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Guidelines for predicting
crop water requirements

by

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FOREWORD

‘‘And with water we have made all which is living’’ ...

Man, throughout history, has been able to develop skills to deal with his environment. He has developed plants and improved crop varieties adapted to his needs. He has developed suitable practices to use water, fertilizers and pesticides most effectively to increase crop production. But he has not been able to master climate and has remained under the threat of drought. With limited water and with the increase in population and the need for more and better food production, water has become the most precious natural resource in most regions of the world; so there is now an imperative need for really effective planning of water utilization in crop production.

Methodologies have been developed to predict the correct amounts of water needed to obtain optimal production of crops. Such methods are developed for climatic, agronomic and soil conditions prevailing in a given area. The transfer of methodologies from one area to another far different from that in which they were developed remains problematic; time and labour-consuming field experiments, sometimes also costly, are frequently required to test and calibrate the methods in a new set of conditions.

The quantitative prediction of irrigation needs in respect to crop production must be accurately known for identification and feasibility analysis of proposed irrigation projects. Guidance is needed on the most promising prediction methods to be applied in determining the most effective use of available water for irrigation. In this paper four widely known prediction methods have been calibrated for different climatic conditions. There are descriptions of the extent to which local conditions, including variations in weather, advection, soil and soil-water, agronomic and irrigation practices and production potential, may affect crop water requirements. The application of derived crop water requirements data to determine irrigation requirements and supply schedules for planned irrigation development project is summarized. For the actual operation of schemes and for water application at the field level still more detailed field research data will be required.

The approach presented in this paper was formulated by the FAO Consultative Group on Crop Water Requirements held in Lebanon 1971 and Rome 1972. It is a pleasure to record our appreciation for the continuing advice and assistance received from Drs A. Aboukhaled of Lebanon, C. van den Berg and P.E. Rijtema of the Netherlands, N.G. Dastane of India and J. Damagnez of France. Guidance in outlining the document was received from Dr. O.M. Ashford (WMO) and Mr. M. Frère (FAO). Much help was obtained from an intensive use made of published and unpublished research results collected by leading research institutes located in different geographic and climatic zones; direct contact was established with prominent researchers in Denmark, Ethiopia, France, Haiti, India, Israel, Kenya, Lebanon, Nigeria, the Netherlands, Philippines, Senegal, Sudan, Syrian Arab Republic, Thailand, Tunisia, U.K., U.S.A., Zaire, Venezuela, and with WMO, IAEA and regional FAO offices in the Near East and Asia and the Far East. Within FAO, the preparation of the paper has been the responsibility of the Water Resources, Development and Management Service of the Land and Water Development Division. An impressive contribution in developing the methodologies for determination of crop water requirements was made during his six-month stay in Rome as a FAO Consultant, by Mr. W.O. Pruitt, University of California, Davis, California, U.S.A. and we gratefully acknowledge his invaluable help. Mr. J. Doorenbos acted as coordinator and editor in all stages of the preparation and contributed the chapters dealing with the effect of local conditions and the application of crop water requirements data in planning irrigation projects.

In this paper the main aim has been to gather together from many sources guidance for the field expert. The methodologies presented are considered adequate for preliminary project planning and can be applied to determine average and peak irrigation requirements for project design purposes. Caution and a critical attitude should be adopted and awareness maintained of the extent to which the presented approach is likely to fit local conditions and experience and, conversely, the influence they may exert on the chosen method. It follows that the methods given should never be used on a purely routine basis.

We would welcome comments and suggestions for improvement of the paper and ultimately we hope that a revised and more complete edition may meet the ambitious goal of presenting methods covering all possible conditions where planning the optimum utilization of water in crop production is most essential.

Edouard Saouma
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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. mi	= 2.59 km^2

Volume

1 in^3	= 16.39 cm^3
1 ft^3	= 28316.8 cm^3
1 ft^3	= 28.32 l
1 gallon (US)	= 3.79 l
1 gallon (Imp)	= 4.55 l
1 acre foot	= 1 233.5 m^3

Temperature

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

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	= 2 682 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

Pressure

1 atmosphere	= 76 cm Hg
1 bar	= 1 013 atm
1 inch Hg	= 0.0334 atm
1 inch H_2O	= 2.49 m bar
1 m bar	= 0.75 mm Hg
1 lb/in^2	= 51.72 mm Hg

Radiation

1 inch/day	= 25.4 mm/day
1 $cal/cm^2/min$	= 1 mm/hour (equivalent evaporation)
1 $cal/cm^2/$ day	= 59 mm/day
mW/cm^2	= 0.083 mm/day
$Joule/cm^2/min$	= 14.2 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)

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

Crop coeff. (Chapter 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 (II)

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

Pan method (IV)

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
v. strong	> 8 m/sec	> 700 km/day

For rough estimation purposes sum of several windspeed 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 waters etc.

Radiation

Blaney-Criddle (I)

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 to 0.8; some 40% of daytime hours full cloudiness or partially clouded for 70% of daytime hours.

or

Blaney-Criddle (I)

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.

SUMMARY

This publication is intended to provide guidance to arrive at criteria for irrigation supply in design, construction and operation of irrigation projects. Methods are presented to predict crop water requirements; the effect of local climatic, soil, crop, soil water and agricultural practices is discussed. The use of crop water requirement data to determine irrigation requirements and supplies for overall planning and operation of irrigation projects is given.

It is hoped that the publication will be used by the practising irrigation engineer who is not a meteorologist, a soil physicist or a plant physiologist by training. The working tools presented should not be used on a purely routine basis; to avoid wrong conclusions and unwarranted generalizations, caution and a critical attitude should be maintained when considering whether the derived data can be applied to a particular situation with the scanty information available.

It is recognized that climate, crop, cropping pattern and intensity, environment and exposure, soils, soil water availability, soil fertility, cultivation and irrigation method and practices should all be included in the determination of crop water requirements. Because of the need to determine crop water requirements data prior to irrigation project design and the difficult and time-consuming procedures involved in obtaining direct measurements of water use by crops under field conditions, a large number of crop water requirement prediction methods have been developed. Several of these methods with the input data needed are given in Table 1. Most of them have been tested and used with varying degrees of success. Frequently, however, they are applied under very different agronomic and environmental conditions to those for which they were developed. It is felt that guidance is required for the user of these methods.

The approach presented in this publication was formulated by the FAO Group on Crop Water Requirements during its meetings held in Lebanon in 1971 and Rome in 1972. The application is defined for different climatic conditions of four widely known prediction methods, and these are: Blaney-Criddle, Radiation, Penman and Pan Evaporation. The choice of method should primarily be determined by the type of climatic data available. This approach was selected because it did not prove feasible to analyse the advantages and disadvantages and give general recommendations as to which of the numerous formulae available for estimation of crop water requirements (mentioned in Table 1) should be preferred under certain, but often ill-defined conditions.

In Part I Chapter I.1 the four methods are calibrated against standard reference crop evapotranspiration ETo for a wide range of climates. A definition of ETo is quoted in the Introduction of Part I and is used throughout the publication. Although the choice of method is primarily determined by the type of climatic data available, the methods proposed can be classified according to their level of accuracy for predicting ETo. The Penman and Radiation methods offer the best results for predicting mean crop water requirements for periods as short as 10 days. Depending on the location of the pan, the Pan Evaporation

