and Calif. Dept. of Water Resources, 1975)

2b Derived Blaney-Criddle K values using relationships Fig. 2a along with mean monthly f data for the same locations

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1/ The many published K values were helpful, however, in developing the crop coefficients (kc) for many crops listed in Part 1.2.

The values for 'a' and 'b' of the relationship ETo = a + b f or ETo = a + b p(0.46T + 8) are given for 'b' in Table 1 for different levels of RHmin, n/N and Uday; the values of 'a' range from -2.3 to -1.6 and are based on a = 0.0043 RHmin - n/N - 1.41. The values of 'a' and 'b' can be used to compute ETo from available data rather than using the graphical method presented in Part I.1.1.

The computer programme (Appendix III) uses the same equation for 'a'; the table for the 'b' values is included in the programme and interpolates between the different ranges of RHmin, n/N and Uday, but for Uday greater than 10 m/sec a value of 10 m/sec is assumed. The results will show some difference between these and the methods given in the draft 1975 English edition of this publication.

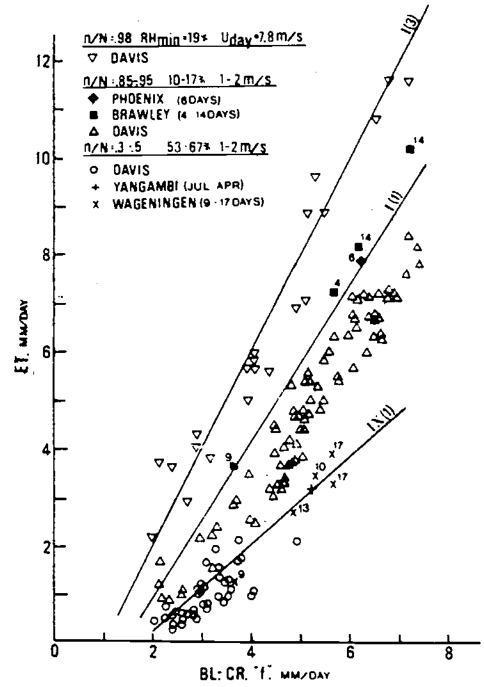


Fig. 3 ETgrass versus the Blaney-Criddle f in mm/day for five locations and three out of 27 relationships given in Fig. 1, Part I.1.1.

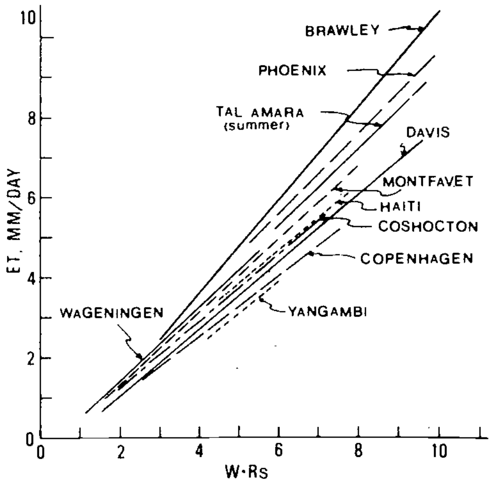
Table 1 Values of b of relationship ETo = a + b f

n/N	RHmin % 0	20	40	60	80	100	
0	0.84	0.80	0.74	0.64	0.52	0.38	U_2 day = 0 m/sec
0.2	1.03	0.95	0.87	0.76	0.63	0.48	
0.4	1.22	1.10	1.01	0.88	0.74	0.57	
0.6	1.38	1.24	1.13	0.99	0.85	0.66	
0.8	1.54	1.37	1.25	1.09	0.94	0.75	
1.0	1.68	1.50	1.36	1.18	1.04	0.84	
0	0.97	0.90	0.81	0.68	0.54	0.40	U_2 day = 2 m/sec
0.2	1.19	1.08	0.96	0.84	0.66	0.50	
0.4	1.41	1.26	1.11	0.97	0.77	0.60	
0.6	1.60	1.42	1.25	1.09	0.89	0.70	
0.8	1.79	1.59	1.39	1.21	1.01	0.79	
1.0	1.98	1.74	1.52	1.31	1.11	0.89	
0	1.08	0.98	0.87	0.72	0.56	0.42	U_2 day = 4 m/sec
0.2	1.33	1.18	1.03	0.87	0.69	0.52	
0.4	1.56	1.38	1.19	1.02	0.82	0.62	
0.6	1.78	1.56	1.34	1.15	0.94	0.73	
0.8	2.00	1.74	1.50	1.28	1.05	0.83	
1.0	2.19	1.90	1.64	1.39	1.16	0.92	
0	1.18	1.06	0.92	0.74	0.58	0.43	U_2 day = 6 m/sec
0.2	1.44	1.27	1.10	0.91	0.72	0.54	
0.4	1.70	1.48	1.27	1.06	0.85	0.64	
0.6	1.94	1.67	1.44	1.21	0.97	0.75	
0.8	2.18	1.86	1.59	1.34	1.09	0.85	
1.0	2.39	2.03	1.74	1.46	1.20	0.95	
0	1.26	1.11	0.96	0.76	0.60	0.44	U_2 day = 8 m/sec
0.2	1.52	1.34	1.14	0.93	0.74	0.55	
0.4	1.79	1.56	1.32	1.10	0.87	0.66	
0.6	2.05	1.76	1.49	1.25	1.00	0.77	
0.8	2.30	1.96	1.66	1.39	1.12	0.87	
1.0	2.54	2.14	1.82	1.52	1.24	0.98	
0	1.29	1.15	0.98	0.78	0.61	0.45	U_2 day = 10 m/sec
0.2	1.58	1.38	1.17	0.96	0.75	0.56	
0.4	1.86	1.61	1.36	1.13	0.89	0.68	
0.6	2.13	1.83	1.54	1.28	1.03	0.79	
0.8	2.39	2.03	1.71	1.43	1.15	0.89	
1.0	2.63	2.22	1.86	1.56	1.27	1.00	

2.2 Radiation Method

The method in essence is based on the Makkink formula (1957) or ETp = a ($\Delta/\Delta + \gamma$)Rs - b with ETp and Rs in mm of evaporation. The coefficient a = 0.61 and b = 0.12 found applicable in the Netherlands, was determined for different values of RHmean and Uday, using available measured ETo and climatic data; $\Delta/\Delta + \gamma$ is expressed as W.

Relationships between ETo and W.Rs are shown in Figure 4 for ten locations. Rather than giving for each relation the climatic description under which it would apply, the relationships were defined for different values of RHmean and Uday. No reasonable explanation can be given as to why RHmean proved more satisfactory than RHmin as used in the Blaney-Criddle method. An example of analysis is given in Figure 4b which shows three of the 16 relationships used in Figure 2, Part I.1.2. Numerous daily and weekly data from Brawley, Copenhagen, Davis, Montfavet, Tal Amara and Wageningen were used together with monthly data from other locations in developing the relationships shown in Part I.1.2. Solar radiation (Rs) was used rather than net radiation (Rn). The use of Rn would have resulted in somewhat less empiricism but would have required additional measured data and/ or computations in application.



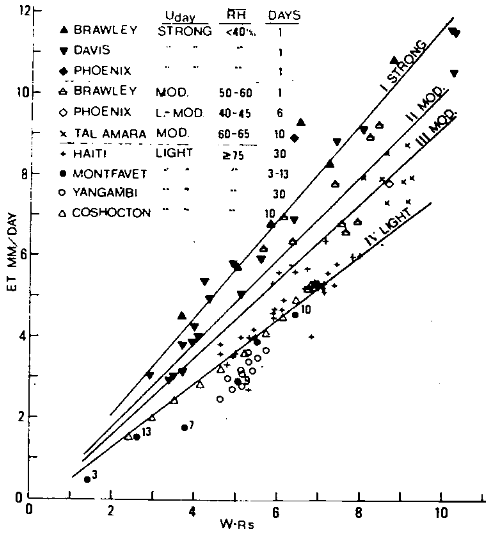


Fig. 4 a Relationships for ETgrass and W.Rs for ten locations

4 b 'b' values for three out of the 16 relationships for ranges of RHmean and Uday

Values of b were determined for discrete levels of RHmean and Uday. Table 2 serves as a reference table for computing ETo as against the graphical method in Part I.1.2. This table is in a condensed form included in the computer programme (Appendix III). The value of a = -0.3 for the y-intercept was found to be a good approximation for all conditions.

Table 2 Values of 'b' in the Radiation Method as a function of RHmean and mean daytime wind. ETo = b.W.Rs - 0.3 mm/day with ETo and Rs both in mm/day

Daytime wind m/sec	(RHmax + RHmin) / 2 %									
	10	20	30	40	50	60	70	80	90	100
0	1.04	1.02	.99	.95	.91	.87	.82	.76	.70	.64
1	1.09	1.07	1.04	1.00	.96	.91	.85	.79	.73	.66
2	1.13	1.11	1.08	1.04	.99	.94	.88	.81	.74	.67
3	1.17	1.15	1.11	1.07	1.02	.97	.90	.83	.76	.69
4	1.21	1.18	1.14	1.10	1.05	.99	.92	.85	.78	.70
5	1.24	1.21	1.17	1.13	1.07	1.01	.94	.87	.80	.72
6	1.27	1.24	1.20	1.15	1.09	1.03	.96	.89	.81	.73
7	1.29	1.26	1.22	1.17	1.11	1.05	.98	.91	.83	.74
8	1.31	1.28	1.24	1.19	1.13	1.07	1.00	.92	.84	.75
9	1.34	1.30	1.26	1.21	1.15	1.09	1.01	.93	.85	.76
10	1.36	1.32	1.28	1.23	1.17	1.10	1.02	.94	.86	.77

2.3 Penman Method

The original Penman method (1948, 1956) is based on evaporation of a (smooth) water surface. Evidence of the wide range of published relationships indicates that in particular the effect of wind for different climates must be considered (Rijtema, 1965; Aboukhaled et al., 1971; Wright and Jensen, 1972). To avoid the necessary local calibration of the wind function (fu) in the Penman formula requiring additional data input, and to arrive at a single function that is applicable under different climatic conditions and easy to use, f(u) was calculated for sets of data which were grouped according to mean windspeed (u) and $f(u) = [ETo - W.Rn] \div [(1 - W)(ea - ed)]$.1/ Results for three locations are given in Figure 5 and for 9 locations in Figure 6.

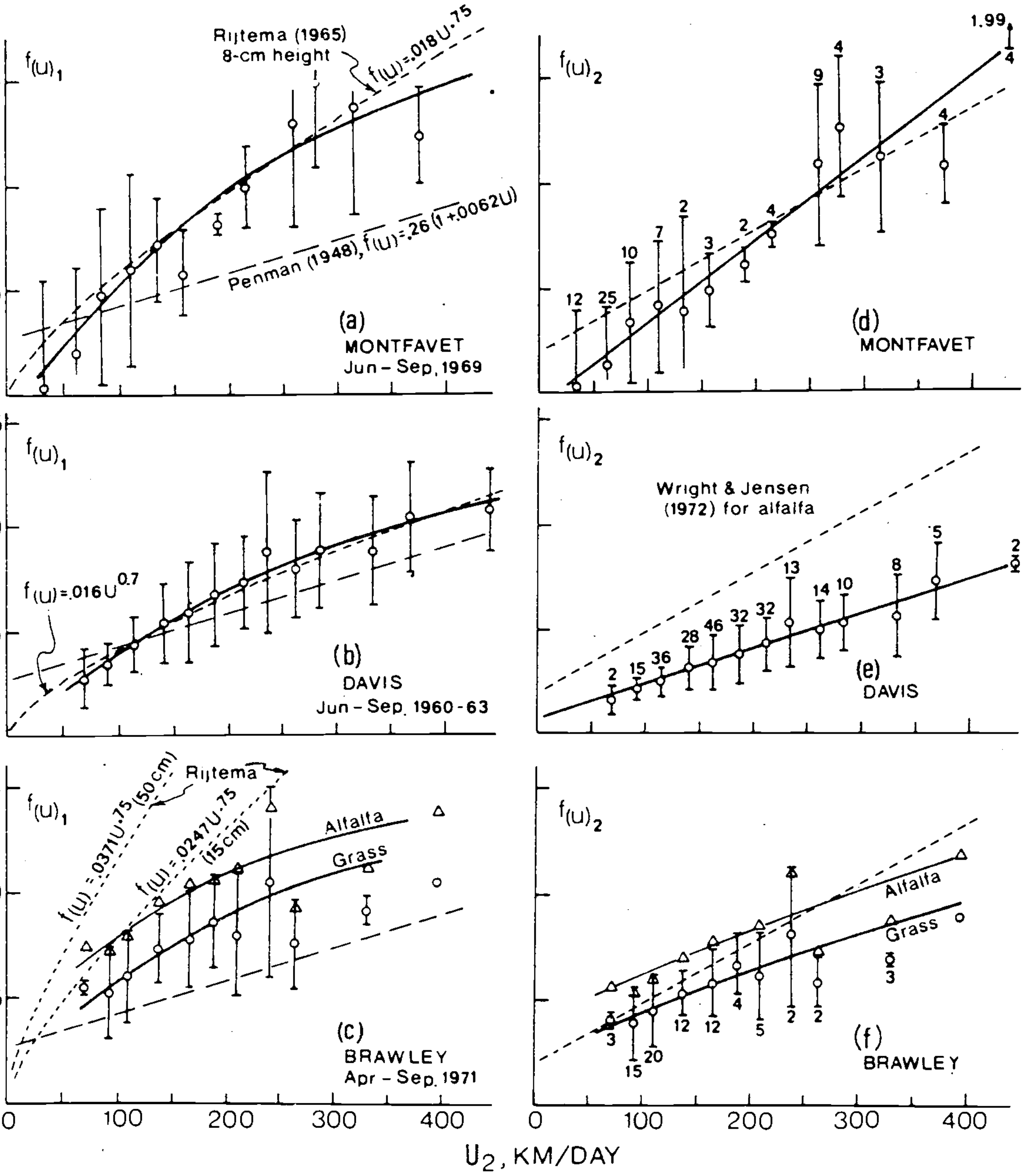


Fig. 5 Relation for wind in the Penman equation. Bars through mean f(u) data represent ± one standard deviation. The number of days of record for each mean f(u) is indicated if more than one day

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1/ With the assistance of R.G. Thomas and J. Ph. Culot a computer programme was developed to perform the necessary calculations.

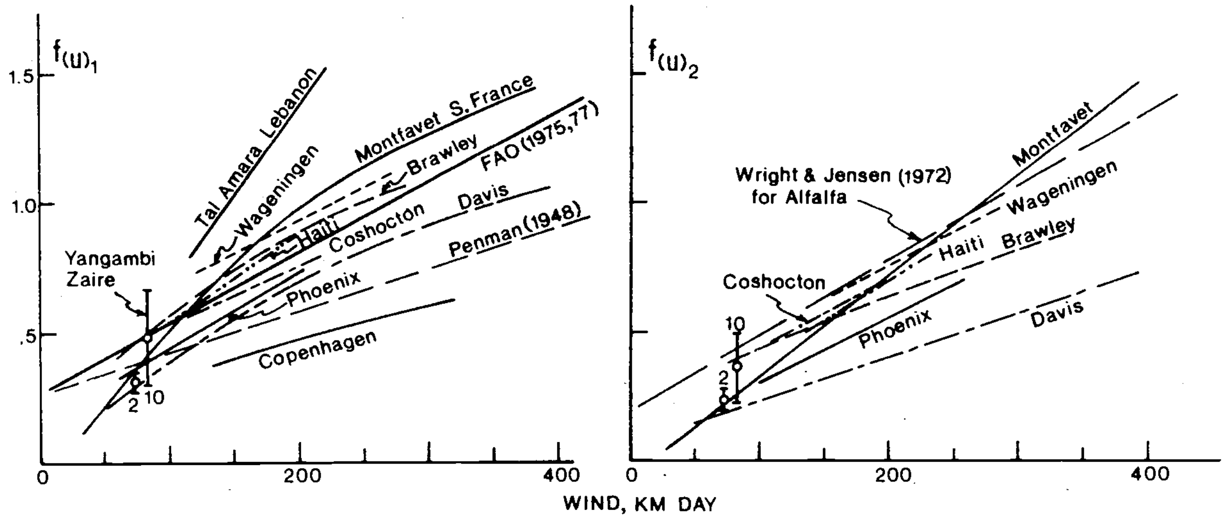

Fig. 6 Wind function relationships for nine locations; 6a is based on use of (ea - ed)$_1$ and 6b on (ea - ed)$_2$. Except for Coshocton, Yangambi and Haiti the relationships involve late spring to early autumn conditions

The difference in form and magnitude of f(u) found here as well as in the literature is for an important part due to the manner in which the components of the Penman formula are calculated, in particular the saturation deficit (ea - ed) and net radiation (Rn). The effect of the manner in which (ea - ed) in mbar is calculated is shown by an example for 20 days at Davis (Figure 7). The lowest values, (ea - ed)$_1$, are based on ea at (Tmin + Tmax)/2, and on ed = ea(RHmin + RHmax)/200; the values (ea - ed)$_2$ related to the average of (ea - ed) at Tmin and (ea - ed) at Tmax; the highest values (ea - ed)$_3$ relate to a more heavy weight given to daytime conditions and ea is based on T = (4 Tmax + Tmin)/5. Values of (ea - ed)$_1$ were used in deriving Figures 5a, b, c and 6a; values of (ea - ed)$_2$ in deriving Figures 5d, e, f and 6b.

As to net radiation (Rn), measured data are seldom available. From a practical point of view it is important that Rn can be determined from relationships which need not be locally determined, but are more universally applicable and much easier to use. Net Rn or solar radiation were available at the locations used for the analyses. However, where the necessary climatic data at locations subsequently tested were not available, net shortwave radiation (Rns) was determined from Rns = (1 - α)(a + bn/N)Ra where α = 0.25, a = 0.25 and b = 0.50. Net longwave radiation (Rnl) was determined from Rnl = (σTk^4)(0.34 - 0.044$\sqrt{ed}$)(0.1 + 0.9n/N). Values of Ra, N and W were obtained from Smithsonian Meteorological Tables (1951).

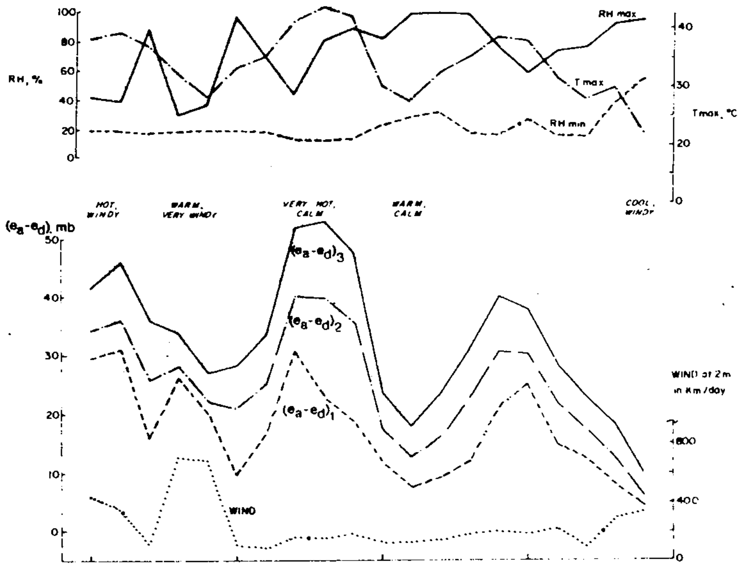

Fig. 7 Saturation deficit (ea - ed) for 20 days at Davis under a wide range of conditions using (i) ea at Tmean, (ii) average of ea - ed at Tmax and Tmin and (iii) ea at T = (4 Tmax + Tmin)/5

Results of analysis similar to Figures 5 and 6 were used to arrive at a single wind function f(u). The relationships in Figure 5a, b and c using (ea - ed)$_1$ relate best to a power function for f(u). Results in Figure 5a for Montfavet closely agree with f(u) = 0.018U$^{0.75}$ for 8 cm high grass as reported by Rijtema (1965); Figure 5b for Davis closely agrees with f(u) = 0.016U$^{0.7}$ for U = 50 to 400 km/day. Figure 5c for alfalfa 20-80 cm tall at Brawley is in good agreement with the Rijtema function for a 15 cm tall crop and U = 60 to 150 km/day, but is smaller at higher U values; the Rijtema function for crop height of 50 cm is well above the alfalfa data averaging about 50 cm tall. The f(u) relationships in Figure 5d, e and f using (ea - ed)$_2$ are rather different from Figure 5a, b and c. The relation for these as well as other locations is nearly linear; also, the magnitude of f(u) is much lower since the computed value of (ea - ed) is larger. Comparing the functions with those by Wright and Jensen (1972) for 20 cm or taller alfalfa at Idaho, the f(u) for grass at Montfavet is somewhat greater for windspeed > 260 km/day, but smaller for windspeed < 260 km/day. The Wright and Jensen function for alfalfa exceeds the f(u) for grass at Davis but agrees with f(u) values (not shown) for alfalfa 30-80 cm tall at Davis in mid-summer. It underpredicts f(u) for alfalfa at Brawley at windspeeds up to 250 km/day. Results are shown for several locations in Figure 6 with for Figure 6a using $(ea - ed)_1$ and for Figure 6b using $(ea - ed)_2$. The spread of f(u) relations points to severe limitation of applying the Penman method to a wide range of conditions although some of the spread can be due to experimental error, techniques used, and advection. From wind considerations alone, locally calibrated wind functions must be applied or additional corrections are necessary when using a single f(u) function.

To avoid local calibration and to simplify the use of the Penman method a single, straight-line relationship was selected, i.e. $f(u) = 0.27(1 + U/100)$ where U is mean windspeed in km/day at 2 m height (Figure 6a). Also, the simpler $(ea - ed)_1$ calculation was preferred. However, the use of this single wind function for a wide range of conditions cannot lead to generally reliable estimates of ETo; consequently additional corrections are necessary.

In deriving the necessary corrections consideration was given to daytime and night time weather conditions, particularly to wind and air humidity (Tanner and Pelton, 1960). The Penman method was shown to be highly reliable if hourly as compared to mean daily weather data were used (McIlroy and Angus, 1960; Pruitt and Lourence, 1966; Van Bavel, 1966). As to the effect of the daily wind distribution on ETo, for example, total 24-hr wind is almost equal at Davis and at Tal Amara, but 40% more wind occurs during daytime hours at Tal Amara than at Davis. Windspeed at Tal Amara approaches maximum when radiation is highest, whereas in Davis maximum windspeed is reached around 17.00 hr when radiation is at a lower level. With the pattern of wind at Tel Aviv, the effect on ETo of the 131 km daytime wind is probably as great as the 153 km for Tal Amara and probably twice as effective as the 110 km for Davis (Figure 8).

As to the combined effect of wind and humidity, at Tal Amara even with more severe advection (perhaps 400-600 km/day) than indicated by the mean conditions given in Figure 8, calm conditions still prevail by early morning before sunrise with RHmax approaching 70 to 90%. This produces a mean (ea - ed) which is not very high considering the severe advection of the daytime period. As a result the Penman method even with the selected wind function tends to underestimate ETo by 20 to 30%. On the other hand, a similar strong advection period at Davis usually involves strong day and night wind with RHmax usually remaining below 35 to 40%. A very large (ea - ed) results which, combined with a large total 24-hr wind, results in predicted ETo from 30 to 300% greater than actual ETo with the higher values relating to winter conditions only when radiation is low even on clear days.