Table 1 FORMULAE TO ESTIMATE CROP WATER REQUIREMENTS

Formula	Variables														Result
	Temperature	Air Humidity	Dry-wet Bulb	Daylight hrs.	Sunshine hrs/ Cloud Cover	Radiation	Wind Velocity	Evaporimeter	Crop Data	Crop Factor	Soil Factor	Correction Factor	Precipitation	Barograph	
Makkink 1957 Holland	X					X									ETp(grass), monthly.
Blaney-Criddle 1964 USA	X			X						X					CU crop, monthly.
Jensen-Haise 1963 USA	X			(X)	(X)	X				X		(X)			ETp crop and ET crop.
Penman 1948-56 UK	X	X		(X)	(X)	X	X			(X)					Eo or ET crop.
Bouchet	X	X						X				X			ETp crop.
Halkais 1955 USA								X				X			CU crop.
Lowry-Johnson 1942 USA	X											X			ET of valley, entire growing season.
Thornthwaite 1955 USA	X				(X)							X			ET crop, monthly, under 60-70% avail.soil water.
Turc-Langbein 1954 France	X												X		Eo or ET crop, annual river basin.
Sarov USSR	X											X			ET for optimum product.
Haude 1952 Germany			X	(X)			(X)					X			ET crop.
Skvortsov 1950 USSR			X									X			ET crop.
Blaney-Morin 1942 USA	X	X		X						X					ET crop, monthly.
Prescott 1949 USA	X	X	X									X			ETp crop.
Halstead 1951 USA	X	X	X	X											ETp crop.
Rohwer 1931 USA	X	X					X				X			X	ET crop.
Ivanov 1957 USSR	X	X													ET crop under optimum water conditions.
Kostiakov USSR	X	X										X			ET crop.
Turc 1954 France	X	X		X	X	(X)									ET crop.
Hargreaves 1956 USA	X	X		X						X					Eo (A pan) or ET crop.
Turc 1953 France	X					X				X	X		X		ET crop.
Christiansen 1966 USA	X	X			X	X	X					X			Eo (A pan).
Thornthwaite-Mather	X				(X)						X	X	X		ET and water balance.
Munson 1960 USA	X		X			X	X			X		X			PE index, CU.
Walker	X			(X)	X	(X)						X			Eo (A pan) or ET crop.
Olivier 1961 UK	(X)	(X)	X		(X)	X					X		X		Basic water requirements for crop/land unit.
Rijtema 1957 Holland	X	X		(X)	(X)	X	X		X						ETp crop.
McIlroy 1961 Australia	X	X	(X)	(X)	(X)	X	X			X					ETp crop.
Linacre 1967 Australia	X	X		X	X	X	X		X						ET crop.
Van Bavel 1956 USA	X			X	X	(X)						X			ETp crop.
Sverdrup 1952 USA	X	(X)	X				X					X		X	ET per unit surface.

() = when essential parameters are unavailable.

method may be graded next, although this method could be superior for pans with excellent siting and for light winds. In many climates the Blaney-Criddle method is best for periods of one month or more. To reach the relationships presented, use was made of data obtained from many research stations and publications listed in the Appendices. In Chapter I.2 the relationship between crop evapotranspiration ET(crop) and the reference crop ETo is given by crop coefficients kc for the different crops, stages of growth, length of growing season and prevailing climatic conditions. Since ETo is used as the standard reference for the four methods presented, one set of kc values applies to all methods. To arrive at the kc values presented, the sources mentioned in Appendix II were consulted and extensive use was made of published material. Once ETo and kc have been determined for a given period ET(crop) can be found as shown in Chapter I.3. In Chapter I.4, the extent to which local conditions can have an appreciable effect on crop water requirements is given; these include local variations in climate, advection, soil water availability, irrigation methods and practices, agronomic practices and production level.

In Part II, the use of crop water requirement data in determining field irrigation requirements is discussed. Methods are suggested to calculate the variables composing the field water balance, which in turn forms the basis for predicting seasonal and peak field irrigation requirements, and field irrigation schedules. Attention is given to water required to compensate for inefficiency in field application, and for cultural practices and leaching of salts.

In Part III discussions are centred around the use of crop water requirement data to determine seasonal and peak project water supply for the purpose of project planning. Methods are suggested for evaluating field supply schedules while considering different methods of water delivery. Suggestions are also made for applied research which may be necessary and for the refinement of field supply schedules once the project is in operation.

The methods proposed in this publication for determining crop water requirements, field irrigation requirements and irrigation supply are considered adequate for preliminary project planning. It should be realized that local practical, technical, social and economic considerations may have a great effect on the final planning criteria selected.

It will be noted that certain information or calculation procedures are repeated under different headings; this has been done intentionally to maintain continuity or sequence.

Throughout the text or in tables and figures an asterisk indicates the example or calculation being discussed. Abbreviations such as RHmax, ETo and Vs are given on the same line for ease of presentation (i.e. not RH_{max}, ET_o or V_s which is the common practice).

PART I. CALCULATION OF CROP EVAPOTRANSPIRATION, ET (Crop)

INTRODUCTION

It is generally recognized that climate is one of the most important factors determining the amount of water loss by evapotranspiration from the crop. Apart from the climatic factors, evapotranspiration for a given crop is also determined by the crop itself and so are growth characteristics. Local environment, soil and soil water conditions, fertilizers, insect and disease infestations, agricultural and irrigation practices and other factors may also influence growth rates and resulting evapotranspiration.

Methods are used to predict evapotranspiration from climatic variables owing to the difficulty of obtaining accurate direct measurements under field conditions. Most prediction formulae use a differentiation between the components of climate and crop. Such formulae often have to be applied under climatic and agronomic conditions very different to those for which they were originally developed. It is therefore important to test the accuracy of the formulae before using them under a new set of conditions. Not only the degree of accuracy required for predicting evapotranspiration, but also the choice of formula is conditioned by the climatic variables obtaining which must have been measured with sufficient accuracy over a certain number of years.

Testing prediction formulae in a new set of conditions is laborious, time consuming and costly. Yet crop water requirement data are frequently needed at short notice for regional and preliminary project planning and to determine average and peak water requirements for overall irrigation project design. In order to overcome the limitations that different climatic conditions have on the accuracy of the prediction formulae and to disseminate the wealth of information available on the growth characteristics of the crop in relation to crop evapotranspiration, four widely used prediction formulae have been tested against measured evapotranspiration data for different geographic areas and climatic conditions.

The approach followed was to relate magnitude and variation of evapotranspiration to one or more climatic factors (day length, temperature, humidity, wind, sunshine). For this, measured evapotranspiration data from a grass cover were used, assuming that evapotranspiration of grass occurs largely in response to climatic conditions. A reference value, ETo, was introduced and defined as ‘‘the 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’’. Four prediction formulae are presented to calculate ETo, viz.: adaptations of the Blaney-Criddle, the Radiation, the Penman and the Pan Evaporation method. Each method was calibrated against measured ETo data collected from different locations and climates. Choice of method to be used to calculate ETo is primarily based on the type of climatic data available for the area of investigation. Applying one of the four formulae described, ETo can be computed for each 30 or 10 day period using the mean climatic data for the period considered. ETo is expressed in mm per day and represents the mean value over that period. Since for a given climate ETo will vary from year to year, an analysis should be made of magnitude and frequency of extreme values of ETo for which a frequency distribution analysis on ETo may be required.

To know the evapotranspiration of the crop, ET(crop), the relation between ETo and ET(crop) was studied using data from different locations and climates. For the selected crop, its stage of development and prevailing climatic conditions is given by the crop coefficients, kc. ET(crop) is found for a given 30 or 10 day period by ET(crop) = kc ETo. Since the four prediction formulae to calculate ETo have been calibrated against the same reference crop evapotranspiration, the presented crop coefficients apply to each method.

ET(crop) thus determined refers to evapotranspiration of a disease-free crop, growing in a large field (one or more hectares) under optimal soil conditions including sufficient water and fertility and achieving full production potential of that crop under the given growing environment. Local conditions and agricultural practices may have a substantial effect on ET(crop) which might require some correction.

CALCULATION PROCEDURES

Before calculating ET(crop), a review should be made of completed climatological and agricultural surveys and of specific studies and research carried out on crop water requirements in the area of investigation. Available measured climatic data should be reviewed; if possible, meteorological and research stations should be visited and environment, siting, type of instruments and observation and recording practices appraised to evaluate accuracy of available data. Data relevant to types of crops grown, cropping pattern, and agricultural and irrigation practices should be collected.

After this review, the procedure is to determine ET(crop) from available meteorological and crop data.

1. Calculation of reference crop evapotranspiration, ETo

Based on meteorological data available, select prediction method to calculate reference crop evapotranspiration, ETo. If a complete set of meteorological data is available, the choice of method should be based on the required level of accuracy in predicting ETo. The Penman and Radiation method offer the best results for periods as short as 10 days. Depending on the location of the pan, the Pan method may be graded next, although for pans with excellent siting and for light winds, pan data may be superior. In many climates the Blaney-Criddle method is best applied for periods of one month or more. Minimum input data for each method are given below, indicating measured data required and general knowledge of weather needed for each method:

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

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

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; present frequency distribution on ETo.

2. <u>Selection of crop coefficient, kc</u>

   Select crop growing period.
   Determine crop characteristics, time of planting or sowing, rate of crop development, growing period.
   Select crop coefficient, kc, for given crop and stage of crop development under prevailing climatic conditions, and prepare for each a crop coefficient curve.

3. <u>Calculation of crop evapotranspiration ET(crop)</u>

   Calculate for each 30 or 10 day period crop evapotranspiration or
   ET(crop) = kc ETo.

4. <u>Consideration of factors affecting ET(crop) under prevailing local conditions</u>

   Determine effect of climate and its variability over time and space on ET(crop).
   Determine the effect of soil water availability on ET(crop).
   Determine the effect of agricultural and irrigation practices on ET(crop).
   Consider relationship between ET(crop) and level of crop production.

CHAPTER I.1 CALCULATION OF REFERENCE CROP EVAPOTRANSPIRATION, ETo

METHOD I - BLANEY-CRIDDLE

The Blaney-Criddle equation (1950) is one of the most widely used methods to estimate crop water requirements. An adaptation of this method is suggested to calculate the reference crop evapotranspiration, ETo, for areas where only measured air temperature data are available.

The original Blaney-Criddle approach involves temperature, t, and percentage of daytime hours, p, as climatic variables to predict the effect of climate on evapotranspiration. This is called the consumptive use factor f, whereby $f = 25.4\ (p \times t)/100$ when temperature is in degree Fahrenheit (^{o}F) and p is the percentage of annual daylight hours which occur during the period considered, or $f = p\ (0.46\ t + 8.13)$ when temperature is in degree Celsius (^{o}C). An empirically determined consumptive use crop coefficient (K) is then applied to establish the consumptive water requirement. Consumptive water requirement is defined as ''the amount of water potentially required to meet the evapotranspiration needs of vegetative areas so that plant production is not limited from lack of water''.

Crop water requirements will however vary widely between climates having similar air temperature; for example, between very dry and very humid climates, or between generally calm and very windy conditions. The effect of climate on crop water requirements is thus not fully defined by the temperature and day length related f factor alone. Consequently the consumptive use crop coefficient K will need to vary not only with the crop but also with climatic conditions. The value of K is thus very much time and place dependent and local field experiments are normally required to determine the value for K.

In order to define better the effect of climate on crop water requirements but still applying the original consumptive use factor f, for this publication, the factor f was calculated for a large number of locations and different climates. In addition to temperature for these locations, humidity, sunshine and wind data were available as well as grass evapotranspiration data locally measured. Relationships were developed between the Blaney-Criddle f factor and reference crop (grass) evapotranspiration ETo taking into account general levels of humidity, sunshine and wind. The results are shown in Figure 1.

Having calculated the f factor for a given location using temperature and day length data, the value of ETo can then be determined graphically from Fig. 1. Since general levels of humidity, wind and sunshine are to be considered, an improved prediction of the effect of climate on evapotranspiration should be obtainable.

Recommended relationships

The Blaney-Criddle factor f in mm is expressed as

$$f = p\ (0.46\ t + 8.13) \qquad \text{using } ^{o}C$$

or

$$f = 25.4\ \frac{p \times t}{100} \qquad \text{using } ^{o}F$$

where t is the mean of the daily maximum and minimum temperature in ^{o}C or ^{o}F over the month considered; p is the mean daily percentage of annual daytime hours obtained from Table 2 for a given month and latitude. Factor f is expressed in mm per day and represents the mean value over the given month.

For the Blaney-Criddle f values thus determined, Figure 1 depicts recommended relationships to determine ETo estimates. The value of f is given on the X-axis and the value of ETo can be read from the Y-axis. Relationships are presented in Fig. 1 for three levels of daytime minimum humidity (RHmin) and three levels of the ratio actual to maximum possible sunshine hours (n/N). Additionally, relationships are given for three ranges of daytime wind conditions (U) at 2 metre height. Information on general weather conditions, including RHmin, n/N and U_2 may be obtained from published weather descriptions or from local sources.

The nomenclature used to depict general levels of humidity, sunshine and wind is given under Climatological Nomenclature in the introductory pages of this publication.

Several selected relationships would normally be required for the same location since one or more of the three climatic variables considered would probably show major changes according to season. Also the combination of weather conditions selected for Fig. 1 may require interpolation between the relationships given. For example, the dotted line in Fig. 1, Block II involves light to moderate wind.

Since factor f is expressed in mm per day ETo is also expressed in mm per day and represents the mean daily value of the period considered, which is usually one month. To find monthly ETo in mm, the value needs to be multiplied by the number of days of each month.

After determining ETo from Fig. 1, ET(crop) can be predicted using the appropriate crop coefficient kc, or ET(crop) = kc x ETo. Crop coefficients are given in Chapter I.2.

Additional considerations

The adaptation of the Blaney-Criddle method presented should only be used when temperature data are the only specific weather data available. The empiricism involved in any ET prediction method using a single weather factor is inevitably high. Only for weather conditions similar in nature does a generally positive correlation seem to exist between Blaney-Criddle f values and ETo. As shown in Fig. 1, the relation between factor f and ETo therefore varies widely between climates, for example, very dry as compared to very humid climates, or between light and strong winds.

In this publication the use of crop coefficients (K) normally employed in the original Blaney-Criddle approach is rejected because: (i) the original crop coefficients (K) are heavily dependent on local conditions, and the wide variety of K values reported in literature makes the selection of this value rather difficult; (ii) the relationship between Blaney-Criddle f values and ETo can be adequately described for a wide range of temperatures for areas having only minor variations in RHmin, n/N and U; and (iii) once ETo has been determined by each of the methods proposed, one set of crop factors (kc) can be used to determine ET(crop).

The use of the Blaney-Criddle method to calculate mean daily ETo should normally be applied for periods no shorter than one month. Unless verification of the general prevailing weather conditions (RH(min), n/N, and U_2) can be obtained, predictions are obviously highly questionable. Considerable care is thus needed in the use of this method since for a particular month n/N may vary greatly from year to year and consequently ETo. Hence, it is suggested that ETo should be calculated for each calendar month for each year of record rather than by using mean temperatures based on several years' records.

This method should not be used in equatorial regions where temperatures remain fairly constant but other weather parameters will change. It should not be used either for small islands where air temperature is generally a function of the surrounding sea temperature showing little response to seasonal change in radiation. At high altitudes the approach becomes uncertain due to the fairly low mean daily temperature (cold nights) even though daytime radiation levels are high. Also in climates with a high variability in sunshine hours during transition months (e.g. monsoon climates, mid-latitude climates during spring and autumn) the method could be misleading.

Sample calculations

First using mean daily temperature and daylength data for one month only, an example provides the necessary simple calculation procedure to obtain the mean daily value of $f = p(0.46\ t + 8.13)$ in mm for the given month. Then mean daily data for each month and for the whole year are given to illustrate the selection of relationships between prevailing weather conditions and of the value of ETo for each month using Fig. 1. ETo can be determined graphically or by machine calculations using coefficients indicated for each relationship shown. A format for the necessary calculation procedures is given at the end of this sub-chapter.

Figures and tables to be used:

Fig. 1	Prediction of ETo from Blaney-Criddle f factor for different conditions of relative humidity, daily sunshine hours and daytime wind.
Tab. 2	Mean daily percentage of annual daytime hours for different latitudes.

EXAMPLE:

given: Cairo, Arab Republic of Egypt;
latitude: 30° N
altitude: 95 m

month		July
tmax	Σ tmax daily values/31	35°C
tmin	Σ tmin daily values/31	22°C
tdaily mean =	$\frac{\Sigma \text{tmean}}{31}$ or $\left[\frac{\Sigma \text{tmax}}{31} + \frac{\Sigma \text{tmin}}{31}\right] \div 2$	28.5°C
p	select from Table 2 for 30°N	0.31
$f = p(0.46\ t + 8.13)$	$0.31\ (0.46 \times 28.5 + 8.13)$	6.6 mm/day
RH(min)	from Climates of Africa, Griffith (1972) Table XXVIII	35% (medium)
n/N		> 0.8 (high)
U_2 daytime	from Rijtema and Aboukhaled (1973)	3 m/sec (moderate)
ETo	Fig. 1 - Block II	8.1 mm/day

Based on general information and references (Climates of Africa, Griffith 1972) the following breakdown for Cairo can be made:

	RH(min)	n/N	U_2 daytime	Block	Line
Jan - March	Medium	Medium	Light to moderate	V	2
April - May	Low to medium	High to medium	Moderate	(IV, V, I & II) 1/	2
June - July	Medium	High	Moderate	II	2
Aug - Sept	Medium	High	Light to moderate	II	1 - 2
Oct - Dec	Medium	Medium	Light to moderate	V	1 - 2

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
tmean °C		15	17.5	21	25.5	27.5	28.5	28.5	26	24	20	15.5
pmean	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+8.13)	3.5	3.8	4.4	5.1	6.1	6.6	6.6	6.3	5.6	5.0	4.2	3.5
ETo mm/day	2.3	2.6	3.4	5.8 1/	7.3 1/	8.1	8.1	6.9	5.9	4.2	3.2	2.3

1/ Borderline RH(min) and n/N conditions suggest a compromise between Blocks $\begin{array}{c|c} IV & V \\ \hline I & II \end{array}$, using curve 2 for moderate wind in all cases.