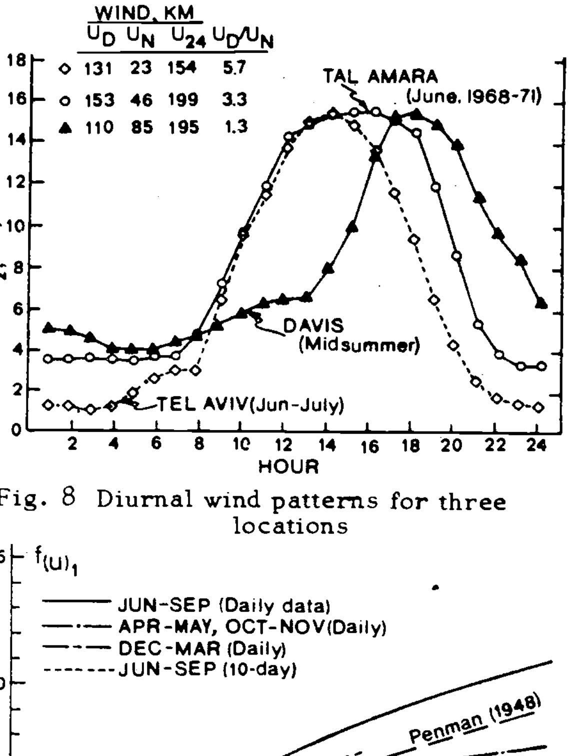

Fig. 8 Diurnal wind patterns for three locations

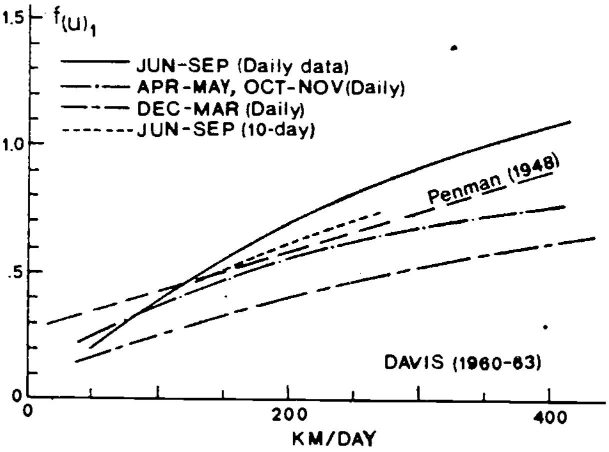

Fig. 9 Wind function relationships for different seasons (daily and 10-daily data, Davis)

The effect of wind and humidity on ETo is more pronounced when evaporative conditions (or radiation) are high as compared to when evaporative conditions (or radiation) are low. Subsequently the analysis of f(u) was carried out for different periods of the year. Figure 9 shows the change in the f(u) relationship with season. Similar results were obtained for most locations well away from the equator. The f(u) relationships appeared smaller during winter than in summer. This is in agreement with the crop coefficients used in the original Penman method, ranging from 0.6 in winter to 0.8 in summer. Additional corrections based on day length and greater weight to (ea - ed) during the day were suggested earlier (Penman and Schofield, 1951). Rather than day length, the level of radiation was used herein for further analysis.

For the Penman formula with $f(u) = 0.27 (1 + U/100)$ and $(ea - ed)_1$, the interactions between U, RH and Rs and their combined effect on calculated ETo against measured ETo were analysed. Values for the correction factor c for the presented Penman method for discrete levels of Rs, RHmax, U and Uday/Unight were determined using available hourly, daily and weekly data (Table 3). The range of c values extends to conditions which may seldom occur, such as weekly periods with average windspeeds of 3 to 6 m/sec. In most climates high windspeed/low humidity/low radiation conditions may only occur for very short (or daily) periods. As a result of using a single wind function some correction is required for zero wind.

The same c values are used in the computer programme (Appendix III). The computer programme interpolates between the various ranges of Rs, RHmax, Uday and Uday/Unight ratio with upper and lower limit as indicated in Table 3 but does not extrapolate, i.e. the programme uses RHmax = 30.0 for values of RHmax <30 percent etc.

Table 3 Correction Factor c in the Presented Penman Method

	RHmax = 30%				RHmax = 60%				RHmax = 90%			
Rs mm/day	3	6	9	12	3	6	9	12	3	6	9	12
Uday m/sec	Uday/Unight = 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
	Uday/Unight = 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
	Uday/Unight = 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
	Uday/Unight = 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

2.4 Pan Evaporation Method

Evaporation pans are used in many climates to estimate crop water needs for weekly or longer periods based on the results of studies in India by Ramdas (1959), in Israel by Stanhill (1961, 1962), in USA by Pruitt and Jensen (Washington State 1955), Campbell et al. (Hawaii, 1959), Pruitt (Washington State 1960), Stephens and Stewart (Florida 1963), Chang (Hawaii 1963) and California Dept. of Water Resources (1975), in South Africa by Thompson et al. (1963), in Australia by McIlroy and Angus (Melbourne 1964), in Venezuela by Lopez and Mathison (Caugua 1966), in Lebanon by Sarraf (Tyr and Tal Amara 1969), in Haiti by Goutier and Frère (1972). A review of the method is given by Linacre and Till (1969).

The pan evaporation method for weekly or longer periods may give less problems than the methods mentioned earlier, particularly when the pan is located in a large grass field that is properly managed and well irrigated. For instance, the original Penman method gives good results in calculating ETo at Tyr on the coast of Lebanon; it underpredicts ETo by 30 to 40 percent at Tal Amara in the inland Bekaa Valley, Lebanon. For the two locations the relation between ETo and Epan shows much less difference when taking into account pan environment and climatic conditions (Aboukhaled et al. 1971). This is supported by the results presented for 10 sites and based on references quoted above (Figure 10). The Kp values for Melbourne and Prosser in Figure 10 are somewhat higher since ETclover and grass-clover mix are some 15 percent greater than ETo. The effect of climate, particularly humidity, on the value of Kp can be noted for the three California locations, with Kp decreasing with decreasing RH.

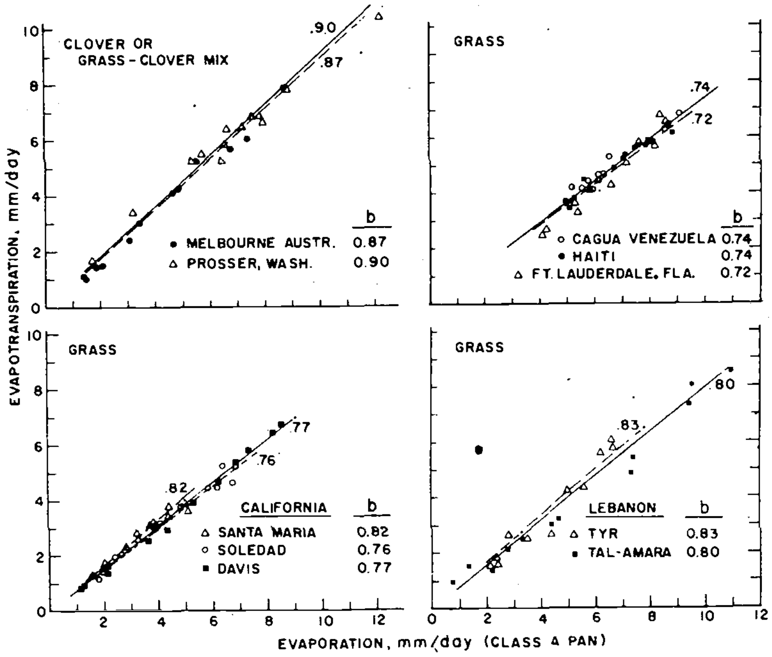

Fig. 10 Evapotranspiration versus Class A pan evaporation for locations indicated

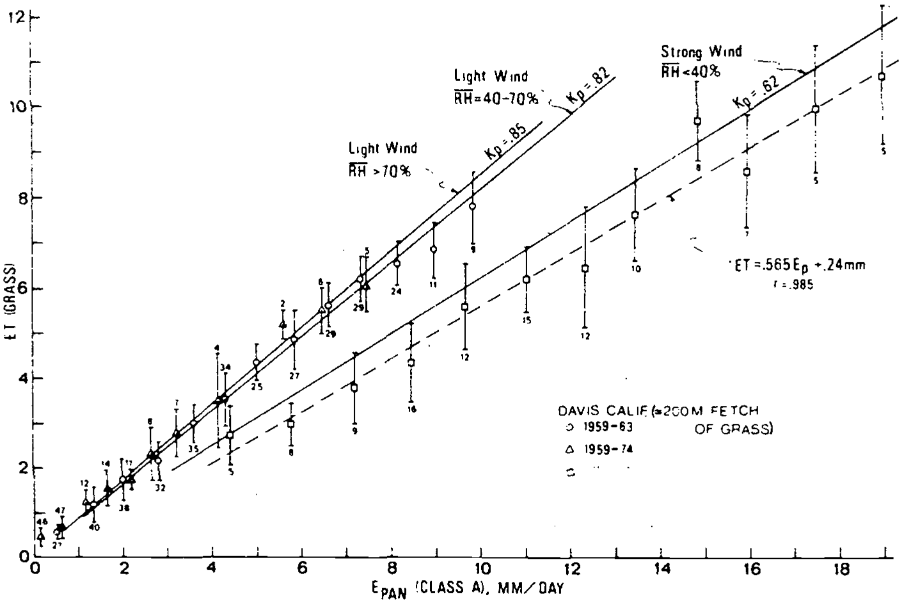

Fig. 11
Mean ETgrass versus Epan (Class A) for three combinations of RHmean and Umean. Upwind distance or fetch of green grass is 200 to 300 m. Solid lines represent relationships for Class A pan, Case A (Part I.1.4)

To analyse the effect of humidity and wind on the relation ETo and Epan, the data from Figure 10 and many other studies including the 15-year study at Davis were grouped in various combinations of RHmean and Umean. One example is shown in Figure 11 for three such combinations; the solid lines represent the relationships between ETo and Epan as given by the Kp value, Class A pan, Case A for upwind distance of the irrigated crop or fetch of 200 to 300 m, Table 18 (Part I.1.4). The dashed line respresents the strong wind/low humidity combination and indicates lower Kp values than given in Table 19 (Part I.1.4). It is the actual regression relationship for these data. Since some of the data relate to perennial ryegrass, with visual signs of wilting (curling of leaves) sometimes noted, the more conservative Kp values seemed advisable. However 94 out of total 115 days were for alta fescue grass, which showed no signs of wilting even under the severe conditions involved.

The effect of local pan environment is shown by an early study under arid conditions by Pruitt (1960). During mid-summer months in South Central Washington State, USA, Epan at a surface pan located in dry fallow field was some 30 percent higher compared to similar sized surface pans located in a grass field. Epan of a sunken pan was some 40 percent higher in dry fallow fields. Less than 10 percent difference between pans sited in cropped and non-cropped fields was found for cool, humid coastal climate (Lompoc, Calif.) by Nixon (1966). Ramdas (1957) reported results similar to a 1957-59 study at Davis. In Davis USWB Class A and sunken pan (both 121 cm in diameter and 25.4 cm deep) were placed centrally (i) within different sized circular shaped areas of frequently irrigated and mowed grass plots all located in large fallow fields (Case A) and (ii) within different sized non-cropped circular shaped plots located within a large irrigated grass field (Case B). The effect on the ratio ETo/Epan or Kp for various combinations of humidity and wind and different pan environments was subsequently analysed. The need for Kp values as low as 0.5 is shown for pans located in large dry uncropped areas. Epan under conditions with upwind distance of bare land of some 60 km was some 70 percent higher than for an irrigated pasture environment with light to moderate wind conditions in the San Joaquin Valley (Calif. Dept. of Water Resources, 1975). The low Kp value would apply in semi-arid areas where pan measurements are taken prior to irrigation development.

In adapting the Tables 18 and 19 (Part I.1.4) for the computer programme, the Kp values are related to discrete levels of RHmean and Umean. The programme assumes RHmean = 30 percent for values listed under low, 57 percent for medium and 84 percent for high RH. The programme interpolates between 30 and 84 percent but not beyond these values. The Kp values listed under light, moderate, strong and very strong wind relate to windrun of 84, 260, 465 and 700 km/day respectively. The programme interpolates logarithmically for distance of fetch; it does not extrapolate for fetch beyond 1 000 m. The programme includes only Class A pan, Case A and B, and not sunken Colorado pans.

3 ACCURACY OF ESTIMATING ETo

The choice of method will in many instances depend on the type of climatic data available for the given location. Only general indications as to accuracy of the methods to predict ETo can be given for different climates since no baseline type of climate exists. In testing against measured ETo, the presented methods appear to be in good agreement for a wide range of climates (Figure 12) except possibly at higher altitudes and where the correction factor c in the Penman equation is relatively large (Tal Amara). Additional adjustment may be required as is given for the Blaney-Criddle method (Part I.1.1) for spring and summer months in semi-arid and arid areas with upwind

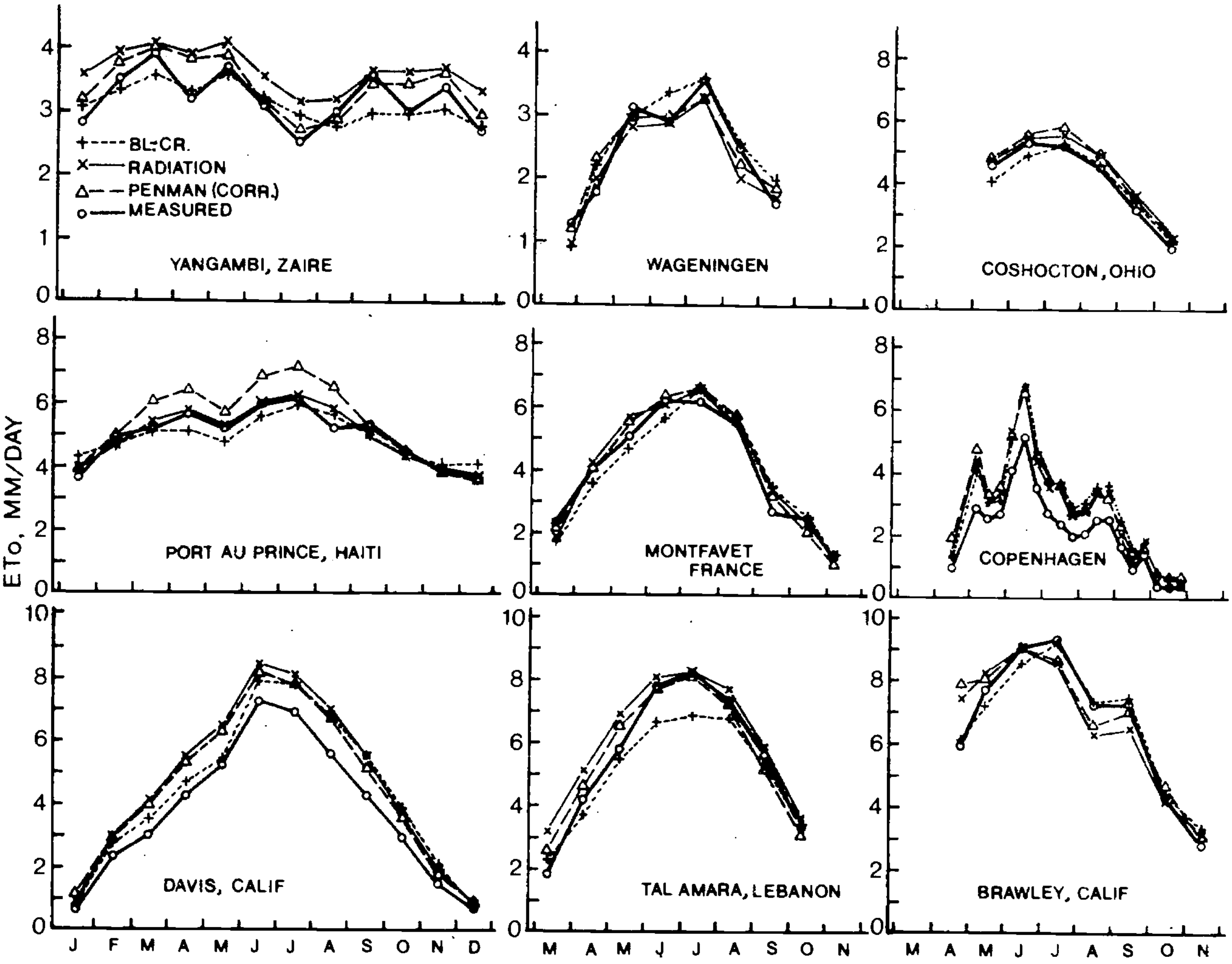

Fig. 12 Measured and Calculated ETo using Presented Methods

adjustment of 10 percent for each 1 000 m altitude change above sea level. For Tal Amara at 900 m, this would still leave a 10 percent underprediction of ETo for June and July.

Overpredictions compared to measured ETo are noted in Figure 12 for Davis and Copenhagen. This may be caused by the frequency of irrigating the lysimeter and its surroundings. At most sites drainage-type lysimeters were used with soil water constantly near field capacity. In the case of the 6.1 meter diameter weighing lysimeter at Davis, during 1959-63 the available soil water was depleted to half before the next irrigation. Analysing the data for the periods with up to 1/3 soil water depletion gave, however, similar results.

The presented Penman method uses Uday/Unight ratio, the Blaney-Criddle and Radiation methods use day time wind. For Figure 12 the ratio Uday/Unight applied is for Phoenix, Arizona, 1.5; Coshocton, Ohio, 2.0; Port au Prince, Haiti, 2.5; Yangambi, Zaire, 2.0; Wageningen, Netherlands, 2.5; Montfavet, France, daily data in groups of 1 to 1.25, 1.25 to 1.75, up to 3.5 to 4.0. The computer programme assumes 2.0 if no estimate is provided.

In summary, the presented methods may give slightly conservative estimates of ETo in humid regions; they may possibly over-estimate ETo by 10 to 15 percent at some mid-latitude, semi-arid locations; they may under-estimate ETo by 5 to 10 percent in very hot, dry desert locations with light wind. Difference will occur in similar climates, as for instance the climates resembling those of Northern Europe; the overprediction for Copenhagen is in contrast to the good results found in Wageningen. The results for the 9 locations in Figure 12 reflect the availability of accurate measured climatic data. For most locations the climatic data may need to be partly obtained by extrapolation from nearby stations, from general descriptions of climates, or from local estimates particularly on RH, n/N and U when applying the Blaney-Criddle or Radiation methods, and less accuracy can be expected.

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APPENDIX III

COMPUTER PROGRAMME FOR ESTIMATION OF REFERENCE CROP EVAPOTRANSPIRATION

by S.K. Gupta, W.O. Pruitt, J. Lonczak and K.K. Tanji
Water Science and Engineering Section, University of California, Davis, USA[1]

Introduction

The computer programme is based on the methods to calculate reference crop evapotranspiration (ETo) as presented in Part 1.1. The programme can be used to calculate on a routine basis the daily, weekly or monthly ETo data for several locations in development projects. Also, it can be used to process climatological data of a given country and to provide in tabular form or on maps the evapotranspiration data needed for general project planning. Particularly for areas with considerable annual or monthly variation in climate, frequency analysis of ETo using each year of climatic record would provide improved estimations of water requirement data for planning purposes. Since large amounts of computations are involved, the programme will provide an efficient means to perform these calculations at a reasonable cost. It would replace the graphical and computational techniques as presented in Part 1.1.

Capabilities of the Computer Programme

The programme determines the values of reference crop evapotranspiration (ETo); conversion to evapotranspiration for different crops must be done manually using techniques described in Part 1.2. Estimates of ETo can be computed using daily, weekly, 10-day or monthly average values of climatological data. If more frequent data are provided for each month, the average monthly value of ETo is also printed. The programme is designed to handle the input climatological data regardless of units used, with the programme handling the necessary conversions.

Hardware and Software Requirements

The programme was developed and tested on a Burroughs B6700. Provisions for use on other computers with a minimum of difficulty have been made. Local computer consultants may be contacted for minor syntax error to suit a given system. The hardware requirements are:

FORTRAN IV COMPILER

One disk or tape unit	Burroughs
Memory (words)	4474
Printer (positions)	122
Compilation (CPU)	0.15 min

Description of the Programme

The programme consists of one main programme, five subroutines, and a function subprogramme. The subroutines are: BLANEY, RADIAT, PENMAN, CORPEN, ETPAN. CORPEN is the subroutine for Part 1.1.3 whereas PENMAN relates to use of the basic equation only (or with C = 1.0). All climatological data are read in the main programme and if no error in input data from a given station occurs, estimation of ETo by use of various subroutines is done. A macro-flow chart of programme functions is shown in Figure 1 of this Appendix. The main features are:

1. Print option. Through variable "NPRINT" user has choice of getting different levels of outputs as given below.
   NPRINT = 0 prints only station name and ETo estimates.
   = 1 prints above + converted data. (See example for Davis, California at end of this Appendix.)
   = 2 prints above + input data without conversion. (See example for Brawley.) Each card is printed as read. For first run this option is recommended. This will assist in identifying the specific card with format error, if any.
2. If neither measured sunshine (or cloudiness), solar radiation, nor net radiation data are available calculation by RADIAT is omitted.
3. Similarly, if neither measured relative humidity, sunshine data nor solar radiation data are available, calculation by PENMAN and CORPEN is omitted.
4. Estimation by Pan methods needs specification on length of fetch and case as described in Part 1.1.4. These specifications do not change daily or even monthly in many cases and therefore have been omitted from each data set of daily, weekly or monthly average values. There is an option to change these specifications by specifying "NREAD" as 1. For first data card of daily or average value "NREAD" should be made as 1 and on next card (not a data card). Fetch and case are to be read if EPAN estimation is desired.

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[1] Major portions of programme development were done under NSF-RANN Project on Nitrate in Effluents from Irrigated Lands (GI 34733X, GI 43664 and AEN 74-11136 AO1) University of California.

5. If mean average pressure (PMB) for the year is not defined for the station, the programme automatically uses the following relationship developed by W.O. Pruitt using data from a wide range of altitudes in Africa (Griffith, 1971, Climate of Africa, Vol. 10., World Survey of Climatology): $PMB = 1013 - .1152 * ALTITUDE + 5.44 * 10^{-6} * (ALTITUDE)^2$
6. Of the three elements of wind data (24 hour wind, daytime wind and day/night ratio), two have to be read in and the programme calculates the third missing parameter. If only 24-hr wind or daytime wind is given and no day/night ratio (URATIO) is read in, the programme assumes URATIO = 2.0.
7. If from the three humidity terms (Tdewpoint, vapour pressure and relative humidity) only one parameter is given, the programme approximates the others from known physical and mathematical relationships.
8. The equation used in the programme to estimate RS is: $RS = (0.25 + 0.50\ n/N)\ RA$ where RS = solar radiation; RA = extra-terrestrial radiation; n/N = ratio of actual to maximum possible bright sunshine hours. If a local reliable relationship based on a wide range of n/N and RS is available, the card given at sequence 2340 may be modified.