April (f = 5.1 mm) $\begin{array}{c|c} 5.8 & 4.8 \\ \hline 6.9 & 5.7 \end{array}$ or ETo = 5.8 mm/day

May (f = 6.1 mm) $\begin{array}{c|c} 7.4 & 6.2 \\ \hline 8.7 & 7.3 \end{array}$ or ETo = 7.4 mm/day

If machine calculation is used, expressions are presented which directly predict reference evapotranspiration ETo for mean dail percentage of annual daytime hours (p) and mean daily temperature (t).

or $ETo = \underline{a} + \underline{b} \, [p \, (0.46 \, t + 8.13)]$

Values of a and b for different combinations of RH(min) n/N and U_2 are given in Fig. 1.

EXAMPLE:

given: Cairo;

latitude: 30°N

altitude: 95 m

Jan - Mar	$ETo = -2.17 + 1.29 \, [p \, (0.46 \, t + 8.13)]$ 1/
Apr - May	$ETo = -2.25 + 1.59 \, [p \, (0.46 \, t + 8.13)]$ 2/
June - July	$ETo = -2.50 + 1.61 \, [p \, (0.46 \, t + 8.13)]$
July	$ETo = -2.50 + 1.61 \, [0.31 \, (0.46 \times 28.5 + 8.13)] = 8.1$ mm/day
Aug - Sept	$ETo = -2.45 + 1.49 \, [p \, (0.46 \, t + 8.13)]$ 1/
Oct - Dec	$ETo = -2.17 + 1.29 \, [0.46 \, t + 8.13)]$ 1/

1/ interpolation for wind speed of around 2 m/sec (light to moderate)

2/ average of constants in 4 equations, curve 2 in Blocks I, II, IV and V

Table 2 MEAN DAILY PERCENTAGE (p) OF ANNUAL DAYTIME HOURS FOR DIFFERENT LATITUDES

Latitude North South 1/	Jan July	Feb Aug	Mar Sept	Apr Oct	May Nov	June Dec	July Jan	Aug Feb	Sept Mar	Oct Apr	Nov May	Dec 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.

Table 2a

VALUE OF BLANEY-CRIDDLE f VALUE FOR DIFFERENT TEMPERATURES AND DAILY PERCENTAGE OF ANNUAL DAYLIGHT HOURS

t°C p%	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
.14	1.1	1.3	1.4	1.5	1.7	1.8	1.9	2.0	2.2	2.3	2.4	2.6	2.7	2.8	2.9	3.0	3.2	3.3	3.5	3.6	3.7
.16	1.3	1.4	1.6	1.7	1.9	2.0	2.2	2.3	2.5	2.6	2.8	2.9	3.1	3.2	3.4	3.5	3.7	3.8	4.0	4.1	4.2
.18	1.5	1.6	1.8	2.0	2.1	2.3	2.5	2.6	2.8	3.0	3.1	3.3	3.5	3.6	3.8	3.9	4.1	4.3	4.4	4.6	4.8
.20	1.6	1.8	2.0	2.2	2.4	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.8	4.0	4.2	4.4	4.6	4.8	4.9	5.1	5.3
.22	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6	5.8
.24	2.0	2.2	2.4	2.6	2.8	3.1	3.3	3.5	3.7	3.9	4.2	4.4	4.6	4.8	5.0	5.3	5.5	5.7	5.9	6.1	6.4
.26	2.1	2.4	2.6	2.8	3.1	3.3	3.5	3.8	4.0	4.3	4.5	4.7	5.0	5.2	5.5	5.7	5.9	6.2	6.4	6.7	6.9
.28	2.3	2.5	2.8	3.0	3.3	3.6	3.8	4.1	4.3	4.6	4.9	5.1	5.4	5.6	5.9	6.1	6.4	6.7	6.9	7.2	7.4
.30	2.4	2.7	3.0	3.3	3.5	3.8	4.1	4.4	4.6	4.9	5.2	5.5	5.8	6.0	6.3	6.6	6.9	7.1	7.4	7.7	8.0
.32	2.6	2.9	3.2	3.5	3.8	4.1	4.4	4.7	5.0	5.3	5.5	5.8	6.1	6.4	6.7*	7.0	7.3	7.6	7.9	8.2	8.5
.34	2.8	3.1	3.4	3.7	4.0	4.3	4.6	5.0	5.3	5.6	5.9	6.2	6.5	6.8	7.1	7.5	7.8	8.1	8.4	8.7	9.0
.36	2.9	3.3	3.6	3.9	4.3	4.6	4.9	5.2	5.6	5.9	6.2	6.6	6.9	7.2	7.6	7.9	8.2	8.6	8.9	9.2	9.6
.38	3.1	3.4	3.8	4.1	4.5	4.8	5.2	5.5	5.9	6.2	6.6	6.9	7.3	7.6	8.0	8.3	8.7	9.0	9.4	9.7	10.1
.40	3.3	3.6	4.0	4.4	4.7	5.1	5.5	5.8	6.2	6.6	6.9	7.3	7.7	8.0	8.4	8.8	9.1	9.5	9.9	10.2	10.6
.42	3.4	3.8	4.2	4.6	5.0	5.3	5.7	6.1	6.5	6.9	7.3	7.7	8.1	8.4	8.8	9.2	9.6	10.0	10.4	10.8	11.1

FORMAT FOR CALCULATION OF BLANEY-CRIDDLE METHOD

DATA	Country: U.A.R Period : July 1972	Place: Cairo	Latitude : 30 °N Longitude: 30°	Altitude: 95 m	
t mean =28.5°C	t mean	data	28.5		
latitude = 30 °N	p	Table 2	0.31		
	f	Table 2a		6.6	
RH (min) =(35) %		estimate	med		
n/N =(0.83)		estimate	high		
U_2 daytime =(3) m/sec		estimate	mod.		
		Fig. 1	Block/line	II ⋮ 2	
		Fig. 1		ETo	8.1 mm/day

FORMAT FOR CALCULATION OF BLANEY-CRIDDLE METHOD

DATA	Country: Period :	Place:	Latitude : Longitude:	Altitude: m	
t mean = °C	t mean	data			
latitude = °	p	Table 2			
	f	Table 2a			
RH (min) = %		estimate			
n/N =		estimate			
U_2 daytime = m/sec		estimate			
		Fig. 1	Block/line	⋮	
		Fig. 1		ETo	mm/day