Card Preparation

Preparation of data deck as listed below is specific for the given programme. The data for each station are grouped into two parts: (i) data which remain constant for the station (A1, A2 and A3) and (ii) daily, weekly or monthly (or any number of days) average values. It is advised that data available on punched cards for any location be converted into the following form through a separate, independent programme.

A1 1st Card for each station:

Col 1-30	(5A6)	STA (30 character alphanumeric station code)
Col 31-35	(F5.0)	ALT (altitude of station in metres)
Col 36-40	(F5.0)	LAT (latitude of station in decimal)
Col 41	(A1)	HEMIS (hemisphere "N" or "S")
Col 42-50		Blank
Col 51-55	(F5.0)	UHT (height (metres) of wind measurements)
Col 56-60	(F5.0)	PMB (mean annual pressure in millibars if available) Programme will use a computed value if not given here.

A2 2nd Card for each station: factors for conversion, identification of status of data and selection of print option. For most of the factors see the comment cards in the programme.

Col 1-5	(F5-0)	FU24 (factor for converting 24-hr wind data to km/day)
Col 6-10	(F5.0)	FUDAY (Factor for converting daytime wind data to m/sec)
Col 11-15	(F5.0)	FACTED (factor for converting vapour pressure (ED) values to millibars)
Col 16-20	(F5.0)	FACTRS (factor for converting solar radiation (RS) to equivalent mm/day) (see comment cards in the programme)
Col 21-25	(F5.0)	FACTEP (factor for converting EPAN data to mm/day) (Monthly total evaporation in mm or inches must be converted to daily mean evaporation since programme will not handle this data.)
Col 26	(A1)	UNITT (flag for temperature data "C" or "F")
Col 27-36		Blank
Col 37	(I1)	UNIT N (flag for identifying the sunshine/cloudiness data) = 1, 2, 3, 4, or 5 (see comments in programme for details, sequence nos. 925-990)
Col 38		Blank
Col 39	(I1)	RHFLAG (flag for identification of RH data) = 1 if RH data are based on measurements (if actual dewpoint temperature data or vapour pressure are used, then RHFLAG = 1 since programme will automatically calculate RHmax, RHmean and RHmin.) = 2 if RH data are estimated
Col 40		Blank
Col 41	(I1)	UFLAG (flag for wind data) = 1 if U24 or UDAY are measured data = 2 if U24 or UDAY are estimated data
Col 42		Blank
Col 43	(I1)	NFLAG (flag for sunshine or NRATIO (n/N) data) = 1 if measured or RS is measured = 2 if estimated
Col 44		Blank
Col 45	(I1)	NPRINT (option for printing input data) = 0, only results are printed = 1, prints above + converted data

= 2, prints above + unconverted input data as read - - suggested for first run.

(NOTE: RHFLAG, UFLAG and NFLAG are provided to compute at least the Blaney method if no measured data on relative humidity, wind and sunshine are available for a particular station, but reasonable estimates can be made. In this case the use of Radiation or Penman is generally not desirable. However, for some regions there may be enough first-order weather stations to allow climate maps to be prepared with reasonably accurate isolines of n/N, Tdewpoint or vapour pressure, wind, etc. The necessary data for stations having only temperature data can be obtained by interpolation and calculations based on Radiation and Penman methods can thus be made. A "1" should be used in Col. 39, 41 and 43 as if data were measured.)

A3 3rd Card of each station specifying the options for various methods. Selection of one up to all of the methods can be specified depending on the status of climatological data.

Col 1-4		Blank
Col 5	(I1)	NBLANY (=1, estimates ET by Blaney and = 0, omits it)
Col 6-9		Blank
Col 10	(I1)	NRADIA (=1, estimates ET by Radiation method provided sunshine, n/N, or solar radiation are the measured data, or obtained as indicated a few comments back. A zero (0) in Col 10 indicates calculations based on Radiation method should not be made.)
Col 11-14		Blank
Col 15	(I1)	NPENMN (=1, estimates ET by Penman-FAO <u>equation</u> (with C = 1.0), provided relative humidity, wind, and sunshine data are measured data, or as indicated above, and = 0, omits it)
Col 16-19		Blank
Col 20	(I1)	NCORPN (=1, estimates ET by corrected Penman method if the data of relative humidity, wind and sunshine are measured data or as indicated above, and = 0, omits it)
Col 21-24		Blank
Col 25	(I1)	NETPAN (=1, estimates ETo by EPAN provided actual pan evaporation, FETCH and CASE are specified, and = 0, omits it)

A4 4th Card of each station.

Col 1-3	(A3)	SID (station identification in alphanumeric code in 3 characters on each card. These may be left blank if desired since these are not used in the programme.)
Col 4-5	(I2)	MONTH
Col 6-7	(I2)	DAY (should be inputted = 0 if only average monthly data are used, or = day of first date for weekly or 10-day periods, e.g. 1, 11, 21 for 10-day periods)
Col 8-9	(I2)	YEAR (last two digits of year, or 00 if mean data for multi-year records are used)
Col 10	(I1)	NREAD (flag for changing the FETCH and CASE values of ETPAN. = 1, needs next card "A5" and = 0, or blank for no change)
Col 11-15	(F5.0)	TMAX (daily or average daily maximum temperature. If no no decimal is used Col 15 must serve as location fov unit digit)
Col 16-20	(F5.0)	TMIN (daily or average daily minimum temperature)
Col 21-25	(F5.0)	TDEW (dewpoint temperature -- see sequence nos 830-840) Note: If no vapour pressure or RH data are available, a reliable estimate of TDEW is by assuming TDEW = TMIN, (or that the air is saturated at TMIN). This is reasonable for sub-humid climates but not for drier climates, especially when windy at time of TMIN.
Col 26-30	(F5.0)	RHMAX (maximum relative humidity -- see sequence nos 702-785). Note: If no dewpoint or vapour pressure data are available, RHMAX must be estimated if a Radiation method estimate of ETo is desired.
Col 31-35	(F5.0)	RHMIN (minimum relative humidity -- see sequence nos 790-815). Note: If no dewpoint or vapour pressure data are available, RHMIN must be estimated to obtain even a Blaney-Criddle estimate of ETo.
Col 36-40	(F5.0)	ED (vapour pressure -- sequence nos 440-450)

Col 41-45 (F5.0)	UDAY (mean daytime 0700-1900 hrs) wind -- see sequence nos 875-900). Note: If 24-hr wind data is not available, UDAY (or U24) must be estimated to obtain ETo estimates.
Col 46-50 (F5.0)	U24 (24 hour wind total)
Col 51-55 (F5.0)	NACT (hours of bright sunshine or cloudiness in oktas or tenths)
Col 56-60 (F5.0)	NRATIO.(ratio of actual to possible sunshine hours).Note: If no sunshine, cloudiness or RS data are available, NRATIO must be estimated to obtain even a Blaney-Criddle estimate of ETo.
Col 61-65 (F5.0)	RS (solar radiation)
Col 66-70 (F5.0)	RN (net radiation -- included in programme for research institutes where Rn may be measured)
Col 71-75 (F5.0)	EPAN (24-hour evaporation from USA Class A pan -- see sequence nos 460-470)
Col 76-80 (F5.0)	URATIO (ratio of daytime wind (0700-1900) to nighttime wind (1900-0700). Programme uses 2.0 if no basis for estimating)

Card A4 is repeated for all data sets for a given station. Blank card at the end of the data sets, reads the data for new station from Card A1. Whenever Col 10 is non-zero, the Card A5 has to be provided as next card.

A5 Card for reading new value of FETCH and CASE.

Col 1-10 (F10.0)	FETCH in metres (if no decimal is used Col 10 must serve as location for unit digit)
Col 11 (A1)	CASE ("A" or "B" -- see Part I.1 for details) (Present programme does not include methodology involving data from other than Class A pans.)

Test Data and Examples of Output

Examples from two locations in California are provided to illustrate the programme. The input data, column by column and card by card are provided not only for illustrative reasons but also as samples of test data to check newly punched programmes for a given computer.

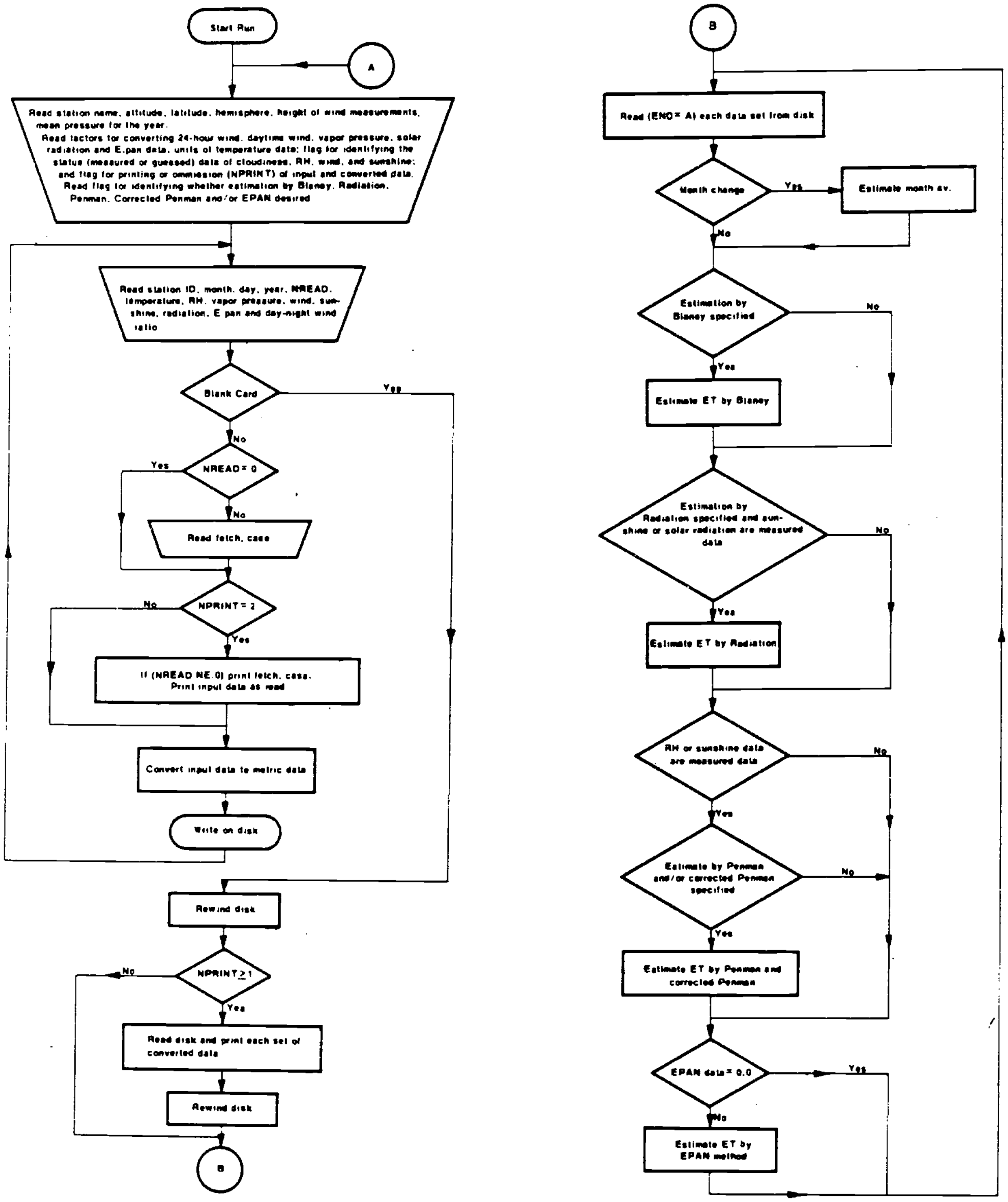
The examples provide first an illustration to compute ETo from mean climatological data for a multi-year record. For the pan data for Brawley, the reason for changing Case and FETCH relates to the particular situation found. The Class A pan is in a 10 m x 10 m weather station planted to Bermuda grass with the surrounding 4 ha field assumed to be non-cropped continuously. The change in Case (B to A and back to B) relates to the generally dormant condition of the Bermuda grass within the weather station during the November-February period (CASE B) as compared to its green-growing characteristic from March-October (CASE A). Assuming the 4 ha upwind field is dry all year, this results in a 5 m fetch of green grass for the Case A period of the year, but with the grass dormant, a fetch for the Case B situation of 5 m plus the 4 ha field or say around 200 m in the direction from which the prevailing winds come.

The Davis data are presented for a particular month (October 1960) to illustrate: (i) daily ETo calculation from daily weather data; (ii) 10-day mean ETo calculated from mean weather data for 10-day periods; and (iii) monthly mean ETo from mean weather data for the month (not mean of several years as for Brawley). The use of a "1" in Col 45 of Card A2 illustrates the case where only converted weather data are presented, as compared to the use of a "2" for Brawley with both original and converted data printed out. The use of a "0" would result in a printing of only the calculated ETo data.

As to the results the following observations can be made:

1. For Brawley a reasonable agreement exists month by month for all methods, although EPAN values run 10-14% low. This may be due to the fact that the 4 ha field was in crops about half the years of record. During such years the fetch in Case A periods would be some 200 with Kp values some 15% higher than selected by the programme.
2. For Brawley, little difference is noted between Penman and corrected Penman. The need for correction, however, is demonstrated by the daily Davis computations.
3. For Davis, the very high estimates by the Penman equation ($C = 1.0$) on days involving strong day and night winds combined with medium radiation during October and the low RHmax at night, are quite unrealistic. The agreement between corrected Penman and the other methods is quite good.
4. The Davis data illustrate the considerably better response of the Blaney-Criddle and Radiation methods to day by day weather changes than could possibly be expected using for example the original Blaney-Criddle, Makkink or Jensen-Haise methods. The availability of n/N, RH and wind data (or their reasonable estimates) remains a crucial requirement.
5. The rather close agreement (for each method) between ETo calculated from daily, 10-day or monthly weather data is surprisingly good for this particular set of data. Such close agreement may be somewhat fortuitous but at least is encouraging considering the rather extreme variability of wind and relative humidity day by day.

Figure 1. MACRO-FLOW CHART



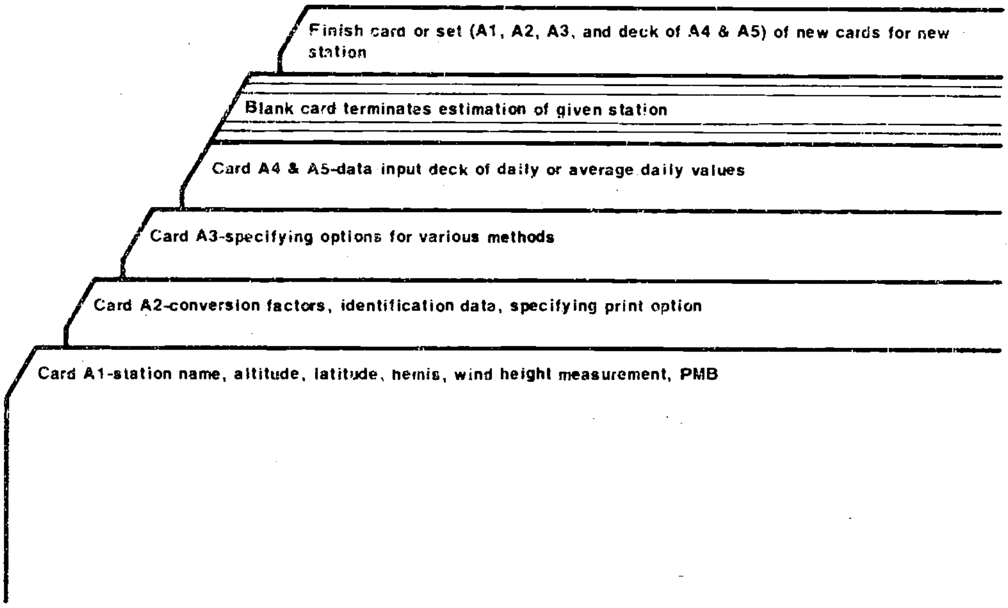


Figure 2. DECK SETUP FOR INPUT DATA OF PROGRAM

```
FILE 1=ETDATA,UNIT=DISK,RECORD=24,BLOCKING=15,AREA=50,TS,SAVE=7      00000105
C--------------------------------------------------------------------00000120
C   ABOVE DECLARATION OF FILE 1 IS AS PER BURROUGHS B6700.            00000125
C   FOR OTHER INSTALLATIONS THIS MAY NEED TO BE CHANGED.              00000130
C   FOR EXAMPLE IBM 360 NEED DECLARATION OF FILE BY SEPARATE D.D.CARD. 00000135
C   MAXIMUM LENGTH OF RECORD IS 22 AND NUMBER OF RECORDS ARE AS PER THE 00000140
C   NUMBER OF CARDS TO BE READ.                                       00000145
C   BLOCKING MAY BE CHANGED, BUT THIS MAY MAKE MINOR DIFFERENCE IN COST 00000150
C   LOCAL CONSULTANT OF GIVEN COMPUTER CAN GIVE BEST SUGGESTIONS.     00000155
C--------------------------------------------------------------------00000160
C--------------------------------------------------------------------00000165
C                                                                     00000170
C             THIS COMPUTER PROGRAM  HAS DEVELOPED                    00000175
C                            BY                                       00000180
C        S.K.GUPTA, W.O.PRUITT, J.LONCZAK, AND K.K.TANJI              00000185
C        DEPARTMENT OF LAND, AIR, AND WATER RESOURCES                 00000190
C        WATER SCIENCE AND ENGINEERING SECTION                        00000195
C        UNIVERSITY OF CALIFORNIA,                                    00000200
C        DAVIS, CALIFORNIA  U.S.A.                                    00000205
C                                                                     00000210
C                                                                     00000215
C          THIS IS A COMPUTER PROGRAM BASED ON "CROP WATER            00000220
C       REQUIREMENTS" BY J. DOORENBOS AND W. O. PRUITT, IRRIGATION    00000225
C       AND DRAINAGE PAPER 24 (SECOND EDITION), WATER RESOURCES       00000230
C       DEVELOPMENT AND MANAGEMENT SERVICE, LAND AND WATER DEVELOPMENT 00000235
C       DIVISION, F.A.O. OF UNITED NATIONS, ROME.                     00000240
C                                                                     00000245
C          IT ESTIMATES REFERENCE CROP EVAPOTRANSPIRATION (ETO)       00000250
C       BY ANY OR ALL OF THE FOLLOWING METHODS:                       00000255
C          1) BLANEY-CRIDDLE(FAO)                                     00000260
C          2) RADIATION(FAO)                                          00000265
C          3)  MODIFIED PENMAN(FAO) WITH C = 1.0                      00000270
C          4) MODIFIED PENMAN(FAO)WITH CORRECTION                     00000275
C          5) PAN EVAPORATION(FAO)                                    00000280
C                                                                     00000285
C--------------------------------------------------------------------00000290
                                                                      00000295
      FUNED(TDEW)= EXP(54.878919-6790.4985/TDEW)-5.02808*ALOG(TDEW))  00000300
      REAL LAT, RACT, RTBL, RTBL1, RTBL2, RRATIO                      00000305
      INTEGER MONTH, DAY, YEAR, UNITN                                 00000310
      DOUBLE PRECISION ESTACT(2,2),SUNDAT(5),STA(5)                   00000315
      REAL RNTBL(11,12), WTS(5,14), RAN(11,12), RMAS(11,12)           00000320
      DATA SIGMA / 2.0E-9 /                                           00000325
                                                                      00000330
C     THE ABOVE VALUE OF SIGMA IS EQUIVALENT TO USING L=584 CAL/GM WATER00000335
C     SINCE SIGMA=11.71*10E-8 CAL /CM.CM                              00000340
                                                                      00000345
C--------------------------------------------------------------------00000350
C     THIS PROGRAM DOES THE FOLLOWING                                 00000355
C             READS IN ALL INPUT DATA                                 00000360
C             CONVERTS THE DATA INTO METRIC UNITS                     00000365
C             CALCULATES THE NEEDED MEANS                             00000370
C             ADJUSTS THE WIND MEASUREMENTS TO 2 M HEIGHT.            00000375
C             ESTIMATES THE SOLAR RADIATION IF NOT GIVEN              00000380
C             CALLS THE SUBROUTINE BY WHICH THE ESTIMATION IS DESIRED. 00000385
C                                                                     00000390
C     LIST OF INPUT SYMBOLS                                           00000395
C             *******************************************************00000400
C             ALT = STATION ALTITUDE                                  00000405
C             CASE = A OR B (SEE DETAILS IN CHAPTER 1.1)              00000410
C                  - REQUIRED ONLY IF PAN EVAPORATION ESTIMATE OF ETO 00000415
C                    VALUE IS DESIRED                                 00000420
C             DAY = TWO DIGIT REPRESENTATION OF DAY (IE. 08)          00000425
C                 = 00 IF MONTHLY DATA ARE GIVEN                      00000430
C                 - REQUIRED ON ALL DAILY AND MONTHLY DATA CARDS      00000435
C             ED - DAY'S ACTUAL VAPOR PRESSURE IF DATA ARE DAILY      00000440
C                - MEAN OF DAILY VP'S IF DATA ARE MONTHLY             00000445
C                - OPTIONAL BUT SUGGESTED FOR INCREASING ACCURACY     00000450
C             EPAN - DAY'S EVAPORATION FROM CLASS A PAN               00000455
C                  = MEAN OF DAILY EVAP'S IF DATA ARE MONTHLY         00000460
C                  - REQUIRED ONLY IF PAN EVAPORATION VALUE ARE DESIRED 00000465
C             FACTED = FACTOR FOR CONVERTING "ED" VALUES TO MILLIBARS 00000470
C                    - 1.0  IF ED DATA ARE IN TERMS OF MILLIBARS      00000475
C                    - 1.33 IF ED DATA ARE IN MILLIMETERS OF MERCURY  00000480
C                     - 33.78 IF ED DATA ARE IN INCHES OF MERCURY     00000485
C             FACTEP - FACTOR FOR CONVERTING EPAN DATA INTO MM/DAY    00000490
C                    - 1 IF DATA ARE ALREADY IN MM/DAY                00000495
C                    - 25.4 IF DATA ARE IN IN/DAY                     00000500
C             FACTRS = FACTOR FOR CONVERTING RS DATA INTO MM/DAY      00000505
C                    - 1 IF DATA ARE ALREADY IN MM/DAY                00000510
C                    - 0.017 IF DATA ARE IN CAL/DAY                   00000515
C                    = 0.408 IF DATA ARE IN MEGA JOULES/M*M           00000520
C             FETCH = LENGTH OF UPWIND GREEN CROP FROM PAN FOR CASE A 00000525
C                   - UPWIND DRY SURFACE FOR CASE B                   00000530
C                   - REQUIRED ONLY IF PAN EVAPORATION VALUE IS DESIRED 00000535
C             FUDAY  = FACTOR FOR CONVERTING DAY TIME WIND DATA       00000540
C                    -  1. 0 IF UDAY IS IN M/SEC                      00000545
C                    -  0.447 IF UDAY IS IN MPH                       00000550
C                    -  0.278 IF UDAY IS IN KM/HR                     00000555
C                    -  0.515 IF UDAY IS IN KNOTS                     00000560
C             FU24 - FACTOR FOR CONVERTING WIND DATA TO KM/DAY.       00000565
C                  = 1.0 IF  U24 IS ALREADY IN KM/DAY                 00000570
C                  - 24 IF U24 IS IN KM/HR                            00000575
C                = 38.6 IF U24 IS IN MPH                              00000580
C                  - 1.609 IF U24 IS IN MILES/DAY                     00000585
C                  = 44.47 IF U24 IS IN KNOTS                         00000590
C             HEMIS - HEMISPHERE (N OR S)                             00000595
C             LAT = STATION LATITUDE IN DEGREES N OR S (IS ALWAYS POS.) 00000600
C             MONTH = TWO DIGIT REPRESENTATION OF MONTH (IE. 02)      00000605
C                   - REQUIRED ON ALL DAILY AND MONTHLY DATA CARDS    00000610
C             RACT - HOURS OF BRIGHT SUNSHINE OR                      00000615
C                  - CLOUDINESS IN OKTAS OR TENTHS (SEE FACTR)        00000620
C             RFLAG  = FLAG FOR SUNSHINE OR RRATIO DATA               00000625
C                    - 1 IF MEASURED OR AS GIVEN                      00000630
C                    = 2 IF ESTIMATED                                 00000635
C             *******************************************************00000640
C             NBLANY - FLAG FOR BLANEY ET ESTIMATION.                 00000645
C             NCORPN - FLAG FOR CORRECTED PENMAN ET ESTIMATION.       00000650
C             NETPAN - FLAG FOR PAN EVAPORATION ET ESTIMATION.        00000655
C             NPENMN - FLAG FOR PENMAN ET ESTIMATION(C=1.0).          00000660
C             NRADTA - FLAG FOR RADIATION ET ESTIMATION.              00000665
C                    = 1 IF DESIRED                                   00000670
C                    - 0 IF NOT DESIRED                               00000675
C             *******************************************************00000680
C            NPRINT - 0 IF INPUT DATA IS NOT TO BE PRINTED.           00000685
C                   - 1 IF ALONGWITH RESULTS,INPUT DATA AFTER CONVERSION00000690
C                       ARE TO BE PRINTED.                            00000695
C                   - 2 IF IN ADDITION TO ABOVE THE INPUT DATA AS READ 00000700
C                        ARE TO BE PRINTED.                           00000705
C                        FOR FIRST RUN MAKE NPRINT=2.                 00000710
C             RRATIO - RATIO OF ACTUAL SUNSHINE HOURS TO POSSIBLE     00000715
C             NREAD - FLAG FOR READING NEW VALUES OF URATIO,FETCH & CASE00000720
C                   - 0 OR BLANK IF NO CHANGES ARE DESIRED            00000725
C                   - 1 IF ALL OR ANY ONE OF THE PARAMETERS ARE TO BE 00000730
C                     CHANGED.                                        00000735
C             PMB - MEAN PRESSURE IN MILLIBARS FOR THE YEAR.          00000740
C             RHFLAG = FLAG FOR RELATIVE HUMIDITY DATA                00000745
C                    = 1 IF DATA ARE ACTUALLY COLLECTED DATA          00000750
C                    - 2 IF DATA ARE ESTIMATED                        00000755
C             RHMAX = MAX RELATIVE HUMIDITY FOR THE DAY               00000760
C                   = MEAN OF DAILY MAX RH'S IF DATA ARE MONTHLY.     00000765
C                   - REQUIRED ON ALL DAILY OR MONTHLY DATA CARDS     00000770
C                     UNLESS ED OR TDEWPOINT ARE GIVEN.               00000775
C                     IF NONE OF THREE IS AVAILABLE,ESTIMATE IS REQUIRED00000780
C                     IN CASE METHOD II  CALCULATION IS DESIRED.      00000785
C             RHMIN = MIN RELATIVE HUMIDITY FOR THE DAY.              00000790
C                   - MEAN OF DAILY MIN RH'S IF DATA ARE MONTHLY.     00000795
C                   - REQUIRED ON ALL DAILY OR MONTHLY DATA CARDS     00000800
C                     UNLESS ED OR TDEWPOINT IS GIVEN.                00000805
C                     IF NONE OF THREE IS AVAILABLE,ESTIMATE IS REQUIRED00000810
C                     IN CASE METHOD I CALCULATION IS DESIRED.        00000815
C             RS - SOLAR RADIATION IN TERMS OF EQUIVALENT EVAPORATION. 00000820
C             STA  - STATION NAME.                                    00000825
C             TDEW = DAY'S DEW POINT TEMPERATURE IF DATA ARE DAILY.   00000830
C                  - MEAN OF DAILY DPT'S IF DATA ARE MONTHLY.         00000835
C                  - OPTIONAL BUT SUGGESTED IF ED ARE NOT GIVEN.      00000840
C             TMAX - MAXIMUM TEMPERATURE FOR DAY IF DATA ARE DAILY.   00000845
C                  = MEAN OF MAX DAILY. TEMPS IF DATA ARE MONTHLY     00000850
C                  - REQUIRED ON ALL DAILY OR MONTHLY DATA CARDS.     00000855
C             TMIN - MINIMUM TEMPERATURE FOR DAY IF DATA ARE DAILY.   00000860
C                  = MEAN OF MIN DAILY TEMPS IF DATA ARE MONTHLY.     00000865
C                  - REQUIRED ON ALL DAILY OR MONTHLY DATA CARDS.     00000870
C             UDAY = MEAN DAYTIME WIND SPEED (IE. BETWEEN 0700 AND 1900)00000875
C                    IF NOT KNOWN AND U24 DATA ARE UNAVAILABLE,ESTIMATE00000880
C                    MUST BE GIVEN IN CASE USE OF METHOD I & II ARE   00000885
C                    DESIRED.                                         00000890
C                    IF U24 KNOWN, ESTIMATE OF UDAY/UNIGHT MUST BE MADE00000895
C                    OTHERWISE PROGRAM USES 2.0 FOR URATIO.           00000900
C             U24 =  24 HOUR WIND TOTAL.                              00000905
C             UFLAG  - FLAG FOR WIND DATA.                            00000910
C                    - 1 IF U24 OR UDAY  IS MEASURED DATA.            00000915
C                    - 2 IF U24 OR UDAY IS ESTIMATED.                 00000920
C             UNITN - CONVERSION FLAG FOR SUNSHINE/CLOUDINESS DATA.   00000925
C                   - 1 IF SUNSHINE DATA ARE GIVEN IN SUNSHINE HOURS  00000930
C                          AS A DECIMAL                               00000935
C                   - 2 IF SUNSHINE DATA ARE GIVEN IN SUNSHINE HOURS  00000940
C                          AS HOURS AND MINUTES SEPARATED BY A        00000945
C                          DECIMAL POINT                              00000950
C                   = 3 IF SUNSHINE DATA ARE GIVEN INVERS    IN TERMS 00000955
C                          OF OKTAS OF CLOUDINESS                     00000960
C                   = 4 IF SUNSHINE DATA ARE GIVEN INVERSELY IN TERMS 00000965
C                          OF TENTHS OF CLOUDINESS                    00000970
C                   = 5 IF NO SUNSHINE/CLOUDINESS DATA ARE GIVEN.     00000975
C                    NOTE:- IF RS DATA ARE GIVEN, PROGRAM WILL COMPUTE00000980
C                    RRATIO, IF RS NOT AVAILABLE EITHER, ESTIMATE MUST00000985
C                    THEN BE INCLUDED.                                00000990
C             UNITT = FLAG FOR TEMPERATURE DATA                       00000995
C                   - C IF INPUT DATA ARE IN DEGREES CELCIUS          00001000
C                   - F IF INPUT DATA ARE IN DEGREES FAHRENHEIT       00001005
C             URATIO- RATIO  OF UDAY/UNIGHT(IN CONSISTENT UNITS)      00001010
C                     IF NO BASIS FOR ESTIMATING, 2.0 VALUE IS ASSUME00001015
C             UHT - HEIGHT IN METERS FROM GROUND LEVEL AT WHICH THE   00001020
C                          WIND MEASUREMENTS WERE TAKEN.              00001025
C             YEAR - LAST TWO DIGITS OF YEAR (IE. 75)                 00001030
/ALL /                                                                00001035
C             *******************************************************00001040
C  NOTE:- RHFLAG,UFLAG AND RFLAG ARE READ IN TO ELIMINATE USE OF PENMAN 00001045
C         OR RADIATION  IF SOME DATA ARE ROUGH ESTIMATE INSTEAD OF    00001050
C         MEASURED INFORMATION.                                       00001055
C          IF INTERPOLATED DATA ARE AVAILABLE FROM MAPS OF A REGION   00001060
C          SHOWING LINES OF EQUAL TDEW POINT, RH,  RRATIO ETC.,A      00001065
C          FLAG = 1 MAY BE DESIRED EVEN THOUGH TEMPERATURE DATA       00001070
C          ALONE ARE MEASURED DATA.                                   00001075
C--------------------------------------------------------------------00001080
C                                                                     00001085
C********************************************************************00001090
C         PROGRAM CONSTANTS.                                          00001095
C********************************************************************00001100
      ESTACT(1,1)="ACTUAL"                                            00001105
      ESTACT(1,2)=" DATA"                                             00001110
      ESTACT(2,1)="ESTIMA"                                            00001115
      ESTACT(2,2)="TED   "                                            00001120
                                                                      00001125
      SUNDAT(1)="SUNHRS"                                              00001130
      SUNDAT(2)="SUNDEC"                                              00001135
      SUNDAT(3)=" OKTAS"                                              00001140
      SUNDAT(4)="TENTHS"                                              00001145
      SUNDAT(5)="NODATA"                                              00001150
C********************************************************************00001155
C                THE CONSTANTS AND CONVERSION FACTORS OF THE GIVEN    00001160
C          STATION ARE READ AND PRINTED.                              00001165
C********************************************************************00001170
    1 READ (5,500,END=300) STA, ALT, LAT, HEMIS, UHT, PMB             00001175
      READ (5,510) FU24,FUDAY,FACTED,FACTRS,FACTEP,UNITT,UNITN,RHFLAG, 00001180
     # UFLAG,RFLAG,NPRINT                                             00001185
      READ (5,520) NBLANY, NRADTA, NPENMN, NCORPN, NETPAN             00001190
                                                                      00001195
      IF(PMB.LE.0.0)PMB = 1013 - .1152*ALT + 5.44*10.E-6*ALT*ALT      00001200
                                                                      00001205
C**** ABOVE EQ. IS DERIVED FROM LONG TIME MEAN PMB FOR NUMBER OF STATION 00001210
C     IN AFRICA(CLIMATE OF AFRICA,VOL 10,WORLD SURVEY OF CLIMATOLOGY) 00001215
                                                                      00001220
      IEND = 0                                                        00001225
      NCASE = 0                                                       00001230
      PRINT 621                                                       00001235
      PRINT 620                                                       00001240
      PRINT 600, STA, ALT, LAT, HEMIS, UHT, PMB                       00001245
      PRINT 620                                                       00001250
      IF(NPRINT.EQ.0) GO TO 5                                         00001255
      PRINT 620                                                       00001260
      PRINT 610, FU24, FUDAY, FACTED, FACTRS, FACTEP, UNITT, UNITN,   00001265
     #         ESTACT(RHFLAG,1),ESTACT(RHFLAG,2),ESTACT(UFLAG,1),     00001270
     #         ESTACT(UFLAG,2),ESTACT(RFLAG,1),ESTACT(RFLAG,2)        00001275
      PRINT 620                                                       00001280
C********************************************************************00001285
C             THIS 100 LOOP READS IN EACH DAILY OR MONTHLY DATA CARD  00001290
C       AND IMMEDIATELY PRINTS THE DATA BACK OUT.  IT THEN ADJUSTS,   00001295
C       CONVERTS, AND CALCULATES VARIOUS VALUES TO OBTAIN THE NEEDED  00001300
C       PROGRAM VALUES.  FINALLY IT WRITES THESE CONVERTED DATA OUT TO 00001305
C       DISK AND READS THE NEXT CARD.                                 00001310
C********************************************************************00001315
    5 DO 100 I=1,5000
      READ(5,530,END=105)STA,MONTH,DAY,YEAR,NREAD,TMAX,TMIN,TDEW,RHMAX, 00001320
     # RHMIN,ED,UDAY,U24,RACT,RRATIO,RS,RN,EPAN,URATIO                00001325
      IF(MONTH.EQ.0.AND.DAY.EQ.0)GO TO 105                            00001330
      IF(NREAD.EQ.0)GO TO 10                                          00001335
C********************************************************************00001340
C          NREAD = 1 WHEN FETCH AND CASE HAS TO BE READ AGAIN         00001345
C********************************************************************00001350
      READ(5,540) FETCH,CASE                                          00001355
   10 IDAY = IDAY + 1                                                 00001360
      EA=0.0                                                          00001370
      IF(NPRINT.LT.2) GO TO 25                                        00001375
      IF (I.NE.1) GO TO 20                                            00001380
      PRINT 621                                                       00001385
      PRINT 620                                                       00001390
      PRINT 625                                                       00001395
      PRINT 620                                                       00001405
      PRINT 630, SUNDAT(UNITN)                                        00001410
   20 IF(NREAD.NE.0)PRINT 632,FETCH,CASE                              00001415
      PRINT 634, MONTH,DAY,YEAR,TMAX,TMIN,TDEW,RHMAX,RHMIN,ED,UDAY,U24, 00001420
     #          RACT,RRATIO,RS,RN,EPAN,URATIO                         00001425
C********************************************************************00001430
C             CALCULATING TMEAN AND RHMEAN, AND CONVERTING THE        00001435
C       TEMPERATURE DATA TO CELCIUS IF NECESSARY.                     00001440
C********************************************************************00001445
   25 IF(RHMAX.GT.100.0.OR.RHMIN.GT.100.0)PRINT 624, RHMAX,RHMIN      00001450
      RHMEAN=(RHMAX+RHMIN)/2.0                                        00001455
```

```
      TMEAN=(TMAX+TMIN)/2.0                                             00001A60
      IF (UNITT.IS."C") GO TO 30                                        C0001A65
      TMAX = (TMAX-32.0) * 5.0/9.0                                      00001AT0
      TMIN = (TMIN-32.0) * 5.0/9.0                                      00001AT5
      TMEAN = (TMEAN-32.0) * 5.0/9.0                                    00001A60
      IF (TDEW.NE.0.0) TOEW = (TOEW-32.0) * 5.0/9.0                     00001A65
   30 TK = TMEAN + 273.16                                               00001A90
      IF(TDEW.NE.0.0)TKDEW = TOEW +  2T3.16                             00001A95
C.................................................................00001500
C        AOJUSTING FOR MEASUREMENT NEIGHT IF IT IS OTHER THAN 2 METERS. 00001505
C.................................................................00001510
      A = 0.)T                                                          00001515
      IF(UHT.LE.2.0) A = 0.22                                           00001520
      UHTCF = ((2.0/UHT)**A)                                            00001525
      UOAT = UOAT * UHTCF                                               00001530
      U2A = U2A * UHTCF                                                 00001535
C.................................................................00001540
C        CORRECTION FACTORS MULTIPLIEO.                                 000015A5
C.................................................................00001550
      U2A = U2A * FU2A                                                  00001555
      IF(UOAT.EQ.0.0) GO TO 35                                          00001560
      UDAT = UDAT * FUOAT                                               000015A5
   35 IF(U2A.EQ.0.0.AND.UOAT.EO.0.0) OO TO 40                           000015T0
      UNIGHT = 0.0                                                      000015T5
      IF(U2A.NE.0.0.AND.UOAT.NE.0.0) UNIGHT = U2A/A3.2 * UOAT           00001560
      IF(UNIOHT.NE.0.0.AND.UDAT.NE.0.0.AND.URATIO.EO.0.0)               00001565
     # URATIO = UOAT/UNIOHT                                             00001590
                                                                        00001595
C.....IF NO URATIO DATA IS GIVEN OR POSSIBLE FROM DATA URATIO = 2.0     00001600
                                                                        00001605
      IF(URATIO.EO.0.0) URATIO = 2.0                                    00001610
      IF(U2A.NE.0.0.AND.UOAT.EQ.0.0) UDAT=U2A*URATIO/(A3.2*(1+URATIO))  00001615
      IF(U2A.EQ.0.0.AND.UDAT.NE.0.0) U2A=A3.2*UOAT*(1+1./URATIO)        00001620
C.................................................................00001625
C        FROM GIVEN WINO DATA OTHER WINO DATA ARE ESTIMATEO.            00001630
C.................................................................00001635