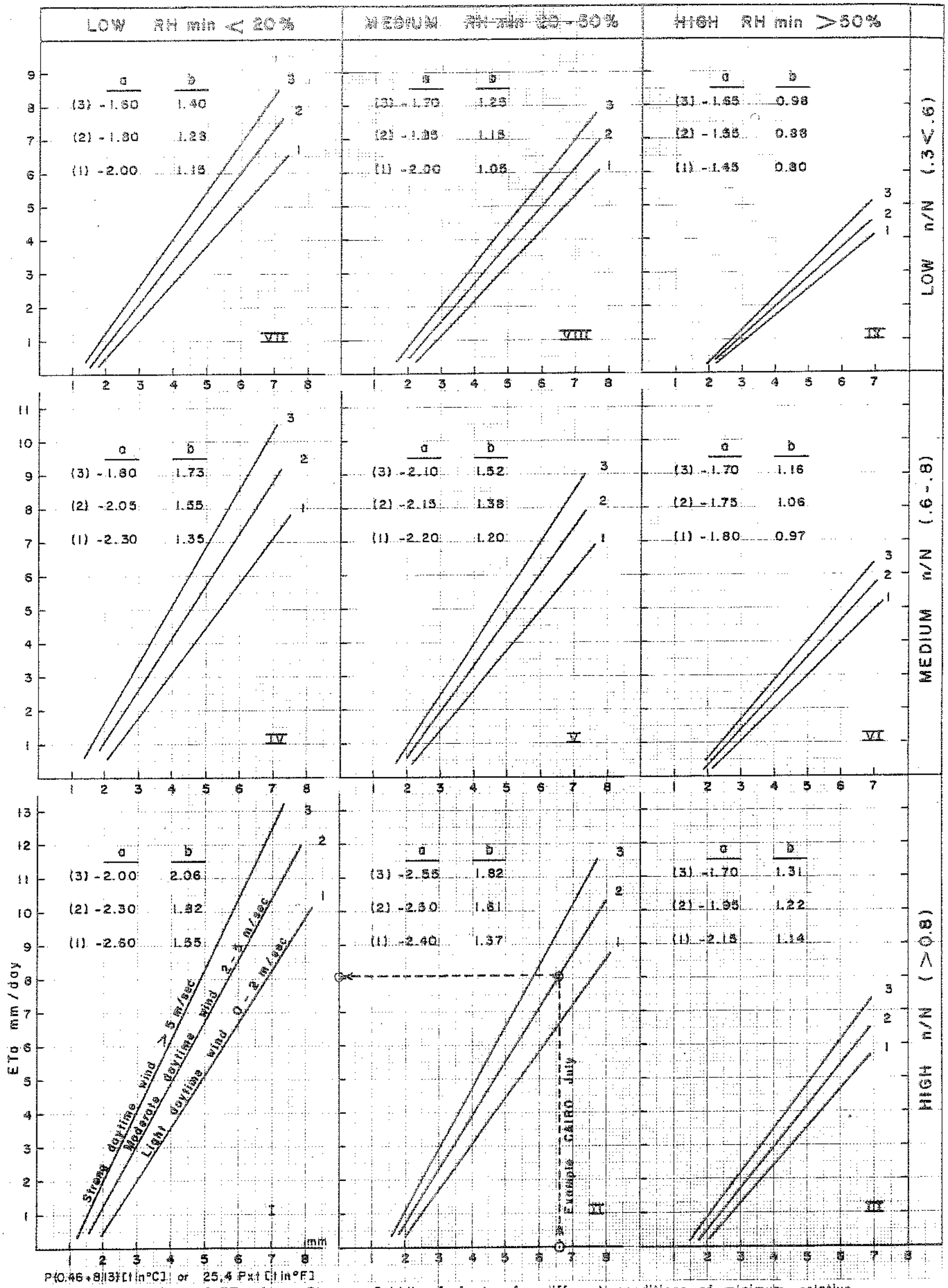

Fig. 1 Prediction of ETo from Blaney - Criddle f factor for different conditions of minimum relative humidity, daily sunshine hours, and daytime wind.

METHOD II - RADIATION

For areas where available climatic data include measured air temperature and sunshine or cloudiness or radiation, but not wind and humidity, the radiation method is suggested to predict the effect of climate on crop water requirements. Direct measurement of the duration of bright sunshine hours or if not available, cloud observations can be used to obtain a measure of solar radiation. In addition, only general levels of humidity and wind are required and such information may be obtained from published weather descriptions or from local sources.

The method predicts the effect of climate on crop water requirements. For this publication the radiation formula was calculated for a large number of locations and different climates. For these locations, apart from measured data on temperature and solar radiation, wind and humidity data were also available, as well as locally measured grass evapotranspiration data. Relationships were developed between the radiation term and reference crop (grass) evapotranspiration, ETo, taking into account humidity and wind conditions. The result is shown in Figure 2.

Results from the Radiation Method should be more reliable than those from the Blaney-Criddle approach outlined earlier. In fact, in equatorial zones, on small islands, or at high elevations, the radiation method should be more reliable even if measured bright sunshine or cloudiness data are not available, in which case data from solar radiation maps prepared for most locations in the world would provide the necessary solar radiation data. 1/

Recommended relationships

The relationship suggested to calculate reference crop evaporation ETo from temperature and radiation data is:

$$ETo = a + b.W.\ Rs$$

where ETo is reference crop evapotranspiration in mm/day and represents the mean value over the period considered, i.e. 30 or 10 days, Rs is the solar radiation expressed in equivalent evaporation in mm/day, and W a weighting factor which depends on temperature and altutude; a and b are coefficients for which the values are given in Fig. 2. The relationships presented in Fig. 2 between the radiation terms W.Rs and ETo take into account general weather conditions, notably mean relative humidity and daytime wind. From available measured data on temperature and radiation the radiation term W.Rs is calculated first. For the prevailing conditions of mean relative humidity and daytime wind the value of the radiation term if given in Fig. 2 on the X-axis and the value of ETo can be read from the Y-axis. Both are expressed in mm/day and represent the mean value for the period concerned.

1/ See for instance Solar Radiation and Radiation Balance Data; routine observations for the whole world published under WMO auspices in Leningrad, U.S.S.R.
WMO, Data of the Intern. Geoph. Year, Forms E1, E2 and E3.
J.N. Black (1956). Distribution of solar radiation over the earth's surface.
J.F. Griffith (1971). World Survey of Climatology, Elsevier.

The following procedure is suggested to calculate values of solar radiation Rs and weighting factor W and to select the appropriate relationship between W.Rs and ETo.

i) Solar radiation, Rs

Solar radiation Rs is only a portion of the radiation received at the top of the atmosphere. The latter is referred to as extra-terrestrial radiation Ra. It is a function of latitute and time of the year only and hence can be calculated without reference to weather conditions. Values of Ra can be expressed in equivalent evaporation in mm/day which is a measure of the intensity of radiation; converted into heat it can be related to the energy required to evaporate water from an open surface. 1/ Values of Ra for different latitudes and times of the year are given in Table 3. Only a portion of the extra-terrestrial radiation received at the outer atmosphere penetrates to the earth's surface since a part is scattered and absorbed when passing through the atmosphere. The radiation received at the earth's surface is referred to here as solar radiation, Rs.

Solar radiation can be measured directly but recording is generally restricted to main agricultural stations and research centres. Frequently such data is not available for the area of investigation. However, solar radiation can be adequately predicted from available bright sunshine duration records or from cloudiness observations. From sunshine data, solar radiation can be derived as follows:

$$Rs = (0.25 + 0.50\ n/N)\ Ra$$ 2/

where n/N is the ratio between actual to maximum possible bright sunshine hours. Values of N for different months and latitudes are given in Table 4. Observations on daily bright sunshine hours n using, for instance, the Campbell Stokes sunshine recorder, should be made locally. Both n and N are expressed in mean daily value, hours, and Rs is obtained in mean equivalent evaporation in mm/day for the period considered.

EXAMPLE:

Given:	Cairo; July; latitude 30^{o}N sunshine n, mean = 11.5 hr/day
Calculation:	extra-terrestrial radiation Ra for latitude 30^{o} N and month of July from Table 3 is 16.8 mm/day Value of N for latitude 30^{o}N and month of July from Table 4 is 13.9 hr/day Solar radiation Rs from Ra = 16.8 mm/day, N = 13.9 hr/day and n = 11.5 hr/day is (0.25 + 0.50 x 11.5/13.9) 16.8 = 11.2 mm/day

Cloudiness observations can be used to calculate solar radiation. Several daily visual observations of cloud cover are needed for a sufficiently long period. Cloudiness is expressed either in tenths (0 to 10) or in oktas (0 to 8) which must first be converted to

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1/ Radiation can be measured in several units. For equivalent evapotranspiration mm/day see Conversion Factors in the introductory pages.

2/ For practical purposes values of 0.25 and 0.50 can be used. For some regions locally determined values have been determined and are listed in Appendix IV.

the n/N ratio. To shorten correlations between cloudiness and solar radiation, for some areas the direct relationship between cloudiness and the ratio Rs/Ra has been established (Frère and Rijks, 1974):

Cloudiness - oktas	0	1	2	3	4	5	6	7	8
Humid equatorial highlands, Rs/Ra	.66	.62	.59	.56	.52	.49	.46	.42	.39
Semi-arid climate, Rs/ Ra	.70	.67	.64	.61	.58	.56	.53	.50	.46

Values of Ra for a given latitude and time of the year can be obtained from Table 3. However, it is preferable to use locally derived data on the relationship between cloudiness and sunshine. Sometimes sky observations are made which are expressed in four classes; conversion is approximately: clear day = 1 okta, partial cloud = 3 oktas, clouds = 6 oktas, overcast = 8 oktas. The conversion of the visual observations of cloudiness into equivalent values of n/N can be obtained from the following table. Scatter in conversion factors from location to location has been noted which indicates a degree of inaccuracy when using cloudiness data for obtaining daily bright sunshine hours.

Cloudiness (tenths)	0	.2	.4	.6	.8	Cloudiness (oktas)*	0	.2	.4	.6	.8
0	.95	.9	.9	.9	.9	0	.9	.9	.9	.85	.85
1	.85	.85	.85	.85	.8	1	.85	.85	.8*	.8	.8
2	.8	.8	.8	.75	.75	2	.75	.75	.75	.7	.7
3	.75	.7	.7	.7	.65	3	.65	.65	.65	.6	.6
4	.65	.65	.6	.6	.6	4	.55	.55	.5	.5	.45
5	.55	.55	.5	.5	.5	5	.45	.4	.4	.35	.35
6	.5	.45	.45	.4	.4	6	.3	.3	.25	.25	.2
7	.4	.35	.35	.3	.3	7	.15	.15	-	-	-
8	.3	.25	.25	.2	.2						
9	.15	.15	.15	-	-						
10	-	-	-	-	-						

* oktas: a scale where 8.0 is full cloudiness

EXAMPLE:

Given:	Latitude 34^{o} S, month of June Cloudiness, oktas = 1.4
Calculation:	Extra-terrestrial radiation Ra for latitude 34^{o} S for month of June from Table 3 is 6.8 mm/day Value of n/N for cloudiness equal to 1.4 oktas from table above or locally determined conversion factor is 0.8 Solar radiation Rs for Ra = 6.8 mm/day and ratio n/N = 0.8 is (0.25 + 0.50 x 0.8) 6.8 = 4.4 mm/day

ii) Weighting factor, W

The weighting factor W includes the effect of temperature and elevation in the relation between the radiation received on the earth surface, Rs, and reference crop evapotranspiration, ETo 1/. Values of W as related to temperature and altitude are given in Table 6. Temperature reflects the mean temperature in °C for the period considered. Where temperature is given as tmax and tmin, the temperature to be used equals (tmax + tmin)/2.

EXAMPLE:

Given:	Cairo; altitude 95 m tmean 28.5°C
Calculation:	from Table 6 for altitude = 95 m and tmean = 28.5°C the value of W is equal 0.77

Prediction of reference crop evapotranspiration, ETo

As shown in Fig. 2, the relationship between the radiation term W.Rs and reference crop evapotranspiration, ETo, depends greatly on climate. The relationship between W.Rs and ETo is given in Fig. 2 for four general levels of mean relative humidity and four levels of daytime wind (07.00 - 19.00 hr).

The nomenclature used to depict general levels of mean humidity and daytime wind is given in the Table of Climatic Nomenclature at the beginning of the publication.

After calculating the radiation term W.Rs and selecting the appropriate humidity and wind conditions, the value of ETo can be determined graphically using Fig. 2. The value of W.Rs is given on the X-axis and the value of ETo is given in the Y-axis. They are expressed in mm/day and represent the mean daily value for the period considered.

EXAMPLE:

Given:	Cairo; July; latitude 30°N; altitude 95 m,	
	tmean:	28.5°C
	Sunshine n mean:	11.5 hr
	Wind daytime:	moderate (some 3m/sec)
	Rel. humidity mean:	medium (some 55%)

Calculation: For given condition solar radiation Rs = 11.2 mm/day and weighting factor W = 0.77 or W.Rs is equal 8.6 mm/day
With mean relative humidity equal to 55% Blocks II and III of Fig. 2 should be used. For W.Rs equal 8.6 mm/day on X-axis, from Y-axis the ETo value read is respectively 8.0 and 7.3 mm/day or average is 7.7 mm/day 2/.

Additional considerations

Specific conditions of wind and humidity are not included and only general levels of these two climatic variables are considered. Except for equatorial regions, the amount of radiation received at the earth's surface, Rs, varies considerably from season to season and for each season from year to year. The radiation method suggested must of necessity remain empirical in nature. One distinct advantage of this approach to the Blaney-Criddle is that, with the inclusion of calculated or measured radiation and with a partial consideration of temperature, only general levels of daytime wind and mean relative humidity need to selected.

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/ Instead of obtaining the value of ETo by graphical means, machine calculation can also be used. ETo can be calculated selecting the appropiate b value from general knowledge of RH mean and daytime wind or ETo = a + b.W.Rs. The value of a is in all cases - 0.3. In the above example ETo = - 0.3 + $\underline{0.88 + 0.98}$ x 8.6 = 7.7 mm/day.

The analysis of data from a wide range of climates has shown that no additional breakdown into general levels of temperature is needed as long as mean relative humidity is used rather than the minimum relative humidity as in the Blaney-Criddle formula. The inclusion of the weighting factor W appears furthermore to remove the seasonal cycling effect that normally exists between ETo and solar radiation Rs. For similar conditions of daytime wind and mean relative humidity, a good correlation was shown to exist between measured ETo and W.Rs for a wide range of temperature conditions.

Since climatic conditions for each month or shorter period vary from year to year and consequently ETo, it is suggested that ETo be calculated for each month or period for each year of record rather than use mean radiation and mean temperature data based on several years of record. A higher value of ETo than is obtained by using mean data may have to be selected to ensure that water requirements will be met with a high degree of certainty.

As mentioned before, the method is considered more reliable than the Blaney-Criddle approach, particularly in equatorial regions, on small islands and at high elevations. Even if measured radiation, sunshine data or cloudiness observations are not available, the radiation data should be obtainable from solar radiation maps.

Sample calculations

An example provides the necessary calculation procedure to obtain the mean daily value of ETo = a + b W.Rs in mm for the whole month by using mean daily temperature and sunshine hour data. Then mean daily data for each month for the whole year are given to illustrate the selection of relationships between prevailing humidity and wind conditions and of the value of ETo for each month using Fig. 2. In the latter case measured solar radiation and temperature data are available. As is shown, ETo can be determined graphically or by machine calculations using a and b coefficients indicated for each relationship shown. A format for the necessary calculation procedures is given at the end of this sub-chapter.

Figures and tables to be used:

Number	Variable	Description	Input data
Fig. 2	ETo	Relationship for obtaining ETo from calculated values of W.Rs and general knowledge of mean relative humidity and daytime wind	W.Rs humidity wind sunshine
Tab. 3	Ra	Extra-terrestrial radiation Ra in equivalent evaporation in mm/day for different months of the year and latitude	Latitude month
Tab. 4	N	Maximum possible sunshine duration in hours (N) for different months of the year and latitude	Latitude month
Tab. 5	Rs	Conversion factor for extra-terrestrial radiation Ra to solar radiation Rs for different ratios of actual to maximum possible sunshine hours (0.25 + 50 n/N)	n/N
Tab. 6	W	Values of weighting factor W for the effect of radiation on ETo at different temperatures and altitudes	$t^{o}C$ altitude

EXAMPLE:

Calculation of mean daily ETo in mm/day for given month from measured temperature and bright sunshine data and general levels of mean relative humidity and daytime wind.

Given: Cairo; July; latitude 30°N; altitude 95 m

tmean = 28.5°C
Sunshine n mean = 11.5 hr
Wind, daytime, U2 = moderate (3 m/sec)
Rel. humidity mean = medium (55%)

Calculation:

Ra extra-terrestrial radiation	lat. 30°N	July	Table 3	Ra = 16.8 mm/day
Rs solar radiation Rs = (0.25 + 0.50 n/N) Ra 1/ = c.Ra	lat. 30°N	July	data Table 4 calc Table 5 calc	n = 11.5 hr/day N = 13.9 hr/day n/N = 0.83 c = 0.67 Rs = 11.2 mm/day
W temperature correction on Rs	tmean = 28.5°C altitude = 95 m		Table 6	W = 0.77
W.Rs radiation term			calc	W.Rs = 8.6 mm/day
ETo reference crop evapotranspiration ETo = a + b.W.Rs	wind = mod. RH = med.		Fig. 2 Blocks II & III curve 2	ETo = 7.7 mm/day

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1/ If measured sunshine data is not available, n/N can be obtained from visual cloudiness observation. 0.25 and 0.50 represent averages; for local coefficients see Appendix IV. If available, of course, use measured solar radiation data.

EXAMPLE:

Calculation of mean monthly ETo data based on measured temperature and solar radiation data and approximate levels of daytime wind and mean relative humidity.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
tmean °C	14	15	17.5	21	25.5	27.5	28.5	28.5	26	24	20	15.5
Rs, mm/day	4.96	6.41	8.52	9.85	10.86	11.41	11.24	10.43	9.11	7.12	5.45	4.55
W	.61	.62	.65	.70	.74	.76	.77	.77	.75	.73	.68	.63
W.Rs	3.02	3.97	5.54	6.89	8.04	8.67	8.65	8.03	6.83	5.24	3.71	2.87
Approx. RH mean	III	III	III	II	II	II	av.II & III	av.II & III	III	III	av.III & IV	av.III & IV
Approx. wind	av. 1 & 2	av. 1 & 2	2	2	2	2	2	av. 1 & 2	av. 1 & 2	av. 1 & 2	av. 1 & 2	av. 1 & 2
ETo mm/day	2.1	2.9	4.6	6.4	7.5	8.2	7.7	6.6	5.3	4.0	2.5	1.9

If machine calculation is used, expressions are presented which directly predict ETo from W.Rs. Values of b for different ranges of RH mean and wind are given in Fig. 2. In all cases a = -0.3.