   A0 ED = ED * FACTED                                                  00001640
      RS = RS * FACTRS                                                  00001645
      EPAN = EPAN * FACTEP                                              00001650
C.................................................................00001655
C        CALCULATION OF EA. AND EO IF NOT GIVEN.                        00001660
C.................................................................00001665
      EA = FUNEO(TK)                                                    000016T0
      IF (TOEW.NE.0.0.AND.EO.EO.0.0) EO = FUNED(TKOEW)                  000016T5
      IF(EO.EQ.0.0) EO = RHMEAN*EA/100.0                                00001680
      TKMAX = TMAX + 2T3.16                                             00001685
      TKMIN = TMIN + 2T3.16                                             00001690
      EATMAX = FUNED(TKMAX)                                             00001695
      EATMIN = FUNEO(TKMIN)                                             00001T00
      IF(RHMIN.EQ.0.0.AND.TDEW.NE.0.0) RHMIN = 100.0*EO/EATMAX          00001T05
      IF(RHMAX.EQ.0.0.AND.TDEW.NE.0.0) RHMAX = 100.0*EO/EATMIN          00001T10
      IF(RHMAX.GT.100.0)RHMAX=100.0                                     00001T12
      IF(RHMIN.GT.100.0)RHMIN=100.0                                     00001T13
      IF(RHMEAN.EO.0.0) RHMEAN =(RHMAX + RHMIN)*0.5                     00001T15
      IF (CASE.IS."A") NCASE = 1                                        00001T20
      IF (CASE.IS."B") NCASE = 2                                        00001T25
C.................................................................00001T30
C             THIS SECTION CONVERTS WHATEVER SUNSHINE/CLOUDINESS DATA   00001T35
C        IS GIVEN (IF ANY) TO EITHER SUNSHINE HOURS OR NRATIO.  IF NONE 00001TA0
C        IS OIVEN. THEN NRATIO OR RS MUST BE GIVEN.                     00001TA5
C.................................................................00001T50
      GO TO (60,A5,50,55,65), UNITN                                     00001T55
   A5 NHRS=INT(NACT)                                                    00001TA0
      NMINS=(NACT-NHRS) * 100.0                                         00001T65
      NACT=NHRS + NMINS/60.0                                            00001TT0
      OO TO 60                                                          00001TT5
                                                                        00001T60
   50 NRATIO = 0.95- 0.08T*NACT - 0.003*NACT*NACT                       00001T65
                                                                        00001T90
C  ...  IF NACTUAL IS 8.0 MEANS FULL CLOUDINESS                         00001T95
                                                                        00001600
      NACT=0.0                                                          00001605
      GO TO A0                                                          00001610
                                                                        00001615
   55 NRATIO = 0.95 - 0.066*NACT - 0.0023*NACT*NACT                     00001620
      NACT=0.0                                                          00001625
C.................................................................00001830
C             IF NRATIO IS ZERO . IT IS ESTIMATEO FROM RS.              00001835
C        IN "NNTBL" BELOW. MONTH IS ON THE VERTICAL FROM 1 TO 12. AND   000016A0
C        LATITUDE IS HORIZONTAL FROM 0 TO 50 OEGREES.                   000016A5
C.................................................................00001650
      DATA NNTBL                                                        00001655
     1 / 12.1,11.6,11.A,11.3,11.0,10.T,10.A,10.1, 9.6, 9.2, 8.5,        00001860
     2   12.1,11.9,11.6,11.A,11.5,11.3,11.1,11.0,10.T,10.A,10.1,        00001865
     3   12.1,12.0,12.C,12.0,12.0,12.0,12.0,11.9,11.9,11.9,11.6,        000018T0
     A   12.1,12.2,12.3,12.5,12.6,12.T,12.9,13.1,13.3,13.5,13.6,        000018T5
     5   12.1,12.3,12.A,12.6,13.1,13.3,13.6,1A.0,1A.A,1A.6,15.A,        00001880
     A   12.1,12.A,12.T,13.0,13.3,13.T,1A.0,1A.5,15.0,15.6,1A.3,        00001885
     T   12.1,12.3,12.6,12.9,13.2,13.5,13.9,1A.3,1A.T,15.3,15.9,        00001890
     8   12.1,12.3,12.A,12.A,12.8,13.0,13.2,13.5,13.T,1A.1,1A.5,        00001895
     9   12.1,12.1,12.1,12.2,12.3,12.3,12.A,12.A,12.5,12.A,12.T,        00001900
     A   12.1,12.0,11.8,11.8,11.T,11.A,11.5,11.3,11.2,11.0,10.8,        00001905
     B   12.1,11.9,11.6,11.A,11.2,10.9,10.A,10.3,10.0, 9.6, 9.1,        00001910
     C   12.1,11.6,11.5,11.2,10.9,10.6,10.2, 9.6, 9.3, 8.6, 8.1 /       00001915
                                                                        00001920
   60 IF(NRATIO.NE.0.0) A0 TO A5                                        00001925
      IF (RS.NE.0.0) GO TO 65                                           00001930
      IF (HEMIS.IS."S") MONTH=MOD(MONTH+5,12) + 1                       00001935
      LL=INT(LAT/5) * 5                                                 000019A0
      IF (LAT.GT.50) LL=50                                              000019A5
      L1=LL/5 + 1                                                       00001950
      L2=L1 + 1                                                         00001955
      IF (L2.[illegible]                                                000019A0
      FAC1=(LAT-LL)/5.0                                                 000019A5
      MONTH1 = MONTH                                                    000019T0
      MONTH2 = MONTH                                                    000019T5
      IF (OAT.OT.15) MONTH2=MOD(MONTH,12) + 1                           00001980
      IF (DAT.LT.15.AND.OAT.NE.0) MONTH1=MOD(MONTH+10,12) + 1           00001985
      NTBL1=NNTBL(L1,MONTH1) + FAC1*(NNTBL(L2,MONTH1)-NNTBL(L1,MONTH1)) 00001990
      NTBL2=NNTBL(L1,MONTH2) + FAC1*(NNTBL(L2,MONTH2)-NNTBL(L1,MONTH2)) 00001995
      FAC=DAY - 15                                                      00002000
      IF (FAC.LT.0.0) FAC=FAC + 30.0                                    00002005
      FAC2=FAC/30.0                                                     00C02010
      NTBL=NTBL1 + FAC2 * (NTBL2-NTBL1)                                 00002015
      NRATIO=NACT/NTBL                                                  00002020
      IF (HEMIS.IS."S") MONTH=MOD(MONTH+5,12) + 1                       00002025
C.................................................................00002030
C             THIS SECTION CALCULATES A VALUE FOR RA IF IT IS NEEOEO.   00002035
C        IN "RRAN" AND "RRAS" BELOW MONTH IS ON THE VERTICAL FROM       000020A0
C        1 TO 12. AND LATITUDE IS HORIZONTAL FROM 0 TO 50.              000020A5
C.................................................................00002050
      DATA RRAN                                                         00002055
     1 / 15.0,14.1,13.2,12.2,11.2,10.1, A.9, T.6, A.A, 5.1, 3.9,        000020A0
     2   15.5,1A.9,1A.3,13.5,12.T,11.T,10.T, 9.A, 8.5, T.3, A.1,        00002065
     3   15.7,15.A,15.3,1A.9,14.4,13.T,13.0,12.2,11.3,10.3, 9.3,        000020T0
     A   15.3,15.5,15.A,15.T,15.A,15.5,15.2,1A.T,1A.2,13.5,12.T,        000020T5
     5   1A.4,15.0,15.5,16.0,16.3,16.A,1A.5,1A.A,1A.3,1A.1,15.T,        00002080
     6   13.9,[illegible],15.2,15.6,16.3,1A.T,1T.0,1T.2,1T.3,1T.3,1T.2,  00002085
     T   1A.1,14.7,15.3,15.8,16.3,1A.A,1A.T,1A.6,16.T,16.A,1A.A,        C0002090
     8   1A.8,15.2,15.5,15.8,15.9,15.8,15.T,15.5,15.1,1A.6,1A.0,        C0002095
     9   15.3,[illegible].3,15.1,1A.6,1A.5,13.9,13.2,12.5,11.T,10.9,    00002100
     A   15.4,15.1,14.6,1A.1,13.A,12.A,11.T,10.T, 9.6, 6.5, T.2,        00002105
     B   15.1,[illegible]A,12.7,11.7,10.A, 9.5, 6.2, T.0, 5.6, A.3,     00002110
     C   14.8,[illegible]11.9,10.6, 9.5, 8.3, T.0, 5.T, A.3, 3.9 /      00002115
                                                                        C0002120
      DATA RRAS                                                         00002125
     1 / 15.0,15.T,16.A,16.9,1T.3,1T.6,1T.8,1T.9,17.9,1T.T,1T.A,        00002130
     2   15.5,15.9,1A.2,16.A,1A.5,16.5,1A.3,1A.0,15.T,15.2,14.A,        00002135
     3   15.T,15.T,15.A,15.3,15.0,1A.A,1A.0,13.A,12.A,11.T,10.T,        000021A0
     A   15.3,1A.6,1A.3,13.A,12.9,12.1,11.2,10.2, 9.2, 8.1, 7.0,        000021A5
     5   1A.A,13.T,12.9,12.0,11.0,10.0, 8.9, T.6, A.A, 5.A, A.2,        00002150
     A   13.9,13.0,12.1,11.1,10.0, 6.9, T.6, 6.6, 5.A, A.2, 3.0,        00002155
     T   1A.1,13.3,12.A,11.A,10.A, 9.3, 8.2, T.1, 5.9, A.T, 3.5,        000021A0
     6   1A.8,1A.2,13.5,12.6,11.9,11.0,10.0, 9.0, T.9, 6.T, 5.6,        000021A5
     9   15.3,15.1,1A.8,14.A,1A.0,13.A,12.T,11.9,11.0,10.0, 6.6,        000021T0
     A   15.A,15.T,15.9,15.9,15.8,15.A,15.2,1A.6,1A.2,13.6,12.6,        000021T5
     B   15.1,15.7,16.2,1A.T,17.0,1T.2,1T.2,1T.1,1T.0,16.T,1A.A,        00002180
     C   1A.6,15.6,16.3,16.9,1T.A,1T.T,16.0,18.2,16.3,18.3,18.1         00002185
                                                                        00002190
   66 IF (NRATIO.NE.0.0.AND.RS.NE.0.0) GO TO 85                         00002195
      IF(NRATIO.EO.0.0.AND.RS.EO.0.0) OO TO 80                          00002200
      LL=INT(LAT/5) * 5                                                 00002205
      IF (LAT.GT.50.0) LL=50                                            00002210
      L1=LL/5 + 1                                                       00002215
      L2=L1 + 1                                                         00002226
      IF (L2.OT.11) L2=11                                               00002225
      FAC1=(LAT-LL)/5.0                                                 00002230
      MONTH1 = MONTH                                                    00002235
      MONTH2 = MONTH                                                    000022A0
      IF (OAT.LT.15.ANO.OAT.NE.0) MONTH1=MOO(MONTH+10,12) + 1           000022A5
      IF (DAT.GT.15) MONTH2=MOO(MONTH,12) + 1                           00002250
      IF (HEMIS.IS."S") GO TO TO                                        00002255
      RA1=RRAN(L1,MONTH1) + FAC1 * (RRAN(L2,MONTH1)-RRAN(L1,MONTH1))    00002260
      RA2=RRAN(L1,MONTH2) + FAC1 * (RRAN(L2,MONTH2)-RRAN(L1,MONTH2))    00002265
      GO TO T5                                                          000022T0
   TO RA1=RRAS(L1,MONTH1) + FAC1 * (RRAS(L2,MONTH1)-RRAS(L1,MONTH1))    000022T5
      RA2=RRAS(L1,MONTH2) + FAC1 * (RRAS(L2,MONTH2)-RRAS(L1,MONTH2))    00002280
   T5 FAC=OAT - 15                                                      00002285
      IF (FAC.LT.0.0) FAC=FAC + 30.0                                    00002290
      FAC2=FAC/30.0                                                     00002295
      RA=RA1 + FAC2 * (RA2-RA1)                                         00002300
C.................................................................00002305
C             NERE NRATIO ANO RS ARE CALCULATEO IF NOT GIVEN OR         00002310
C        CALCULATEO ABOVE                                               00002315
C.................................................................00002320
      IF (NRATIO.EQ.0.0) NRATIO=2.0 * RS/RA - 0.5                       00002325
      IF (NRATIO.GT.1.0) NRATIO=0.999                                   00002330
      IF(NRATIO.LT.0.0) NRATIO = 0.0                                    00002335
      IF (RS.EO.0.0) RS=(0.25 + 0.5*NRATIO) * RA                        000023A0
      OO TO 65                                                          000023A5
   80 PRINT 626                                                         00002350
      I = I -1                                                          00002355
      GO TO 100                                                         00002360
C.................................................................00002365
C        CALCULATION OF "N" USING PMB. EA. ANO T.                       000023T0
C.................................................................000023T5
   65 GG=0.0006595 * PMB                                                00002360
      O=(EA/TK) * (6T90.A965/TK - 5.02808)                              00002385
      N=O/(O+OG)                                                        00002390
      IF(RN.NE.0.0) GO TO 95                                            00002395
      TK=TMEAN + 2T3.16                                                 C0002A00
      FT=SIGMA * (TK**A)                                                00002A05
      FEO=0.3A - 0.0AA*SORT(EO)                                         00002A10
      FNN=0.1 + 0.9*NRATIO                                              00002A15
      RN=0.T5*RS - FT*FEO*FNN                                           00002A20
                                                                        00002A25
C.................................................................00002A30
C        NERE THE CONVERTEO OATA ARE WRITTEN ON  OISK.                  00002A35
C.................................................................00002AA0
   95 WRITE (1) MONTH,OAT,YEAR,TMAX,TMIN,TMEAN,RHMAX,RHMIN,RHMEAN,RN,   00002AA5
     #         EA,EO,UOAT,U2A,NACT,NRATIO,RS,EPAN,CASE,FETCH,URATIO,N,  00002A50
     #         NREAO,TOEW                                               00002A51
C.................................................................00002A55
C        ENO OF 100 LOOP.                                               00002AA0
C.................................................................C0002AA5
                                                                        00002AT0
  100 CONTINUE                                                          00002AT5
                                                                        00002A80
C.................................................................00002A85
C             THIS SECTION REAOS THE CONVERTEO OATA BACK OFF OISK ANO   00002A90
C        PRINTS IT OUT FOR COMPARISON.                                  00002A95
C.................................................................00002500
                                                                        00002505
  105 NOATA=I-1                                                         00002510
      REWINO 1                                                          00002515
      IF(NPRINT.EO.0) GO TO 130                                         00002520
                                                                        00002525
      OO 120 I=1,NOATA                                                  
      REAO (1,END=125)MONTH,OAT,YEAR,TMAX,TMIN,TMEAN,RHMAX,RHMIN,RHMEAN,00002530
     #         RN,EA,EO,UOAT,U2A,NACT,NRATIO,RS,EPAN,CASE,FETCH,URATIO,N00002535
     #         ,NREAO,TOEW                                              05002536
      IF (I.NE.1) OO TO 110                                             000025A0
      IF(NOATA.GT.A)PRINT A21                                           000025A5
      PRINT 620                                                         00002550
      PRINT 6A0                                                         00002555
      PRINT A20                                                         00002560
      PRINT 631                                                         000025A5
  110 IF(NREAO.NE.0) PRINT 632,FETCH,CASE                               000025T0
      PRINT A35,MONTH,OAT,YEAR,TMAX,TMIN,TMEAN,TOEW,RHMAX,RHMIN,RHMEAN, 000025T5
     #         EA,EO,UOAT,U2A,NACT,NRATIO,RS,RN,EPAN,URATIO             00002580
                                                                        00002590
  120 CONTINUE                                                          
C.................................................................00002595
C             BELOW THIS POINT THE PROORAM AOAIN REAOS THE CONVERTEO    00002600
C        OATA OFF OISK ANO THEN ESTIMATES ET BY THE OESIREO METHOOS.    00002605
C        MONTHLY AVERAGING IS ALSO OONE.                                00002610
C.................................................................00C02615
  125 REWINO 1                                                          00002620
                                                                        00002625
  130 I = 0                                                             00002630
      GO TO 1A5                                                         00002635
  135 OO 200 I=1,NOATA                                                  00002640
      REAO(1,ENO=205)MONTH,OAT,YEAR,TMAX,TMIN,TMEAN,RHMAX,RHMIN,RHMEAN, 000026A5
     #         RN,EA,EO,UOAT,U2A,NACT,NRATIO,RS,EPAN,CASE,FETCH,URATIO,N 00002650
      IF (I.EO.1) GO TO 150                                             00002A55
      IF (OAT.EO.0) GO TO 155                                           00002660
      IF(MONTH.EQ.MO) GO TO 155                                         000026A5
  1A0 SUMET1 = SUMET1/NOAT                                              00002AT0
      SUMET2 = SUMET2/NOAT                                              00002675
      SUMET3 = SUMET3/NOAT                                              00002A60
      SUMETC = SUMETC/NOAT                                              00002685
      SUMETA = SUMETA/NOAT                                              00002690
      PRINT 620                                                         00002A95
      PRINT A50, SUMET1, SUMET2, SUMET3, SUMETC, SUMETA                 00002T00
      PRINT 620                                                         00002T05
  1A5 SUMET1 = 0.0                                                      00002T10
      SUMET2 = 0.0                                                      00002T15
      SUMET3 = 0.0                                                      00002T20
      SUMETA = 0.0                                                      00002T25
      SUMETC = 0.0                                                      00002T30
      NOAT   = 0                                                        00002T35
      IF(I.EQ.0) GO TO 135                                              00002TA0
      IF(IENO.EO.1)GO TO 1                                              00002TA5
  150 IF(NDATA.GT.A)PRINT 621                                           00002T50
      PRINT 620                                                         00002T55
      PRINT 6A5                                                         00002T60
      PRINT 620                                                         00002T65
      PPINT A55                                                         00002TT0
                                                                        00002TT5
  155 IF (NBLANT.NE.0) CALL BLANET (LAT,HEMIS,MONTH,OAT,TMEAN,RHMIN,    00002T80
     #                            NRATIO,UOAT,ET1)                      00002T85
      IF (NRAOIA.NE.0.ANO.NFLAO.EQ.1)                                   00002T90
     #                   CALL RADIAT (ALT,UDAT,N,RS,RHMEAN,TMEAN,ET2)   00002T95
```

```
      IF(RNYLAG.EQ.2.OR.NFLAG.EQ.2) GO TO 1•0
      IF (NPENPN.NE.0.OR.NCORPN.NE.0)
     *                CALL PENMAN (N,THEAN,EA,ED,U2•,RS,NR,TIO,ET3,RN)
      IF (NCORPN.NE.0) CALL CORPEN (UDAY,U3•,UR,TIO,RNN,X,RI,ET3,ET3C)
  160 IF(ETPAN.EQ.0.OR.KC.IE.EQ.9.OR.FETCH.EQ.0.0) GO TO 165
      IF(NETPAN.NE.0) CALL ETPAN(EPAN,U24,RHMEAN,FETCH,KC,IE,ET•)

  165 SUMET1 = SUMET1 + ET1
      SUMET2 = SUMET2 + ET2
      SUMET3 = SUMET3 + ET3
      SUMETC = SUMETC + ET3C
      SUMET• = SUMET• + ET•
      PRINT ••8, MONTH,DAY,YEAR, ET1, ET2, ET3, ET3C, ET•
      NDAY = NDAY + 1
      MO = MONTH
  200 CONTINUE

  2•5 REWIND 1
      IF(NDAY.GT.1)IEND = 1
      IF(IEND.EQ.1) GO TO 1•0
      GO TO 1
C******************************************************************
C     READ FORMATS
C******************************************************************
  500 FORMAT (9A4,2F5.0,A1,9X,2F5.0)
  510 FORMAT (3F5.0,A4,•X,5(1X,I1))
  520 FORMAT (5(•X,I1))
  530 FORMAT(•3,3I2,I1,•F5.0)
  540 FORMAT(F10.0,A1)
C*********************************************************************
C        PRINT FORMATS
C*********************************************************************
  600 FORMAT (5X,'STATION = ',9A4//5X,'ALTITUDE IN METERS =',F•.1,//,
     *        5X,'LATITUDE IN DEGREES =',F9.1,//,
     *        5X,'HEMISPHERE = ',A1,//,
     *        5X,'HEIGHT OF WIND MEASUREMENT IN METERS =',F•.2,//,
     *        5X,'MEAN PRESSURE FOR THE YEAR IN MILLIBARS =',F9.1)
  610 FORMAT (5X,'FACTOR FOR CONVERTING 24HR WIND TO KM/DAY =',F9.3//,
     *        5X,'FACTOR FOR CONVERTING DAYTIME WIND TO M/SEC =',F9.3//,
     *        5X,'FACTOR FOR CONVERTING ED DATA TO MILLIBARS =',F9.3,//,
     *        5X,'FACTOR FOR CONVERTING RS DATA TO MM/DAY =',F•.3,//,
     *        5X,'FACTOR FOR CONVERTING EPAN DATA TO MM/DAY =',F•.3,//,
     *        5X,'TEMPERATURE DATA IS GIVEN IN DEGREES ',A1,//,
     *        5X,'SUNSHINE/CLOUDINESS FLAG =',I5,/,
     *        5X,'RELATIVE HUMIDITY DATA IS ',A2,//
     *        5X,'WIND DATA IS ',A2,//,
     *        5X,'SUNSHINE DATA IS ',A2)
  620 FORMAT (1H0,120('*')/)
  625 FORMAT (1H1,//)
  62• FORMAT(//' ERROR IN RH ',F10.2,' RHMAX AND RHMIN =',F10.2//)
  629 FORMAT (5X,'CLIMATOLOGICAL DATA AS READ IN WITHOUT CONVERSION')
  62• FORMAT(/,5X,'BOTH NRATIO AND RS ARE EQUAL TO ZERO ESTIMATION FOR
     *THE DAY NOT DONE'//)
  630 FORMAT (1H ,'DATE (M/D/Y)    TMAX    TMIN    TDEW    RHMAX   RHMIN',
     *        '    ED    UDAY    U24    '....'   NRATIO   SOLRAD    RN ',
     *        '   EPAN      URATIO'/)
  63• FORMAT (1H ,'DATE (MDY)  TMAX  TMIN  TMEAN  TDEW  RHMAX  RHMIN',
     *        '  RHMEAN    EA    ED   UDAY   U24  SUNHRS NRATIO SOLRAD',
     *        '    RN     EPAN    URATIO  '/)
  632 FORMAT('  VALUES OF FETCH ',F8.2,',CAIE ',A4)
  634 FORMAT (1H ,I••,2('/',I2),3X,3F7.1,2(F•.1X),3F7.1,F8.2,F•.2,F•.2,
     *        F8.2,F8.2,F10.2)
  635 FORMAT (1H ,I3,2('/',I2),1X,4F6.1,3(F••.1X),F•.1,3(F•.2,1X),F•.2,
     *        F9.2,F10.2)
  640 FORMAT(5X,'CLIMATOLOGICAL DATA FOR MONTH AFTER CONVERSION',
     *        I3,'/',I9,'/',I2,/)
  645 FORMAT(' RESULT OF ET ESTIMATION BY VARIOUS METHODS FOR MONTH',I2,
     *        '/',I•,'/',I2,/)
  6•• FORMAT (/,1H ,130('*'),/)
  648 FORMAT (1H ,2I3,I2,'/',I2,'/',I2,•F10.3)
  650 FORMAT (' MONTH AVG',•X,•(F7.3,10X),/)
  655 FORMAT (1H0,' MONTH/DAY/YEAR',•X,'BLANEY',11X,'RADIATION',10X,
     *        'PENMAN',10X,'CORR. PEN.',11X,'ETPAN'//)
C*********************************************************************
C        PROGRAM END
C*********************************************************************
  999 STOP
      END


      SUBROUTINE BLANEY (LAT,HEMIS,MONTH,DAY,THEAN,RHMIN,NRATIO,
     *                   UDAY,ET1)
      DIMENSION A(3,3), BB(•,•,•), C(2,2), D(2), PP(11,12)
      REAL NRATIO, LAT
C*********************************************************************
C        THIS SECTION INTERPOLATES "P".
C*********************************************************************
      DATA PP
     1 / .2•7,.2•4,.26•,.257,.252,.2••,.23•,.231,.220,.20•,.1•5,
     2   .2••,.248,.246,.2••,.2•1,.257,.253,.2•0,.2•3,.23•,.228,
     3   .20•,.2••,.2•9,.269,.2••,.269,.2••,.268,.268,.2•7,.2••,
     4   .2••,.270,.272,.273,.278,.282,.28•,.2•1,.2•7,.303,.310,
     5   .271,.273,.27•,.261,.287,.2••,.303,.312,.322,.33•,.3••,
     6   .2•8,.280,.285,.2•1,.2•8,.307,.31•,.320,.34•,.355,.371,
     7   .275,.281,.28•,.293,.2••,.305,.313,.321,.330,.3•1,.35•,
     8   .27•,.278,.282,.287,.2•1,.295,.300,.30•,.30•,.315,.322,
     9   .271,.277,.2•0,.281,.281,.281,.281,.281,.281,.281,.281,
     A   .27•,.269,.2•6,.2•7,.23•,.2•1,.258,.25•,.250,.2•5,.2•0,
     B   .26•,.2•7,.2••,.2•0,.254,.2•7,.2•0,.231,.222,.211,.200,
     C   .248,.2••,.2•2,.297,.250,.2•2,.232,.221,.20•,.1•5,.188

      IF (HEMIS.EQ.'S') MONTH=MOD(MONTH+5,12) + 1
      LL=INT(LAT/5) * 5
      IF (LAT.GT.50) LL=50
      L1=LL/5 + 1
      L2 = L1 + 1
      IF (L2.GT.11) L2=11
      FAC =(LAT-LL)/5.0
      MONTH1=MONTH
      MONTH2=MONTH
      IF (DAY.GT.15 ) MONTH2=MOD(MONTH,12) + 1
      IF (DAY.LT.15.AND.DAY.NE.0) MONTH1=MOD(MONTH+10,12) + 1
      P1=PP(L1,MONTH1) + FAC * (PP(L2,MONTH1)-PP(L1,MONTH1))
      P2=PP(L1,MONTH2) + FAC * (PP(L2,MONTH2)-PP(L1,MONTH2))
      IF (HEMIS.EQ.'S') MONTH=MOD(MONTH+5,12) + 1
      FAC=DAY - 15
      IF (FAC.LT.0.0) FAC=FAC+30.0
      FAC2=FAC/30.0
      P=P1 + FAC2 * (P2-P1)
      F=P*(0.•••THEAN + 8.13)

C*********************************************************************
C        THIS SECTION INTERPOLATES ET1 USING A, B, AND F.
C*********************************************************************

      DATA BB / 0.8•, 0.80, 0.7•, 0.••, 0.52, 0.38,
     1          1.03, 0.95, 0.87, 0.7•, 0.•3, 0.•8,
     2          1.22, 1.10, 1.01, 0.88, 0.74, 0.57,
     3          1.38, 1.2•, 1.13, 0.••, 0.85, 0.••,
     4          1.54, 1.37, 1.25, 1.09, 0.••, 0.75,
     5          1.••, 1.59, 1.3•, 1.18, 1.0•, 0.8•,
     6          0.••, 0.90, 0.81, 0.•8, 0.5•, 0.•0,
     7          1.19, 1.08, 0.••, 0.8•, 0.6•, 0.50,
     8          1.•1, 1.2•, 1.11, 0.•7, 0.77, 0.•0,
     9          1.60, 1.•2, 1.25, 1.0•, 0.8•, 0.70,
     A          1.7•, 1.59, 1.3•, 1.21, 1.01, 0.7•,
     B          1.98, 1.78, 1.52, 1.31, 1.11, 0.8•,
     C          1.08, 0.•8, 0.87, 0.72, 0.5•, 0.•2,
     D          1.33, 1.18, 1.03, 0.87, 0.••, 0.32,
     E          1.5•, 1.38, 1.1•, 1.02, 0.82, 0.•2,
     F          1.78, 1.5•, 1.3•, 1.15, 0.9•, 0.73,
     G          2.00, 1.7•, 1.50, 1.28, 1.05, 0.83,
     H          2.1•, 1.•0, 1.••, 1.39, 1.1•, 0.•2,
     I          1.18, 1.06, 0.•2, 0.7•, 0.58, 0.•3,
     J          1.•6, 1.27, 1.10, 0.•1, 0.72, 0.5•,
     K          1.70, 1.•8, 1.27, 1.06, 0.85, 0.64,
     L          1.••, 1.•7, 1.••, 1.21, 0.97, 0.75,
     M          2.18, 1.86, 1.59, 1.3•, 1.0•, 0.85,
     N          2.3•, 2.03, 1.7•, 1.•4, 1.20, 0.95,
     O          1.2•, 1.11, 0.98, 0.7•, 0.60, 0.••,
     P          1.52, 1.34, 1.1•, 0.•3, 0.7•, 0.55,
     Q          1.79, 1.56, 1.32, 1.10, 0.87, 0.••,
     R          2.05, 1.7•, 1.•9, 1.25, 1.00, 0.77,
     S          2.30, 2.•6, 1.••, 1.39, 1.12, 0.87,
     T          2.5•, 2.1•, 1.82, 1.52, 1.2•, 0.•8,
     U          1.29, 1.15, 0.•8, 0.78, 0.41, 0.•5,
     V          1.58, 1.38, 1.17, 0.••, 0.75, 0.56,
     W          1.8•, 1.•1, 1.36, 1.13, 0.89, 0.6•,
     X          2.13, 1.83, 1.5•, 1.28, 1.03, 0.7•,
     Y          2.3•, 2.03, 1.71, 1.•3, 1.15, 0.•5,
     Z          2.•3, 2.22, 1.8•, 1.5•, 1.27, 1.00/

      X=RHMIN
      Y=NRATIO
      Z=UDAY

      I1=INT(X/20.) + 1
      I2=I1 + 1
      IF (I2.GT.6) I2=6
      J1=INT(Y/0.2) + 1
      J2=J1 + 1
      IF (J2.GT.6) J2=6
      K1=INT(Z/2) + 1
      K2=K1 + 1
      IF(K2.GT.6) K2=6
      IF(K1.GT.6) K1 =6
      X1=(I1-1) * 20
      X2=(I2-1) * 20
      Y1=(J1-1) * 0.2
      Y2=(J2-1) * 0.2
      Z1=(K1-1) * 2
      Z2 = (K2-1) * 2

      FACX=0.0
      FACY = 0.0
      FACZ = 0.0

      IF (K1.NE.K2) FACZ=(Z-Z1)/(Z2-Z1)
      C(1,1)=BB(I1,J1,K1) + FACZ * (BB(I1,J1,K2)-BB(I1,J1,K1))
      C(1,2)=BB(I1,J2,K1) + FACZ * (BB(I1,J2,K2)-BB(I1,J2,K1))
      C(2,1)=BB(I2,J1,K1) + FACZ * (BB(I2,J1,K2)-BB(I2,J1,K1))
      C(2,2)=BB(I2,J2,K1) + FACZ * (BB(I2,J2,K2)-BB(I2,J2,K1))

      IF (J1.NE.J2) FACY=(Y-Y1)/(Y2-Y1)
      IF (I1.NE.I2) FACX=(X-X1)/(X2-X1)
      D(1)=C(1,1) + FACY * (C(1,2)-C(1,1))
      D(2)=C(2,1) + FACY * (C(2,2)-C(2,1))
      BP=D(1) + FACX * (D(2)-D(1))
      AP=0.00•3*X - Y - 1.•1

      ET1=AP + BP*F
      RETURN
      END

      SUBROUTINE RADIAT (ALT,UDAY,RN,RI,RHMEAN,TMEAN,ET2)
      DIMENSION BB(•,•)
C*********************************************************************
C        THIS SUBROUTINE CALCULATES AN ET VALUE BY THE RADIATION METHOD,
C*********************************************************************

      A=-0.3

C*********************************************************************
C              INTERPOLATION OF "B".
C        IN "BB" BELOW, UDAY IS ON THE VERTICAL FROM 0.0 TO 10.0
C        AND RHMEAN IS HORIZONTAL FROM 0 TO 100.
C*********************************************************************

      DATA BB / 1.0•, 1.15, 1.23, 1.29, 1.3•, 1.39,
     2          1.02, 1.11, 1.18, 1.24, 1.28, 1.32,
     3          0.•5, 1.04, 1.10, 1.15, 1.1•, 1.23,
     4          0.87, 0.••, 0.•9, 1.03, 1.07, 1.10,
     5          0.7•, 0.81, 0.85, 0.8•, 0.•2, 0.••,
     6          0.••, 0.•7, 0.70, 0.73, 0.75, 0.77/

      X=UDAY
      Y = RHMEAN

      I1=INT(X/2) + 1
      I2 = I1 + 1
      IF (I2.GT.•) I2=•
      IF(I1.GT.6) I1 = •
      J1=INT(Y/20) + 1
      J2 = J1 + 1
      IF (J2.GT.•) J2=6
      X1=(I1-1) * 2
      X2 =(I2-1) * 2
      Y1=(J1-1) * 20
```

```
      Y2 = (J2-1) * 20                                                  00004005
                                                                        00004010
      B=INT2D (I1,I2,J1,J2,X,Y,X1,X2,Y1,Y2,BB,4)                        00004015
                                                                        00004020
      ET2=A + B*W*RS                                                    00004025
      RETURN                                                            00004030
      END                                                               00004035
                                                                        00004040
                                                                        00004045
      SUBROUTINE PENMAN (W,TMEAN,EA,ED,U24,RS,NRATIO,ET3,RN)            00004050
      REAL NRATIO                                                       00004055
                                                                        00004060
C***********************************************************************00004065
C          THIS SUBROUTINE CALCULATES THE UNCORRECTED PENMAN VALUE.     00004070
C***********************************************************************00004075
                                                                        00004080
                                                                        00004085
                                                                        00004090
      U2=U24                                                            00004095
      FU=0.27*(1.0+U2/100.0)                                            00004100
      ET3=W*RN + (1.0-W)*FU*(EA-ED)                                     00004105
      RETURN                                                            00004110
      END                                                               00004115
                                                                        00004120
                                                                        00004125
      SUBROUTINE CORPEN (UDAY,U24,URATIO,RHMAX,RS,ET3,ET3C)             00004130
      DIMENSION CC(4,4,3,4), Y1(2,2,2), Y2(2,2), Y3(2)                  00004135
      REAL NRATIO                                                       00004140
                                                                        00004145
C***********************************************************************00004150
C              THIS SUBROUTINE INTERPOLATES THE PENMAN CORRECTION FACTOR 00004155
C         "C", AND CALCULATES THE CORRECTED PENMAN VALUE.               00004160
C***********************************************************************00004165
                                                                        00004170
      DATA CC                                                           00004175
     1 /  0.86,0.90,1.00,1.00,  0.64,0.71,0.82,0.89,                    00004180
     2    0.43,0.53,0.68,0.79,  0.27,0.41,0.59,0.70,                    00004185
     3    0.96,0.98,1.05,1.05,  0.78,0.86,0.94,0.99,                    00004190
     4    0.62,0.70,0.84,0.93,  0.50,0.60,0.75,0.87,                    00004195
     5    1.02,1.04,1.10,1.10,  0.85,0.92,1.01,1.05,                    00004200
     6    0.72,0.82,0.95,1.00,  0.62,0.72,0.87,0.96,                    00004205
     7    0.86,0.90,1.00,1.00,  0.69,0.76,0.85,0.92,                    00004210
     8    0.53,0.61,0.74,0.84,  0.37,0.48,0.65,0.76,                    00004215
     9    0.96,0.98,1.05,1.05,  0.83,0.91,0.99,1.05,                    00004220
     A    0.70,0.80,0.94,1.02,  0.59,0.70,0.84,0.95,                    00004225
     B    1.02,1.04,1.10,1.10,  0.89,0.98,1.10,1.14,                    00004230
     C    0.79,0.92,1.05,1.12,  0.71,0.81,0.96,1.06,                    00004235
     D    0.86,0.90,1.00,1.00,  0.76,0.81,0.88,0.94,                    00004240
     E    0.61,0.68,0.81,0.88,  0.46,0.56,0.72,0.82,                    00004245
     F    0.96,0.98,1.05,1.05,  0.87,0.96,1.06,1.12,                    00004250
     G    0.77,0.88,1.02,1.10,  0.67,0.79,0.88,1.05,                    00004255
     H    1.02,1.06,1.10,1.10,  0.94,1.04,1.18,1.28,                    00004260
     I    0.86,1.01,1.15,1.22,  0.78,0.92,1.06,1.18,                    00004265
     J    0.86,0.90,1.00,1.00,  0.79,0.84,0.92,0.97,                    00004270
     K    0.68,0.77,0.87,0.93,  0.55,0.65,0.78,0.90,                    00004275
     L    0.96,0.98,1.05,1.05,  0.92,1.00,1.11,1.19,                    00004280
     M    0.85,0.96,1.11,1.19,  0.76,0.88,1.02,1.14,                    00004285
     N    1.02,1.06,1.10,1.10,  0.99,1.10,1.27,1.32,                    00004290
     O    0.94,1.10,1.26,1.33,  0.88,1.01,1.16,1.27                     00004295
                                                                        00004300
      W=RS                                                              00004305
      X=UDAY                                                            00004310
      Y=RHMAX                                                           00004315
      Z=URATIO                                                          00004320
                                                                        00004325
      I1=INT(W/3) + 1                                                   00004330
      IF (I1.EQ.0) I1=3                                                 00004335
      I1=I1/3                                                           00004340
      I2 = I1 + 1                                                       00004345
      IF (I2.EQ.5) I2=4                                                 00004350
      IF(I1.GT.4) I1 = 4                                                00004355
      IF(I1.EQ.0) I1 = 1                                                00004360
      FAC1=(W-I1)/3.0                                                   00004365
      JJ=INT(X/3) * 3                                                   00004370
      IF (JJ.GT.9) JJ=9                                                 00004375
      J1=JJ/3 + 1                                                       00004380
      J2 = J1 + 1                                                       00004385
      IF (J2.EQ.5) J2=4                                                 00004390
      FAC2=(X-JJ)/3.0                                                   00004395
      MM=INT(Y/30) * 30                                                 00004400
      IF (MM.EQ.0) MM=30                                                00004405
      M1=MM/30                                                          00004410
      M2 = M1 + 1                                                       00004415
      IF (M2.EQ.4) M2=3                                                 00004420
      FAC3=(Y-MM)/30.0                                                  00004425
      LL=INT(Z)                                                         00004430
      IF (LL.EQ.0) LL=1                                                 00004435
      L1=LL                                                             00004440
      L2 = L1 + 1                                                       00004445
      IF (L2.EQ.5) L2=4                                                 00004450
      IF(L1.GT.4) L1=4                                                  00004455
      FAC4=(Z-LL)                                                       00004460
                                                                        00004465
      Y1(1,1,1)=CC(I1,J1,M1,L1) + FAC4*(CC(I1,J1,M1,L2)-CC(I1,J1,M1,L1))00004470
      Y1(1,1,2)=CC(I1,J1,M2,L1) + FAC4*(CC(I1,J1,M2,L2)-CC(I1,J1,M2,L1))00004475
      Y1(1,2,1)=CC(I1,J2,M1,L1) + FAC4*(CC(I1,J2,M1,L2)-CC(I1,J2,M1,L1))00004480
      Y1(1,2,2)=CC(I1,J2,M2,L1) + FAC4*(CC(I1,J2,M2,L2)-CC(I1,J2,M2,L1))00004485
      Y1(2,1,1)=CC(I2,J1,M1,L1) + FAC4*(CC(I2,J1,M1,L2)-CC(I2,J1,M1,L1))00004490
      Y1(2,1,2)=CC(I2,J1,M2,L1) + FAC4*(CC(I2,J1,M2,L2)-CC(I2,J1,M2,L1))00004495
      Y1(2,2,1)=CC(I2,J2,M1,L1) + FAC4*(CC(I2,J2,M1,L2)-CC(I2,J2,M1,L1))00004500
      Y1(2,2,2)=CC(I2,J2,M2,L1) + FAC4*(CC(I2,J2,M2,L2)-CC(I2,J2,M2,L1))00004505
      Y2(1,1)=Y1(1,1,1) + FAC3*(Y1(1,1,2)-Y1(1,1,1))                    00004510
      Y2(1,2)=Y1(1,2,1) + FAC3*(Y1(1,2,2)-Y1(1,2,1))                    00004515
      Y2(2,1)=Y1(2,1,1) + FAC3*(Y1(2,1,2)-Y1(2,1,1))                    00004520
      Y2(2,2)=Y1(2,2,1) + FAC3*(Y1(2,2,2)-Y1(2,2,1))                    00004525
      Y3(1)=Y2(1,1) + FAC2*(Y2(1,2)-Y2(1,1))                            00004530
      Y3(2)=Y2(2,1) + FAC2*(Y2(2,2)-Y2(2,1))                            00004535
      Y4=Y3(1) + FAC1*(Y3(2)-Y3(1))                                     00004540
      C=Y4                                                              00004545
                                                                        00004550
      ET3C=ET3*C                                                        00004555
      RETURN                                                            00004560
      END                                                               00004565
                                                                        00004570
                                                                        00004575
      SUBROUTINE ETPAN (EPAN,U24,RHMEAN,FETCH,NCASE,ET4)                00004580
      DIMENSION C(2,2), D(2)                                            00004585
      REAL KP, KKP(3,8,4,2)                                             00004590
C***********************************************************************00004595
C***********************************************************************00004600
```

```
      DATA KKP                                                          00004605
     1 / .55, .65, .75, .50, .60, .65, .45, .50, .60, .40, .45, .50,    00004610
     2   .65, .75, .85, .60, .70, .75, .55, .60, .65, .45, .55, .60,    00004615
     3   .70, .80, .85, .65, .75, .80, .60, .65, .70, .50, .60, .65,    00004620
     4   .75, .85, .85, .70, .80, .80, .65, .70, .75, .55, .60, .65,    00004625
     5   .70, .80, .85, .65, .75, .80, .60, .65, .70, .50, .60, .65,    00004630
     6   .60, .70, .80, .55, .65, .70, .50, .55, .65, .45, .50, .55,    00004635
     7   .55, .65, .75, .50, .60, .65, .45, .50, .60, .40, .45, .50,    00004640
     8   .50, .60, .70, .45, .55, .60, .40, .45, .55, .35, .40, .45/    00004645
                                                                        00004650
      X=RHMEAN                                                          00004655
      Y = U24                                                           00004660
      Z = ALOG10(FETCH)                                                 00004665
      L = NCASE                                                         00004670
   10 IF (X.GT.30) GO TO 15                                             00004675
      I1=1                                                              00004680
      I2 = 1                                                            00004685
      GO TO 30                                                          00004690
   15 IF (X.GT.57) GO TO 20                                             00004695
      I1=1                                                              00004700
      I2 = 2                                                            00004705
      X1=30.0                                                           00004710
      X2 = 57.0                                                         00004715
      GO TO 30                                                          00004720
   20 IF (X.GE.84.0) GO TO 25                                           00004725
      I1=2                                                              00004730
      I2 = 3                                                            00004735
      X1=57.0                                                           00004740
      X2 = 84.0                                                         00004745
      GO TO 30                                                          00004750
   25 I1=3                                                              00004755
      I2=3                                                              00004760
   30 IF (Y.GT.84.0) GO TO 35                                           00004765
      J1=1                                                              00004770
      J2 = 1                                                            00004775
      GO TO 55                                                          00004780
   35 IF (Y.GT.260.0) GO TO 40                                          00004785
      J1=1                                                              00004790
      J2 = 2                                                            00004795
      Y1=87.0                                                           00004800
      Y2 = 260.0                                                        00004805
      GO TO 55                                                          00004810
   40 IF (Y.GT.465.0) GO TO 45                                          00004815
      J1=2                                                              00004820
      J2 = 3                                                            00004825
      Y1=260.0                                                          00004830
      Y2 = 465.0                                                        00004835
      GO TO 55                                                          00004840
   45 IF (Y.GE.700.0) GO TO 50                                          00004845
      J1=3                                                              00004850
      J2 = 4                                                            00004855
      Y1=465.0                                                          00004860
      Y2 = 700.0                                                        00004865
      GO TO 55                                                          00004870
   50 J1=4                                                              00004875
      J2 = 4                                                            00004880
   55 IF (Z.GT.0.0) GO TO 60                                            00004885
      M1=1                                                              00004890
      M2 = 1                                                            00004895
      GO TO 80                                                          00004900
   60 IF (Z.GT.1.00) GO TO 65                                           00004905
      M1=1                                                              00004910
      M2 = 2                                                            00004915
      Z1=0                                                              00004920
      Z2=1.0                                                            00004925
      GO TO 80                                                          00004930
   65 IF (Z.GT.2.0)   GO TO 70                                          00004935
      M1=2                                                              00004940
      M2 = 3                                                            00004945
      Z1=1.0                                                            00004950
      Z2 = 2.0                                                          00004955
      GO TO 80                                                          00004960
   70 IF (Z.GE.3.0)    GO TO 75                                         00004965
      M1=3                                                              00004970
      M2 = 4                                                            00004975
      Z1=2.0                                                            00004980
      Z2 = 3.0                                                          00004985
      GO TO 80                                                          00004990
   75 M1=4                                                              00004995
      M2 = 4                                                            00005000
   80 FACX=0.0                                                          00005005
      FACY=0.0                                                          00005010
      FACZ=0.0                                                          00005015
      IF (M1.NE.M2) FACZ=(Z-Z1)/(Z2-Z1)                                 00005020
      C(1,1)=KKP(I1,J1,M1,L) + FACZ * (KKP(I1,J1,M2,L)-KKP(I1,J1,M1,L)) 00005025
      C(1,2)=KKP(I1,J2,M1,L) + FACZ * (KKP(I1,J2,M2,L)-KKP(I1,J2,M1,L)) 00005030
      C(2,1)=KKP(I2,J1,M1,L) + FACZ * (KKP(I2,J1,M2,L)-KKP(I2,J1,M1,L)) 00005035
      C(2,2)=KKP(I2,J2,M1,L) + FACZ * (KKP(I2,J2,M2,L)-KKP(I2,J2,M1,L)) 00005040
      IF (J1.NE.J2) FACY=(Y-Y1)/(Y2-Y1)                                 00005045
      D(1)=C(1,1) + FACY * (C(1,2)-C(1,1))                              00005050
      D(2)=C(2,1) + FACY * (C(2,2)-C(2,1))                              00005055
      IF (I1.NE.I2) FACX=(X-X1)/(X2-X1)                                 00005060
      KP=D(1) + FACX * (D(2)-D(1))                                      00005065
                                                                        00005070
      ET4=KP * EPAN                                                     00005075
                                                                        00005080
      RETURN                                                            00005085
      END                                                               00005090
                                                                        00005095
                                                                        00005100
      REAL FUNCTION INT2D (I1,I2,J1,J2,X,Y,X1,X2,Y1,Y2,F,N)             00005105
C***********************************************************************00005110
C              THIS FUNCTION PERFORMS A TWO DIMENSIONAL INTERPOLATION   00005115
C        ON THE TABLE FED TO IT.  I AND J ARE THE NUMBERED POSITIONS IN 00005120
C        THE TABLE WHICH THE VALUES TO BE INTERPOLATED FALL BETWEEN.    00005125
C        X1, X2, AND Y1, Y2 ARE THE VALUES IN THE THE TABLE AT THE I    00005130
C        AND J POINTS.  X AND Y ARE THE COORDINATES OF THE VALUE TO     00005135
C        BE INTERPOLATED.  F IS THE ACTUAL TABLE, AND N IS ITS FIRST    00005140
C        DIMENSION.                                                     00005145
C***********************************************************************00005150
      DIMENSION F(N,1)                                                  00005155
      FACX=0.0                                                          00005160
      FACY=0.0                                                          00005165
      IF (I1.NE.I2) FACX=(X-X1)/(X2-X1)                                 00005170
      C1=F(I1,J1) + FACX * (F(I2,J1)-F(I1,J1))                          00005175
      C2=F(I1,J2) + FACX * (F(I2,J2)-F(I1,J2))                          00005180
      IF (J1.NE.J2) FACY=(Y-Y1)/(Y2-Y1)                                 00005185
      INT2D=C1 + FACY * (C2-C1)                                         00005190
      RETURN                                                            00005195
      END                                                               00005200