Cairo

June, ETo = -0.3 + 0.98 W.Rs = 8.2 mm/day

July, ETo = -0.3 + 0.93 W.Rs = 7.7 ,, 1/

August, ETo = -0.3 + 0.86 W.Rs = 6.6 ,, 2/

1/ 0.93 = average b for curve 2, Blocks II & III

2/ 0.86 = average b for curves 1 & 2, Blocks II & III

Table 3

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 4

MEAN DAILY MAXIMUM DURATION OF BRIGHT SUNSHINE HOURS N FOR DIFFERENT MONTHS AND LATITUDES

Northern Lats	Jan.	Feb.	March	April	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	12.9	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 5 CONVERSION FACTOR FOR EXTRA-TERRESTRIAL RADIATION Ra TO SOLAR RADIATION Rs FOR DIFFERENT RATIOS OF ACTUAL TO MAXIMUM POSSIBLE SUNSHINE HOURS (0.25 + 0.50 n/N)

n/N	0.0	0.05	.1	.15	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85	.9	.95	1.0
0.25 + 0.50 n/N	.25	.28	.30	.33	.35	.38	.40	.43	.45	.48	.50	.53	.55	.58	.60	.63	.65*	.68	.70	.73	.75

Table 6 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

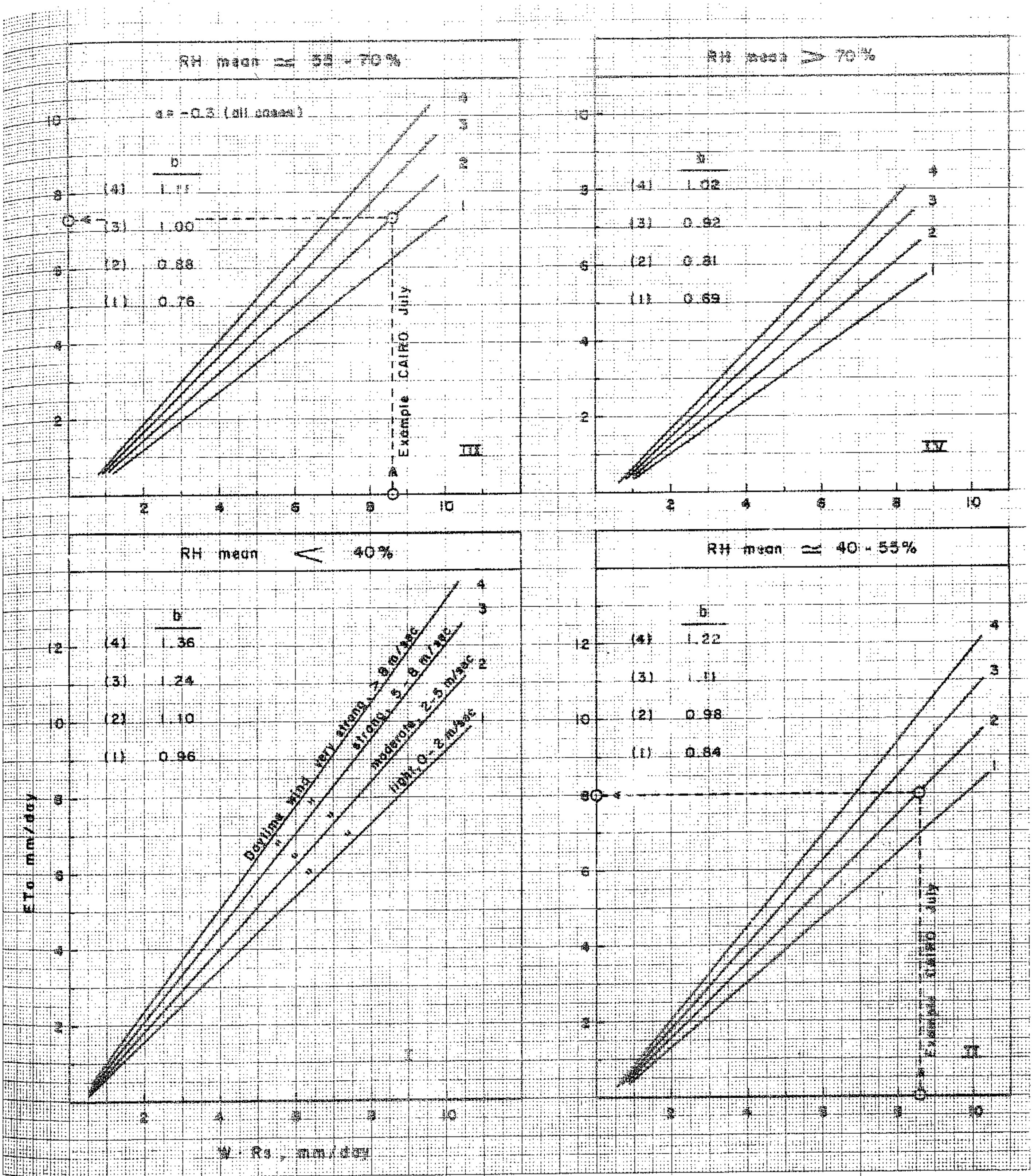
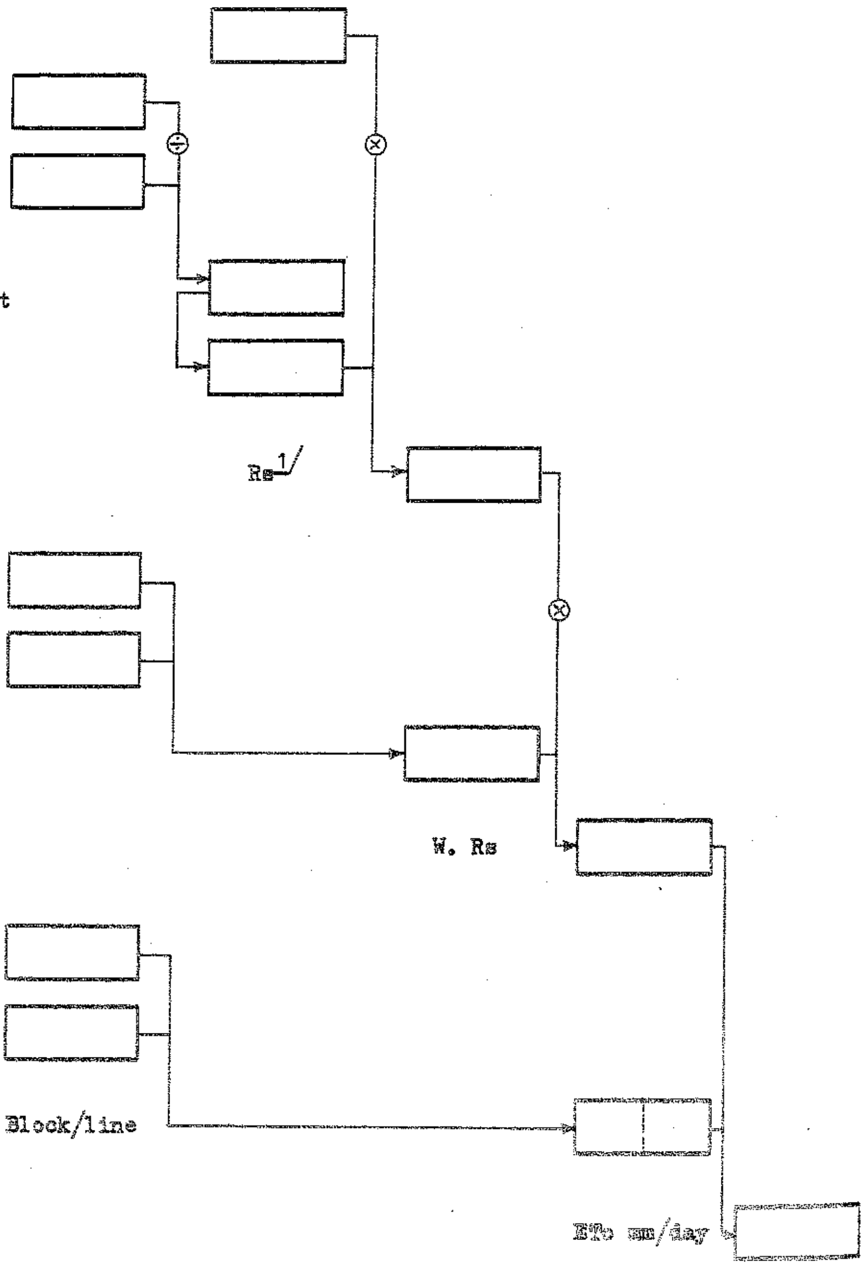


Fig. 2 Relationships for obtaining ETo from calculated values of W·Rs and general knowledge of mean relative humidity and daytime wind.