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COPY OF INPUT DATA(COL. BY COL.) OF EXAMPLES FOR TESTING NEW PUNCHED PROGRAM AT A GIVEN COMPUTER.

C O L U M N  1-80  O F   I N P U T   C A R D S                                  CARD IDENTIFICATION
12345678901234567890123456789012345678901234567890123456789012345678901234567890

BRAWLEY      CALIF            -31.0 33.0N         2.0         MEAN LONG-TERM RECORD       A1
 38.6           .017 25.4F          5 1 1 1 2            T in °F; U in M/hr; Rs in Ly/day;  A2
    1    1    1    1    1                                Ep in in/day                     A3
BC 0100001   70   40   33                      2.6       .85  307      .121  1.6          A4
200.      B                                                                               A5
BC 0200000   74   43   35                      4.2       .87  399      .179  1.5          A4
BC 0300001   79   47   35                      4.2       .90  386      .264  1.3          A4
 5.       A                                                                               A5
BC 0400000   87   55   37                      4.7       .95  621      .368  1.3          A4
BC 0500000   94   61   47                      5.2       .95  683      .466  1.2          A4
BC 0600000  104   68   53                      4.3       .97  715      .523  1.2          A4
BC 0700000  108   77   57                      4.0       .87  645      .503  1.2          A4
BC 0800000  106   76   58                      4.0       .88  606      .464  1.2          A4
BC 0900000  105   71   54                      3.3       .93  536      .400  1.3          A4
BC 1000000   94   60   46                      2.4       .90  438      .269  1.5          A4
BC 1100001   79   46   43                      2.5       .83  326      .165  1.8          A4
200.      B                                                                               A5
BC 1200000   72   40   36                      2.0       .82  283      .112  1.8          A4
                                                                                          BLANK
DAVIS CALIFORNIA.              17.038.5 N          2.0 1010.  DAILY DATA, OCTOBER 1960    A1
  1.0       1.0  1.0  1.0C          5 1 1 1 1            T in °C; U in km/day, Rs, Rn &   A2
    1    1    1    1    1                                Ep in equiv. mm Evap.            A3
DC 1001601 25.6 14.4  0.0  100   35  0.0    0  169 0.00 0.00 7.24 3.21 4.32 1.20          A4
200.0     A                                                                               A5
DC 1002600 26.1  8.3  0.0  100   32  0.0    0  121 0.00 0.00 7.21 3.18 4.57 1.20          A4
DC 1003600 26.7  9.4  0.0  100   21  0.0    0  238 0.00 0.00 7.19 3.11 5.33 1.20          A4
DC 1004600 26.7 11.7  0.0  100   36  0.0    0   74 0.00 0.00 7.28 3.14 3.30 1.20          A4
DC 1005600 27.8 11.7  0.0  100   43  0.0    0  229 0.00 0.00 4.42 2.11 1.78 1.20          A4
DC 1006600 23.9  8.9  0.0  100   51  0.0    0  268 0.00 0.00 4.50 2.04 3.81 1.20          A4
DC 1007600 23.9  8.3  0.0   82   48  0.0    0  239 0.00 0.00 5.68 2.60 3.30 1.20          A4
DC 1008600 22.2 11.7  0.0   42   23  0.0    0  729 0.00 0.00 7.45 2.7312.45 1.20          A4
DC 1009600 21.1 12.8  0.0   41   23  0.0    0  647 0.00 0.00 7.50 2.7214.22 1.20          A4
DC 1010600 19.4  3.9  0.0  100   33  0.0    0  155 0.00 0.00 3.50 1.39 3.81 1.20          A4
DC 1011600 26.1  3.3  0.0  100   33  0.0    0  101 0.00 0.00 6.46 3.09 2.79 1.20          A4
DC 1012600 21.7  6.1  0.0   83   35  0.0    0   77 0.00 0.00 6.53 3.16 2.79 1.20          A4
DC 1013600 22.8  6.7  0.0   57   29  0.0    0  157 0.00 0.00 5.44 2.22 3.81 1.20          A4
DC 1014600 25.6  5.6  0.0   38   20  0.0    0  413 0.00 0.00 7.05 2.29 9.65 1.20          A4
DC 1015600 27.8  8.3  0.0   55   18  0.0    0  437 0.00 0.00 6.31 1.6012.70 1.20          A4
DC 1016600 29.4  5.0  0.0   76   24  0.0    0  123 0.00 0.00 6.73 2.39 4.06 1.20          A4
DC 1017600 28.3  3.9  0.0  100   28  0.0    0  119 0.00 0.00 6.32 2.27 4.06 1.20          A4
DC 1018600 24.4  5.0  0.0  100   26  0.0    0  152 0.00 0.00 6.22 2.29 3.30 1.20          A4
DC 1019600 25.6  5.6  0.0   82   24  0.0    0   72 0.00 0.00 5.78 2.60 2.79 1.20          A4
DC 1020600 27.2  7.8  0.0   87   24  0.0    0   66 0.00 0.00 5.78 2.85 3.30 1.20          A4
DC 1021600 27.8  8.3  0.0  100   20  0.0    0   45 0.00 0.00 5.20 2.52 2.29 1.20          A4
DC 1022600 28.9 10.0  0.0  100   40  0.0    0  169 0.00 0.00 5.64 2.62 4.32 1.20          A4
DC 1023600 22.2  7.8  0.0  100   40  0.0    0  188 0.00 0.00 5.90 1.91 3.30 1.20          A4
DC 1024600 22.2  5.6  0.0   94   35  0.0    0  143 0.00 0.00 5.93 2.65 3.05 1.20          A4
DC 1025600 23.3 11.1  0.0   32   23  0.0    0  238 0.00 0.00 5.95 2.01 3.05 1.20          A4
DC 1026600 21.1 13.3  0.0   32   16  0.0    0  544 0.00 0.00 5.78 2.01 8.64 1.20          A4
DC 1027600 23.3 15.6  0.0   68   21  0.0    0  371 0.00 0.00 5.42 1.68 8.64 1.20          A4
DC 1028600 26.7  5.0  0.0   76   19  0.0    0  328 0.00 0.00 5.71 1.86 7.37 1.20          A4




DC 1029600 26.7  5.0  0.0   73   22  0.0    0  169 0.00 0.00 5.71 2.01 5.59 1.20          A4
DC 1030600 27.8  7.2  0.0   76   22  0.0    0   51 0.00 0.00 5.42 2.37 2.03 1.20          A4
DC 1031600 28.3  7.8  0.0   78   24  0.0    0   81 0.00 0.00 5.27 2.30 3.05 1.20          A4
                                                                                          BLANK
DAVIS CALIFORNIA.              17.038.5 N          2.0 1010. 10-DAY MEAN DATA             A1
  1.0       1.0  1.0  1.0C          5 1 1 1 1                                             A2
    1    1    1    1    1                                                                 A3
DC 10 1601 24.3 10.1        86   35            287           6.20 2.62 5.69 1.20          A4
200.0     A                                                                               A5
DC 1011600 25.9  5.7        78   26            172           6.26 2.48 4.92 1.20          A4
DC 1021600 25.3  8.8        75   26            212           5.63 2.18 4.67 1.20          A4
                                                                                          BLANK
DAVIS CALIFORNIA.              17.038.5 N          2.0 1010. MONTHLY MEAN DATA            A1
  1.0       1.0  1.0  1.0C          5 1 1 1 1                                             A2
    1    1    1    1    1                                                                 A3
DC 1000601 25.2  8.2        80   29            223           6.02 2.42 5.08 1.20          A4
200.0     A                                                                               A5
                                                                                          BLANK
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   STATION = BRAWLEY       CALIF

   ALTITUDE IN METERS =    -31.0                                FACTOR FOR CONVERTING ED DATA TO MILLIBARS =    0.000

   LATITUDE IN DEGREES =     33.0                               FACTOR FOR CONVERTING RS DATA TO MM/DAY =    0.017

   HEMISPHERE = N                                               FACTOR FOR CONVERTING EPAN DATA TO MM/DAY =   25.400

   HEIGHT OF WIND MEASUREMENT IN METERS =      2.00             TEMPERATURE DATA IS GIVEN IN DEGREES :  F

   MEAN PRESSURE FOR THE YEAR IN MILLIBARS =   1016.6           SUNSHINE/CLOUDINESS FLAG =    5

*************************************************************   RELATIVE HUMIDITY DATA IS :  ACTUAL DATA

   FACTOR FOR CONVERTING 24HR WIND TO KM/DAY =   38.600         WIND DATA IS :  ACTUAL DATA

   FACTOR FOR CONVERTING DAYTIME WIND TO M/SEC =    0.000       SUNSHINE DATA IS  :  ACTUAL DATA  (FOR n/N )

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   CLIMATOLOGICAL DATA AS READ IN WITHOUT CONVERSION

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DATE (M/D/Y)     TMAX   TMIN   TDEW   RHMAX   RHMIN     ED     UDAY     U24    SUNHRS   NRATIO   SOLRAD     RN     EPAN      URATIO
                  oF     oF     oF                                      M/hr                     Ly/day            In/day
 VALUES OF FETCH   200.00,CASE B
   1/ 0/ 0       70.0   40.0   33.0     0        0      0.0     0.0     2.6    0.00     0.85    307.00    0.00    0.12      1.60
   2/ 0/ 0       74.0   43.0   35.0     0        0      0.0     0.0     4.2    0.00     0.87    399.00    0.00    0.18      1.50
 VALUES OF FETCH      5.00,CASE A
   3/ 0/ 0       79.0   47.0   35.0     0        0      0.0     0.0     4.2    0.00     0.90    386.00    0.00    0.26      1.30
   4/ 0/ 0       67.0   55.0   37.0     0        0      0.0     0.0     4.7    0.00     0.95    621.00    0.00    0.37      1.30
   5/ 0/ 0       94.0   61.0   47.0     0        0      0.0     0.0     5.2    0.00     0.95    683.00    0.00    0.47      1.20
   6/ 0/ 0      104.0   68.0   53.0     0        0      0.0     0.0     4.3    0.00     0.97    715.00    0.00    0.52      1.20
   7/ 0/ 0      108.0   77.0   57.0     0        0      0.0     0.0     4.0    0.00     0.87    645.00    0.00    0.50      1.20
   8/ 0/ 0      106.0   76.0   58.0     0        0      0.0     0.0     4.0    0.00     0.88    606.00    0.00    0.46      1.20
   9/ 0/ 0      105.0   71.0   54.0     0        0      0.0     0.0     3.3    0.00     0.93    536.00    0.00    0.40      1.30
  10/ 0/ 0       94.0   60.0   46.0     0        0      0.0     0.0     2.4    0.00     0.90    438.00    0.00    0.27      1.50
 VALUES OF FETCH   200.00,CASE B
  11/ 0/ 0       79.0   46.0   43.0     0        0      0.0     0.0     2.5    0.00     0.83    326.00    0.00    0.17      1.80
  12/ 0/ 0       72.0   40.0   36.0     0        0      0.0     0.0     2.0    0.00     0.82    283.00    0.00    0.11      1.80

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   CLIMATOLOGICAL DATA FOR MONTH AFTER CONVERSION

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DATE (MOY)  TMAX  TMIN TMEAN  TDEW  RHMAX  RHMIN RHMEAN   EA     ED   UDAY   U24 SUNHRS NRATIO SOLRAD   RN     EPAN   URATIO
             oC    oC   oC                                mb     mb   m/sec  km                  mm     mm      mm
 VALUES OF FETCH    200.00,CASE B
  1/ 0/ 0   21.1   4.4  12.8   0.0   76     25     51    14.8    6.4   1.4 100.4  0.00   0.85   5.22   1.27    3.07    1.60
  2/ 0/ 0   23.3   6.1  14.7   0.0   73     24     49    16.8    6.9   2.3 162.1  0.00   0.87   6.78   2.37    4.55    1.50
 VALUES OF FETCH      5.00,CASE A
  3/ 0/ 0   26.1   8.3  17.2   0.0   63     20     42    19.7    6.9   2.1 162.1  0.00   0.90   6.56   2.02    6.71    1.30
  4/ 0/ 0   30.6  12.8  21.7   0.0   51     17     34    25.9    7.5   2.4 181.4  0.00   0.95  10.56   4.75    9.35    1.30
  5/ 0/ 0   34.4  16.1  25.3   0.0   60     20     40    32.2   11.0   2.5 200.7  0.00   0.95  11.61   5.77   11.84    1.20
  6/ 0/ 0   40.0  20.0  30.0   0.0   59     19     39    42.4   13.7   2.1 166.0  0.00   0.97  12.16   6.21   13.28    1.20
  7/ 0/ 0   42.2  25.0  33.6   0.0   50     19     35    52.1   15.9   1.9 154.4  0.00   0.87  10.97   5.65   12.78    1.20
  8/ 0/ 0   41.1  24.4  32.8   0.0   54     21     37    49.7   16.5   1.9 154.4  0.00   0.88  10.30   5.20   11.79    1.20
  9/ 0/ 0   40.6  21.7  31.1   0.0   55     19     37    45.2   14.2   1.7 127.4  0.00   0.93   9.11   4.04   10.16    1.30
 10/ 0/ 0   34.4  15.6  25.0   0.0   60     19     40    31.7   10.6   1.3  92.6  0.00   0.90   7.45   2.75    6.83    1.50
 VALUES OF FETCH    200.00,CASE B
 11/ 0/ 0   26.1   7.8  16.9   0.0   89     28     59    19.3    9.4   1.4  96.5  0.00   0.83   5.54   1.70    4.19    1.80
 12/ 0/ 0   22.2   4.4  13.3   0.0   85     27     56    15.3    7.2   1.1  77.2  0.00   0.82   4.81   1.10    2.84    1.80

    ******************************************************************************************************

    RESULT OF ET ESTIMATION BY VARIOUS METHODS FOR MONTH, mm/day

    ******************************************************************************************************

    MONTH/DAY/YEAR          BLANEY           RADIATION           PENMAN           CORR. PEN.          ETPAN


       1/ 0/19 0             2.816             2.672              2.609             2.509             1.867
       2/ 0/19 0             3.854             3.903              4.132             3.968             2.647
       3/ 0/19 0             4.963             4.114              4.475             4.147             4.368
       4/ 0/19 0             6.956             7.661              7.505             7.237             5.767
       5/ 0/19 0             8.346             8.778              8.743             8.775             7.510
       6/ 0/19 0            10.042             9.681              9.321             9.439             8.494
       7/ 0/19 0            10.140             9.110              9.250             9.041             8.021
       8/ 0/19 0             9.263             8.394              8.617             8.447             7.519
       9/ 0/19 0             8.222             7.186              7.139             7.017             6.542
      10/ 0/19 0             5.746             5.244              4.910             4.785             4.537
      11/ 0/19 0             3.403             3.020              2.954             2.967             2.673
      12/ 0/19 0             2.558             2.371              2.223             2.204             1.797

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    MONTH AVE                  6.359             6.011              5.990             5.878             5.145

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    STATION = OAVIS CALIFORNIA.                                    FACTOR FOR CONVERTING EO OATA TO NILLIBARS =     1.000

    ALTITUDE IN NETERS =      17.0                                 FACTOR FOR CONVERTING RS OATA TO NN/OAY =     1.000

    LATITIOE IN OEGREES =      38.5                                FACTOR FOR CONVERTING EPAN OATA TO NN/OAY =     1.000

    HENISPNERE = N                                                 TENPERATURE OATA IS GIVEN IN OEGREES :  C

    HEIGHT OF WINO NEASURENENT IN NETERS =      2.00               SUNSHINE/CLOUDINESS FLAG =     5

    NEAN PRESSURE FOR THE YEAR IN NILLIBARS =   1010.0             RELATIVE HUNIOITY OATA IS :  ACTUAL DATA
-------------------------------------------------------------
    FACTOR FOR CONVERTING 24HR WINO TO KN/OAY =     1.000          WINO DATA IS :  ACTUAL OATA

    FACTOR FOR CONVERTING OAYTIME WINO TO N/SEC =     0.000        SUNSHINE OATA IS  :  ACTUAL DATA (n/N COMPUTED FROM  n/N = 2RS/RA  - 0.5  )

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    CLINATOLOGICAL OATA FOR NONTN AFTER CONVERSION

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OATE (NOY)  TNAX  TNIN TNEAN  TOEW  RHNAX  RHNIN RHNEAN   EA    FO    UOAY   U24 SUNNRS NRATIO SOLRAO   RN     EPAN   URATIO

 VALUES OF FETCN    200.00,CASE A
 10/ 1/60   25.6  14.4  20.0   0.0   100     35     68  23.4  15.8   2.1 169.0  0.00   0.79   7.24   3.21   4.32     1.20
 10/ 2/60   26.1   8.3  17.2   0.0   100     32     66  19.6  13.0   1.5 121.0  0.00   0.80   7.21   3.18   4.57     1.20
 10/ 3/60   26.7   9.4  18.1   0.0   100     21     61  20.7  12.5   3.0 238.0  0.00   0.80   7.19   3.11   5.33     1.20
 10/ 4/60   26.7  11.7  19.2   0.0   100     36     68  22.3  15.1   0.9  74.0  0.00   0.83   7.28   3.14   3.30     1.20
 10/ 5/60   27.8  11.7  19.8   0.0   100     43     72  23.0  16.5   2.9 229.0  0.00   0.31   4.42   2.11   1.78     1.20
 10/ 6/60   23.9   8.9  16.4   0.0   100     51     76  18.7  14.1   3.4 268.0  0.00   0.34   4.50   2.04   3.81     1.20
 10/ 7/60   23.9   8.3  16.1   0.0    82     48     65  18.3  11.9   3.0 239.0  0.00   0.56   5.68   2.40   3.30     1.20
 10/ 8/60   22.2  11.7  17.0   0.0    42     23     33  19.3   6.3   9.2 729.0  0.00   0.91   7.45   2.73  12.45     1.20
 10/ 9/60   21.1  12.8  17.0   0.0    41     23     32  19.3   6.2   8.2 647.0  0.00   0.93   7.50   2.72  14.22     1.20
 10/10/60   19.4   3.9  11.7   0.0   100     33     67  13.7   9.1   2.0 155.0  0.00   0.17   3.50   1.39   3.81     1.20
 10/11/60   26.1   3.3  14.7   0.0   100     33     67  16.7  11.1   1.3 101.0  0.00   0.75   6.46   3.09   2.79     1.20
 10/12/60   21.7   6.1  13.9   0.0    83     35     59  15.9   9.4   1.0  77.0  0.00   0.78   6.53   3.16   2.79     1.20
 10/13/60   22.8   6.7  14.8   0.0    57     29     43  16.8   7.2   2.0 157.0  0.00   0.58   5.44   2.22   3.81     1.20
 10/14/60   25.6   5.6  15.6   0.0    38     20     29  17.7   5.1   5.2 413.0  0.00   0.91   7.05   2.29   9.65     1.20
 10/15/60   27.8   8.3  18.1   0.0    55     18     37  20.7   7.6   5.5 437.0  0.00   0.77   6.31   1.60  12.70     1.20
 10/16/60   29.4   5.0  17.2   0.0    76     24     50  19.6   9.8   1.6 123.0  0.00   0.87   6.73   2.39   4.06     1.20
 10/17/60   28.3   3.9  16.1   0.0   100     28     64  18.3  11.7   1.5 119.0  0.00   0.80   6.32   2.27   4.06     1.20
 10/18/60   24.4   5.0  14.7   0.0   100     26     63  16.7  10.5   1.9 152.0  0.00   0.79   6.22   2.29   3.30     1.20
 10/19/60   25.6   5.6  15.6   0.0    82     24     53  17.7   9.4   0.9  72.0  0.00   0.71   5.78   2.60   2.79     1.20
 10/20/60   27.2   7.8  17.5   0.0    87     24     56  20.0  11.1   0.8  66.0  0.00   0.72   5.78   2.85   3.30     1.20
 10/21/60   27.8   8.3  18.1   0.0   100     20     60  20.7  12.4   0.6  45.0  0.00   0.60   5.20   2.52   2.29     1.20
 10/22/60   28.9  10.0  19.5   0.0   100     40     70  22.6  15.8   2.1 169.0  0.00   0.71   5.64   2.62   4.32     1.20
 10/23/60   22.2   7.8  15.0   0.0   100     40     70  17.1  11.9   2.4 188.0  0.00   0.78   5.90   1.91   3.30     1.20
 10/24/60   22.2   5.6  13.9   0.0    94     35     65  15.9  10.3   1.8 143.0  0.00   0.79   5.93   2.65   3.05     1.20
 10/25/60   23.3  11.1  17.2   0.0    32     23     28  19.6   9.4   3.0 238.0  0.00   0.81   5.95   2.01   3.05     1.20
 10/26/60   21.1  13.3  17.2   0.0    32     16     24  19.6   4.7   6.9 544.0  0.00   0.79   5.78   2.01   8.64     1.20
 10/27/60   23.3  15.6  19.5   0.0    68     21     45  22.6  10.1   4.7 371.0  0.00   0.72   5.42   1.68   8.64     1.20
 10/28/60   26.7   5.0  15.9   0.0    76     19     48  18.0   8.6   4.1 328.0  0.00   0.80   5.71   1.86   7.37     1.20
 10/29/60   26.7   5.0  15.9   0.0    73     22     48  18.0   8.6   2.1 169.0  0.00   0.81   5.71   2.01   5.59     1.20
 10/30/60   27.8   7.2  17.5   0.0    76     22     49  20.0   9.8   0.6  51.0  0.00   0.75   5.42   2.37   2.03     1.20
 10/31/60   28.3   7.8  18.1   0.0    78     24     51  20.7  10.6   1.0  81.0  0.00   0.73   5.27   2.30   3.05     1.20

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RESULT OF ET ESTINATION BY VARIOUS NETNOOS FOR NONTN, mm/day

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MONTH/OAY/YEAR          BLANEY            RADIATION           PENNAN           CORR. PEN.           ETPAN

  10/ 1/1960             4.568              4.134              3.939             3.947              3.477
  10/ 2/1960             3.973              3.857              3.461             3.539              3.733
  10/ 3/1960             5.039              4.274              4.586             4.448              4.138
  10/ 4/1960             3.985              3.904              3.207             3.350              2.737
  10/ 5/1960             3.214              2.367              3.294             2.959              1.411
  10/ 6/1960             2.669              2.204              2.940             2.591              2.993
  10/ 7/1960             3.069              3.070              3.787             3.434              2.579
  10/ 8/1960             6.224              5.721             12.058             7.025              6.510
  10/ 9/1960             6.100              5.472             11.102             6.787              7.726
  10/10/1960             1.940              1.508              2.142             1.980              3.077
  10/11/1960             3.172              3.195              3.072             3.120              2.297
  10/12/1960             2.922              3.305              3.142             3.180              2.281
  10/13/1960             3.138              3.150              3.905             3.450              2.831
  10/14/1960             5.109              4.934              7.892             5.388              6.098
  10/15/1960             5.466              4.514              7.517             5.483              8.072
  10/16/1960             4.059              3.958              3.620             3.541              3.162
  10/17/1960             3.572              3.313              2.862             2.871              3.308
  10/18/1960             3.508              3.230              3.024             2.975              2.653
  10/19/1960             3.153              3.099              3.070             3.064              2.233
  10/20/1960             3.452              3.177              3.244             3.288              2.671
  10/21/1960             3.102              2.761              2.765             2.830              1.875
  10/22/1960             3.631              3.059              3.342             3.232              3.491
  10/23/1960             3.099              2.944              2.692             2.575              2.649
  10/24/1960             2.965              2.959              3.063             3.007              2.448
  10/25/1960             4.258              4.026              5.845             4.258              2.048
  10/26/1960             5.446              4.363             10.370             5.340              5.024
  10/27/1960             4.921              3.714              6.273             4.985              5.851
  10/28/1960             4.373              3.542              5.185             4.406              5.178
  10/29/1960             3.717              3.340              3.792             3.507              4.227
  10/30/1960             3.297              3.036              2.989             2.956              1.594
  10/31/1960             3.416              2.999              3.201             3.122              2.418
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MONTH AVE                3.896              3.527              4.561             3.761              3.573
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    STATION = DAVIS CALIFORNIA.
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    CLIMATOLOGICAL DATA FOR MONTH AFTER CONVERSION

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DATE (MDY)  TMAX  TMIN TMEAN  TDEW  RHMAX  RHMIN RHMEAN   EA    ED   UDAY   U24 SUNHRS NRATIO SOLRAD   RN     EPAN   URATIO

 VALUES OF FETCH   200.00,CASE A
 10/ 1/60   24.3  10.1  17.2  0.0    86     35     61   19.6  11.9   3.6 287.0  0.00   0.60   6.20   2.62   5.69      1.20
 10/11/60   25.9   5.7  15.8  0.0    78     26     52   18.0   9.3   2.2 172.0  0.00   0.72   6.26   2.48   4.92      1.20
 10/21/60   25.3   8.8  17.1  0.0    75     26     51   19.5   9.8   2.7 212.0  0.00   0.70   5.63   2.18   4.67      1.20
----------------------------------------------------------------------------------------------------

RESULT OF ET ESTIMATION BY VARIOUS METHODS FOR MONTH, mm/day

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 MONTH/DAY/YEAR          BLANEY          RADIATION          PENMAN          CORR. PEN.          ETPAN


  10/ 1/1960             4.002             3.643             4.535             4.126             4.305
  10/11/1960             3.775             3.601             3.895             3.690             3.798
  10/21/1960             3.861             3.376             4.262             3.857             3.525
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MONTH AVE                   3.879          3.540          4.231          3.891          3.876
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    CLIMATOLOGICAL DATA FOR MONTH AFTER CONVERSION

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DATE (MDY)  TMAX  TMIN TMEAN  TDEW  RHMAX  RHMIN RHMEAN   EA    ED   UDAY   U24 SUNHRS NRATIO SOLRAD   RN     EPAN   URATIO

 VALUES OF FETCH   200.00,CASE A
 10/ 0/60   25.2   8.2  16.7  0.0    80     29     55   19.0  10.4   2.8 223.0  0.00   0.71   6.02   2.42   5.08      1.20
----------------------------------------------------------------------------------------------------

RESULT OF ET ESTIMATION BY VARIOUS METHODS FOR MONTH, mm/day

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 MONTH/DAY/YEAR          BLANEY          RADIATION          PENMAN          CORR. PEN.          ETPAN


  10/ 0/1960             3.892             3.537             4.244             3.902             3.894
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APPENDIX IV

GLOSSARY
(as related to text)

ACTUAL CROP EVAPOTRANSPIRATION, ETa(crop): rate of evapotranspiration equal to or smaller than predicted ETcrop as affected by the level of available soil water, salinity, field size, or other causes; mm/day

ACTUAL VAPOUR PRESSURE, ed: pressure exerted by water vapour contained in the air; millibar

ADVECTION, horizontal transport of sensible heat by air movement as for instance from large, dry fallow surrounds into irrigated areas

ALLOWABLE SOIL WATER DEPLETION, p.Sa: depth of soil water in the root zone readily available to the crop for given soil and climate allowing unrestricted evapotranspiration as the fraction p of total available soil water between field capacity (Sfc) and wilting point (Sw); mm/m soil depth

AVAILABLE SOIL WATER, Sa: depth of water stored in the root zone between field capacity (Sfc) and wilting point (Sw); mm/m soil depth

AVERAGE INTAKE RATE: rate of infiltration of water into the soil obtained by dividing the total depth of water infiltrated by the total time from start to finish of water application; mm/hour

BASIC INTAKE RATE: rate at which water will enter the soil when after initial wetting of the soil the rate becomes essentially constant; mm/hour

CANOPY INTERCEPTION: depth of precipitation caught and held by plant foliage and lost be evaporation without reaching the ground surface; mm or sometimes percentage of rainfall

CLOTHESLINE EFFECT: horizontal heat transfer (advection) from warm and dry upwind area to a relatively cooler crop field resulting in increased ETcrop; particularly refers to the field border effects or to patchwork of small interspersed fields

CLOUDINESS: degree of cloud cover, usually mean of several observations per day; expressed in oktas (in eighths) of sky covered, or in tenths of sky covered

CONTINUOUS SUPPLY: method of water delivery with continuous but often variable discharge in water distribution system up to inlet of individual farm or field

CONVEYANCE EFFICIENCY, Ec: ratio between water received at the inlet to a block of fields and that released at the projects headworks; fraction

CRITICAL PERIOD: periods during crop growth when soil water stress will have a lasting effect on crop growth and yields

CROP COEFFICIENT, kc: ratio between crop evapotranspiration (ETcrop) and the reference crop evapotranspiration (ETo) when crop is grown in large fields under optimum growing conditions, or ETcrop = kc . ETo; fraction

CROP EVAPOTRANSPIRATION, ETcrop: rate of evapotranspiration of a disease-free crop growing in a large field (one or more ha) under optimal soil conditions, including sufficient water and fertilizer and achieving full production potential of that crop under the given growing environment; includes water loss through transpiration by the vegetation, and evaporation from the soil surface and wet leaves; mm/day

CROPPING INTENSITY: for a given period the percentage of the total scheme area which is under a (irrigated) crop; percentage

CROPPING PATTERN: sequence of different crops grown in regular order on any particular field or fields

CROP WATER REQUIREMENTS: depth of water required by a crop or a diversified pattern of crops for evapotranspiration (ETcrop) during a given period; mm/day as average for given period

DAY LENGTH FACTOR, p: percentage p of total annual daylight hours occurring during the period being considered; percentage

DESIGN FACTOR, α : ratio between canal capacity or maximum discharge in m^3/sec and the maximum daily supply requirements during the peak water use period in m^3/day, or $\alpha = 86400\ Qmax/Vmax$; fraction

DEPTH OF IRRIGATION, d: depth of irrigation, including application losses, applied to the soil in one irrigation application and which is needed to bring the soil water content of root zone to field capacity; mm

DEVELOPMENT STAGE: for a given crop the period between end of initial (emergence) stage and full groundcover or when ground cover is between 10 and 80%; days

DEWPOINT TEMPERATURE, Tdewpoint: temperature to which the air needs to be cooled in order to become saturated and at which water vapour starts to condense; degree Celsius

DISTRIBUTION EFFICIENCY, Ed: ratio of water made directly available to the crop and that released at the inlet of a block of fields; Ed = Eb . Ea; fraction

EFFECTIVE FULL GROUNDCOVER: percentage of groundcover by the crop when ETcrop is approaching maximum - generally 70 to 80% of surface area; percentage

EFFECTIVE RAINFALL, Pe: rainfall useful for meeting crop water requirements; it excludes deep percolation, surface runoff and interception; mm/period

EFFECTIVE ROOTING DEPTH, D: soil depth from which the full grown crop extracts most of the water needed for evapotranspiration; m
ELECTRICAL CONDUCTIVITY, EC: the property of a substance to transfer an electrical charge (reciprocal of resistance). It is measured in ohms of a conductor which is 1 cm long and 1 cm^2; electrical conductivity is expressed as the reciprocal of ohms/cm (mhos/cm); 1 mhos/cm = 1 000 mmhos/cm; 1 mmhos/cm = 1 000 µmhos/cm
ELECTRICAL CONDUCTIVITY, IRRIGATION WATER, ECw: is used as a measure of the salt content of the irrigation water; mmhos/cm
ELECTRICAL CONDUCTIVITY, MAXIMUM, ECmax: is used as a limit of the salt concentration of the soil saturation paste (ECe) beyond which growth would stop (zero yield); mmhos/cm
ELECTRICAL CONDUCTIVITY, SATURATION EXTRACTS, ECe: is used as a measure of the salt content of an extract from a soil when saturated with water; under average conditions ECe = 1.5 ECdw and also is approximately half the salinity of the soil water to which the crop is actually exposed in the soil, mmhos/cm
EVAPORATION, E: rate of water loss from liquid to vapour phase from an open water or wet soil surface by physical processes; mm/day
EVAPOTRANSPIRATION: rate of water loss through transpiration from vegetation plus evaporation from the soil; mm/day
EXTRA-TERRESTRIAL RADIATION, Ra: amount of solar radiation received on a horizontal at the top of the atmosphere; equivalent evaporation mm/day
FIELD APPLICATION EFFICIENCY, Ea: ratio of water made directly available to the crop and that received at the field inlet
FIELD CANAL EFFICIENCY, Eb: ratio between water received at the field inlet and that at the inlet of a block of fields; fraction
FIELD CAPACITY, Sfc: depth of water held in the soil after ample irrigation or heavy rain when the rate of downward movement has substantially decreased, usually 1 to 3 days after irrigation or rain; soil water content at soil water tension of 0.2 to 0.3 atmosphere; mm/m soil depth
FIELD SUPPLY SCHEDULE: stream size, duration and interval of water supply to the individual field or farm
FIELD WATER BALANCE: sum of all gains and losses of water over a given period of time; mm/period
FLEXIBILITY FACTOR, C: coefficient greater than one to account for fluctuations in water supply in excess of those determined for an assumed cropping pattern and cropping intensity
FULL GROUND COVER: soil covered by crops approaching 100% when looking downwards
GROUND COVER: percentage of soil surface shaded by the crop if the sun were directly overhead; percentage
GROUNDWATER TABLE: upper boundary of groundwater where water pressure is equal to atmosphere, i.e. depth of water level in borehole when groundwater can freely enter the borehole; cm below soil surface
GROWING SEASON: for a given crop the time between planting or sowing and harvest; days
INITIAL DEVELOPMENT STAGE: for a given crop the time during germination or early growth when ground cover is less than 10%; days
INITIAL INTAKE RATE: rate at which water will enter the soil when water is first applied; mm/hour
IRRIGATION INTERVAL, i: time between the start of successive field irrigation applications on the same field; days
IRRIGATION REQUIREMENTS: depth of water required for meeting evapotranspiration minus contribution by effective precipitation, groundwater, stored soil water, required for normal crop production plus leaching requirement and water losses and operational wastes, sometimes called gross irrigation requirements; mm/period
LATE-SEASON STAGE: time between the end of the mid-season stage and harvest or maturity; days
LEACHING EFFICIENCY, Le: fraction of the irrigation water applied for salt control (leaching) which was effective
LEACHING REQUIREMENTS, LR: fraction of the irrigation water entering the soil that effectively must flow through and beyond the root zone in order to prevent salinity build-up. This value is the minimum amount of water necessary to control salts; fraction
LEVEL OF SUPPLY: selected water supply on the basis of probability to meet crop irrigation requirements
MAXIMUM NUMBER OF BRIGHT SUNSHINE HOURS, N: number of bright sunshine hours for a 24-hour day with no cloud cover; hours
METHOD OF SUPPLY: method of operating an irrigation system to convey water from the source of supply and to distribute it according to crop requirements to each field served by the system
MID-SEASON STAGE: for a given crop the period between effective full ground cover and the onset of maturity (i.e. leaves start to discolour or fall off); days
NET IRRIGATION REQUIREMENT, In: depth of water required for meeting evapotranspiration minus contribution by precipitation, groundwater, stored soil water; does not include operation losses and leaching requirements; mm/period
NET LONGWAVE RADIATION, Rnl: balance between all outgoing and incoming longwave radiation; almost always a negative value, equivalent evaporation mm/day

NET RADIATION, Rn: balance between all incoming and outgoing short and longwave radiation; $Rn = Rns + Rnl$; equivalent evaporation mm/day

NET SOLAR RADIATION, Rns: difference between shortwave radiation received on the earth's surface and that reflected by the soil, crop or water surface; equivalent evaporation mm/day

OASIS EFFECT: effect of dry fallow surrounds on the micro-climate of a relatively small acreage of land where an air mass moving into an irrigated area will give up sensible heat. For small fields this may result in a higher ETcrop as compared to predicted ETcrop using climatic data collected inside the irrigated area; conversely ETcrop predictions based on weather data collected outside the irrigated fields may over-predict actual evapotranspiration losses

OSMOTIC PRESSURE: equivalent negative pressure to which water must be subjected to bring the saline soil water through a semi-permeable membrane into static equilibrium with pure water; atmosphere

PAN COEFFICIENT, kp: ratio between reference evapotranspiration ETo and water loss by evaporation from an open water surface of a pan or ETo = kp x Epan; fraction

PAN EVAPORATION, Epan: rate of water loss by evaporation from an open water surface of a pan; mm/day

PEAK OR MAXIMUM SUPPLY, Vmax: average daily supply requirement during the peak water use period for given crop or cropping pattern and climate; m^3/day

PEAK SUPPLY PERIOD: water use period for a given crop or cropping pattern during the month or period thereof of highest water requirements; mm/day

PLANT POPULATION: number of plants per unit of crop area

PRECIPITATION: total amount of precipitation (rain, drizzle, snow, hail, fog, condensation, hoar frost and rime) expressed in depth of water which would cover a horizontal plane if there is no runoff, infiltration or evapotranspiration; mm/day

PROJECT EFFICIENCY, Ep: ratio between water made directly available to the crop and that released at project headworks; Ep = Ea . Eb . Ec; fraction

PSYCHROMETER: device to measure air humidity; normally consisting of two standard thermometers, one of whose bulb is surrounded by a wet muslin bag and is called wet-bulb thermometer; both should normally be force-ventilated and shielded against radiation (Assmann type)

READILY AVAILABLE SOIL WATER, p.Sa: depth of soil water available for given crop, soil and climate allowing unrestricted evapotranspiration and crop growth; equals allowable soil water depletion; mm/m soil depth

REFERENCE CROP EVAPOTRANSPIRATION, ETo: rate of evapotranspiration from an extended surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water; mm/day

REFLECTION COEFFICIENT, also called albedo, α : ratio between the amount of shortwave radiation received at the earth's surface and that reflected back

RELATIVE HUMIDITY, RH, RHmax, RHmin: actual amount of water vapour in the air relative to the amount of water vapour the air would hold when saturated at the same temperature; RHmax: mean of maximum RH of each day over the period considered; RHmin: mean of minimum RH of each day over the period considered; percentage

ROTATIONAL SUPPLY: supply of water rotated amongst laterals, sub-laterals or field inlets at varied intervals

SATURATION VAPOUR PRESSURE, ea: upper limit of vapour pressure at or when air is saturated at given air temperature; millibar

SEASONAL IRRIGATION REQUIREMENTS: total depth of water, minus contribution by precipitation, groundwater, stored soil water, surface runoff required for normal crop growth during the crop growing season; mm and period

SOIL HYDRAULIC CONDUCTIVITY, k: rate of water flow through a unit cross-section of the soil under a unit hydraulic gradient; also called permeability or transmission; mm/day

SOIL INTAKE (INFILTRATION) RATE: instantaneous rate at which water will enter the soil

SOIL SPECIFIC GRAVITY, As: ratio of the weight of water-free soil to its volume; also called bulk density; g/cm^3

SOIL STRUCTURE: arrangement of soil particles into aggregates which occur in a variety of recognized shapes, sizes and strengths

SOIL TEXTURE: characterization of soil in respect of its particle size and distribution

SOIL WATER CONTENT: depth of water held in the soil; mm/m soil depth

SOIL WATER DEPLETION FRACTION, p: fraction of available soil water (Sfc-Sw) that can be taken by the crop permitting unrestricted evapotranspiration and crop growth; fraction

SOIL WATER STRESS: sum of soil water tension and osmotic pressure to which water must be subjected to be in equilibrium with soil water; also called soil water potential; atmosphere

SOIL WATER TENSION: force at which water is held by the soil or negative pressure or suction that must be applied to bring the water in a porous cup into static equilibrium with the water in the soil; soil water tension does not include osmotic pressure; also called matric potential; atmosphere

SOLAR RADIATION, Rs: amount of shortwave radiation received on a horizontal plane at the earth's surface; equivalent evaporation mm/day

STORED SOIL WATER, Wb: depth of water stored in the root zone from earlier rains, snow or irrigation applications which partly or fully meets crop water requirements in following periods; mm

STREAM SIZE, q: flow selected for supply to field inlet or irrigation block; l/sec or m^3/sec

SUNSHINE HOURS, n: number of hours of bright sunshine per day, also sometimes defined as the duration of traces or burns made on a chart by Campbell Stokes recorder; hours

SUPPLY DURATION, t or T: length of time during which a given stream size is delivered to the field or farm (t) or irrigation block (T) during any part of the irrigation season; hour or day

SUPPLY DURATION FACTOR, ft: is T/I or for a fixed or constant canal discharge the ratio between supply duration in days and the supply interval in days during any part of the irrigation season; fraction

SUPPLY FACTOR, fs: is Q/Qmax or ratio between actual and maximum possible supply in m^3/sec; fraction

SUPPLY INTERVAL, i or I: time interval between the start of successive irrigation supplies at field or farm (i) irrigation block or sector (I); days

SUPPLY ON DEMAND: irrigation water supply to satisfy need for irrigation water at any stream size, duration and interval during the growing season

SUPPLY REQUIREMENT FACTOR, fi: is V/Vmax or ratio between average daily supply requirement over a given period and maximum daily supply requirement during the period of peak water use in m^3/day; fraction

SUPPLY SCHEDULE: stream size, supply duration and supply interval of irrigation water supply to field or irrigation block, during the growing season

TENSIOMETER: a device for measuring the tension of soil water in the soil consisting of a porous, permeable ceramic cup connected through a tube to a manometer or vacuum gauge

TOTAL AVAILABLE SOIL WATER, Sa =(Sfc - Sw): depth of soil water available in the root zone to the crop; difference between field capacity and wilting point; mm/m soil depth

TRANSPIRATION: rate of water loss through the plant which is regulated by physical and physiological processes; mm/day

WET BULB TEMPERATURE, Twetbulb: temperature recorded on a thermometer whose bulb is surrounded by a wet muslin bag, thus lowering the temperature by loss of latent heat through evaporation; degree Celsius

WET BULB DEPRESSION: difference between simultaneous readings of wet and dry bulb thermometers; degree Celsius

WILTING POINT, Sw: depth of soil water below which the plant cannot effectively obtain water from the soil; soil water content at 15 atmospheres soil water tension; mm/m soil depth

WINDSPEED, U_2: speed of air movement at 2 m above ground surface in unobstructed surroundings; mean in m/sec over the period considered, or total wind run in km/day

APPENDIX V

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EXPERIMENTALLY DETERMINED CONSTANTS FOR THE RADIATION EQUATION

$Rs = (a+b\,n/N)\,Ra$

Source		Location or Range of locations	Constants a	b	a+b	Latitude°
As listed by Linacre (1967)						
Black et al.	(1954)	Stockholm and Fairbanks	0.22	0.52	0.74	59+65 N
Monteith	(1966)	Lerwick, U.K.	0.23	0.56	0.79	60 N
Penman	(1948)	Rothamsted, U.K.	0.18	0.55	0.73	52 N
Baier et al.	(1965)	Canada	0.25	0.62	0.87	52 N
Black et al.	(1954)	Kew, U.K.	0.19	0.57	0.76	51 N
von Wijk	(1963)	Gembloux, Belgium	0.15	0.54	0.69	51 N
von Wijk	(1963)	Versailles, France	0.23	0.50	0.73	49 N
		Mean	0.21	0.55	0.76	54°
Tanner et al.	(1960)	Wisconsin, U.S.A.	0.18	0.55	0.73	43 N
de Villele	(1965)	El Aounia	0.28	0.43	0.71	37 N
de Vries	(1958)	Deniliquin, Australia	0.27	0.54	0.81	36 S
Damagnez et al.	(1963)	Tunisia	0.16	0.59	0.75	35 N
Prescott	(1940)	Canberra, Australia	0.25	0.54	0.79	35 S
Black et al.	(1954)	Dry Creek, S. Africa	0.30	0.50	0.80	35 S
Page	(1961)	Capetown, S. Africa	0.20	0.59	0.79	34 S
		Mean	0.23	0.53	0.76	36°
Glover et al.	(1958)	Durban, S. Africa	0.25	0.50	0.75	30 S
Yadov	(1965)	New Delhi, India	0.31	0.46	0.77	29 N
Glover et al.	(1958a)	Pretoria, S. Africa	0.25	0.50	0.75	26 S
Glover et al.	(1958a)	Windhoek, S.W. Africa	0.26	0.52	0.78	23 S
Page	(1961)	Tananarivc, Madagascar	0.30	0.48	0.78	19 S
Smith	(1959)	Jamaica	0.31	0.49	0.80	18 N
		Mean	0.28	0.49	0.77	24°
Fitzpatrick	(1965)	Kimberley, S. Africa	0.33	0.43	0.76	16 S
Cockett et al.	(1964)	Central Africa	0.32	0.47	0.79	15 S
Page	(1961)	Dakar, Senegal	0.10	0.70	0.80	15 N
Yadov	(1965)	Madras, India	0.31	0.49	0.80	13 N
Davies	(1965)	Kano, Nigeria	0.26	0.54	0.80	12 N
Smith	(1960)	Trinidad	0.27	0.49	0.76	11 N
Stanhill	(1963)	Benin City[1/], Nigeria	0.26	0.38	0.64	7 N
		Mean	0.26	0.50	0.76	13°
Davies	(1965)	Accra, Ghana	0.30	0.37	0.67	6 N
Black et al.	(1954)	Batavia (Djakarta)	0.29	0.59[2/]	0.88	6 S
Page	(1961)	Kinshasa, Zaire	0.21	0.52	0.73	4 S
Page	(1961)	Singapore	0.21	0.48	0.69	1 N
Glover et al.	(1958b)	Kabete, Kenya	0.24	0.59	0.83	1 S
Page	(1961)	Kisangani, Zaire	0.28	0.40	0.68	1 N
Rijks et al.	(1964)	Kampala, Uganda	0.24	0.46	0.70	0
		Mean	0.25	0.49[3/]	0.74	3°
Constants developed from studies involving multiple locations						
Fritz and McDonald	(1949)	All in U.S.A.	0.35	0.61	0.96	-
Black et al.	(1954)	Tropics to polar	0.23	0.48	0.71	-
Mateer	(1955)	Canada	0.355	0.68	1.035	-
Glover and McCulloch	(1958)	0-60°	$0.29\cos\phi$[4/]	0.52	-	-
Hounam	(1963)	Australia, 12-43°S	0.26	0.50	0.76	-
Davies	(1965)	West Africa, 5-15°N	0.19	0.60	0.79	-
Page	(1961)	40°N-40°S	0.23	0.52	0.75	-
As listed by Chidley et al. (1970)						
Drummond and Kirsten	(1951)	Capetown, S. Africa	0.29	0.50	0.79	34 S
Stanhill	(1961)	Eastern Mediterranean	0.32	0.47	0.79	31 N
Chidley et al.	(1970)	Saudi Arabia	0.36	0.47	0.83	-
Kimball	(1914)	Virginia, U.S.A.	0.22	0.54	0.76	37 N
Black et al.	(1954)	Salt Lake City, U.S.A.	0.20	0.47	0.67	41 N
Others						
Stanhill	(1965)	Israel (daily)	0.36	0.43	0.79	31 N
Stanhill	(1965)	Israel (weekly)	0.39	0.38	0.77	31 N
Stanhill	(1965)	Israel (monthly)	0.41	0.36	0.77	31 N
Scholte Ubing	(1959)	Netherlands	0.18	0.54	0.72	52 N
Robertson	(1971)	Los Baños, Philippines	0.24	0.54	0.79	15 N
Idso	(1969)	Phoenix, Ariz., U.S.A.	-	-	0.78	33 N

[1/] Davies (1965) gave 0.28 and 0.33 for a and b respectively

[2/] Table by Linacre (1967) indicated 0.29 for Batavia, a likely error since Chidley and Pike (1970) give 0.59 for Djakarta, the same location

[3/] Based on revised figure for Batavia

[4/] ϕ is the latitude in degrees

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1 Irrigation practice and water management, 1972 (Ar* E* F* S*)
1 Rev.1 Irrigation practice and water management, 1984 (E)
2 Irrigation canal lining, 1971 (New edition, 1977, available in E, F and S in the FAO Land and Water Development Series, No. 1)
3 Design criteria for basin irrigation systems, 1971 (E*)
4 Village irrigation programmes – a new approach in water economy, 1971 (E* F)
5 Automated irrigation, 1971 (E* F* S*)
6 Drainage of heavy soils, 1971 (E* F S*)
7 Salinity seminar, Baghdad, 1971 (E* F)
8 Water and the environment, 1971 (E* F* S*)
9 Drainage materials, 1972 (E* F* S*)
10 Integrated farm water management, 1971 (E* F* S*)
11 Planning methodology seminar, Bucharest, 1972 (E* F*)
12 Farm water management seminar, Manila, 1972 (E*)
13 Water use seminar, Damascus, 1972 (E* F*)
14 Trickle irrigation, 1973 (E* F* S*)
15 Drainage machinery, 1973 (E* F*)
16 Drainage of salty soils, 1973 (C* E* F* S*)
17 Man's influence on the hydrological cycle, 1973 (E* F* S*)
18 Groundwater seminar, Granada, 1973 (E* F S)
19 Mathematical models in hydrology, 1973 (E)
20/1 Water laws in Moslem countries – Vol. 1, 1973 (E* F)
20/2 Water laws in Moslem countries – Vol. 2, 1978 (E F)
21 Groundwater models, 1973 (E)
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23 Simulation methods in water development, 1974 (E F* S*)
24 Crop water requirements, (rev.) 1977 (C* E F S)
25 Effective rainfall, 1974 (C* E* F* S*)
26/1 Small hydraulic structures – Vol. 1, 1975 (E F S)
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27 Agro-meteorological field stations, 1976 (E F* S*)
28 Drainage testing, 1976 (E F S)
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32 Deterministic models in hydrology, 1979 (E)
33 Yield response to water, 1979 (C* E F S)
34 Corrosion and encrustation in water wells, 1980 (E)
35 Mechanized sprinkler irrigation, 1982 (C E F S)
36 Localized irrigation, 1980 (Ar C E F S)
37 Arid zone hydrology, 1981 (C** E*)
38 Drainage design factors, 1980 (Ar C E F S)
39 Lysimeters, 1982 (C E F S)
40 Organization, operation and maintenance of irrigation schemes, 1982 (C** E F S**)
41 Environmental management for vector control in rice fields, 1984 (E F S)
42 Consultation on irrigation in Africa, 1987 (E F)
43 Water lifting devices, 1986 (E)
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