FORMAT FOR CALCULATION OF RADIATION METHOD

DATA	Country: Period:	Place:	Latitude: Longitude:	Altitude: m
latitude = °	Ra mm/day	Table 3		
n mean = hr	n	data		
	N	Table 4		
or cloudiness	n/N	calc or Table text		
	0.25+0.50 n/N	Table 5		
		calc	Rs 1/	
altitude = m				
t mean = °C				
	W	Table 6		
		calc		W. Rs
RH mean = %		estimate		
U_2 daytime = m/sec		estimate		
		Fig. 2 Block/line		
		Fig. 2		ETo mm/day



1/ or from solar radiation maps

FORMAT FOR CALCULATION OF RADIATION METHOD

DATA	Country: U.A.R. Place : July 1972	Place: Cairo			Latitude : 30°N Longitude: 30°		Altitude: 95 m
latitude = 30 °N	Ra mm/day	Table 3		16.8			
n mean = 11.5 hr	n	data	11.5				
	N	Table 4	13.9				
or cloudiness	n/N	calc or Table text		0.83			
	0.25+0.50 n/N	Table 5		0.67			
		calc		Rs[1]	11.2		
altitude = 95 m			95				
t mean = 28.5 °C			28.5				
	W	Table 6			0.77		
		calc			W. Rs	8.6	
RH mean = 55 %		estimate	Med				
U_2 daytime = 3 m/sec		estimate	Mod.				
		Fig. 2	Block/line			II+III	2
		Fig. 2				ETo mm/day	7.7

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[1] or from solar radiation maps

METHOD III - MODIFIED PENMAN

For areas where measured data on temperature, humidity, wind and bright sunshine hours or radiation are available, the modified Penman method is suggested since it is likely to provide the most satisfactory results to predict the effect of climate on crop water requirements.

The original Penman (1948) equation predicted the loss of water by evaporation from an open water surface, Eo. Experimentally determined crop coefficients ranging from 0.6 in winter months to 0.8 in summer months were suggested to relate Eo to crop evapotranspiration for the climate in England. The Penman equation consists of two terms, namely the energy (radiation) term and aerodynamic (wind and humidity) term. The relative importance of the two terms varies with climatic conditions. Under calm weather conditions the aerodynamic term is usually much smaller than the energy term. In such conditions the Penman Eo equation using a crop coefficient of 0.8 has been shown to predict ET(grass) 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 serious errors can result in predicting ET(grass) when using 0.8 Eo.

An adaptation of the Penman equation can be used for direct prediction of ET(crop) by the use of appropriate reflection coefficients for incoming solar radiation, the effect of plant resistance to trasnpiration and by inclusion of appropriate wind functions which take into account the change in aerodynamic roughness with growth of crop. This would require additional input data and involve a level of complexity considered beyond the intended scope of this publication.

That approach has not been used here, but in this publication a slightly modified Penman method is suggested to predict the effect of climate on crop water requirements. The formula presented and procedure to follow will enable prediction of the effect of climate on reference crop evapotranspiration ETo. The only variation to the original Penman method (1948) proposed herein involves a revised wind function term and an additional correction for day and night-time weather conditions not representative of climates for which the wind function was determined. To arrive at the relationship presented, use was made of climatic and measured grass evapotranspiration data from research stations mentioned in Appendix II and from references in Appendix III.

To predict the effect of the crop characteristics on crop water requirements, the crop coefficients, kc, presented in Chapter 1.2 can be applied. The crop evapotranspiration, ET(crop) is found by ET(crop) = kc ETo. A two-step approach by first calculating ETo followed by the selection of the appropriate crop coefficient kc to predict ET(crop) is presented rather than suggesting the use of the Penman method for a direct prediction of ET(crop). Some compromise in accuracy may be accepted for the sake of simplicity.

The calculation procedures to estimate ETo may seem rather complicated. This is caused by the fact that the formula contains components which can be derived previously from recorded and related climatic data when no direct measurements are available. For instance, the essential radiation component can be obtained from measured solar radiation from bright sunshine duration or cloudiness observations, and from measured humidity and temperature data for places where no direct measurements of net radiation are available. Computation techniques and tables are given here to facilitate the necessary calculation. A format for calculation is given at the end of this sub-chapter.

Recommended relationships

The form of the equation used in this method is:

$$ETo^{*} = \underbrace{W.\ Rn}_{\text{radiation term}} + \underbrace{(1-W).\ f(u).(ea-ed)}_{\text{aerodynamic term}} \qquad \text{(not adjusted)}$$

where: ETo^{*} is the reference crop evapotranspiration in mm/day (not adjusted)

W is temperature-related weighting factor

Rn is net radiation in equivalent evaporation in mm/day

f(u) is the wind-related function

(ea-ed) is the difference between the saturation vapour pressure at mean air temperature and the mean actual vapour pressure of the air, both in mbar.

To find ETo, the reference crop evapotranspiration, ETo* needs to be adjusted for day and night-time weather conditions.

Brief notes on the variables involved and examples of calculations are given below.

The data used daily in calculating ETo are applied as the mean daily value and represent the mean of such data over the period considered usually one month or ten days.

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. Of particular significance is the use of the wind function which is to be expressed in total wind run in km/day. Use of the correct units for each variable is shown in the calculation examples presented below.

Normally, total wind run per day is the only wind data available. If 24-hour wind totals are used in the original Penman equation there will be a serious overprediction of ETo under conditions of strong day-time winds accompanied by strong night-time winds especially if humidity remains low; conversely, for areas experiencing moderate to strong day-time wind but calm nights the equation will tend to underpredict ETo, especially in dry climates with RHmax of near 100 percent. The separation of day and night computations by matching mean day-time wind with day-time humidity and mean night-time wind with mean night-time humidity would provide an improvement. The procedure is however rather complicated and is not recommended because of the frequent limited availability of the necessary data. Rather, a graphic adjustment of ETo* to obtain ETo is recommended, as shown at the end of this chapter in Fig. 4, for conditions where total wind run during the day-time (07.00-19.00 hr) is twice that of the total wind run at night.

Description of variables involved and methods of calculation

A brief description of the variables involved and units to be used in the equation is given, together with the method of calculation when direct measurements are not available. This is followed by an example to calculate ETo using mean daily data for a one-month period for which a special form has been prepared. Again using mean daily data, ETo is calculated for each month during a year showing examples for adjusting ETo* for day and night-time weather conditions.

Figures and Tables to be used:

Number	Variable	Description	Input data
Table 7	ea	Saturation vapour pressure ea in mbar as function of mean air temperature	t°C
Table 8a	ed	Vapour pressure ed from dry and wet bulb temperature data (aspirated psychrometer)	t°C and t°C wet bulb
Table 8b	ed	Vapour pressure ed from dry and wet bulb temperature data (not ventilated psychrometer)	t°C and t°C wet bulb
Table 8c	ed	Vapour pressure from dewpoint temperature	t°C dewpoint
Table 9	f(u)	Values of wind function f(u) for wind run at a 2 m height in km/day	U_2
Table 10	(1-W)	Values of weighting factor (1-W) for the effect of wind and humidity on ETo at different temperatures and altitudes	t°C altitude
Table 11	W	Values of weighting factor W for the effect of radiation on ETo at different temperatures and altitudes	t°C altitude
Table 12	Ra	Extra-terrestrial radiation Ra expressed in equivalent evaporation in mm/day for different months and latitudes	month latitude
Table 13	N	Mean daily maximum duration of bright sunshine hours for different months and latitudes	month latitude
Table 14	Rns	Conversion factor for extra-terrestrial radiation Ra to net solar radiation Rns for a given reflection of 25 percent and different ratios of actual to maximum sunshine hours $[(1 - \alpha)(0.25 + 0.50\ n/N)]$	n/N $\alpha = 0.25$
Table 15	f(t)	Correction for temperature on net long wave radiation Rnl	t°C
Table 16	f(ed)	Correction for vapour pressure on long wave radiation Rnl	ed
Table 17	f(n/N)	Correction for the ratio actual and maximum sunshine hours on long wave radiation Rnl	n/N
Figure 4	ETo	Adjustment on calculated ETo* for day and night-time wind and humidity conditions	ratio day/nighttime wind and humidity

a) Vapour pressure (ea-ed)

ETo is a function of air humidity. In preference to relative humidity values, the water vapour pressure is used here in terms of the difference between the mean saturation water vapour pressure, ea, and the mean actual water vapour pressure, ed.

Air humidity data are reported in various ways, mostly 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, cases I, II or III will apply. Vapour pressure must be expressed in mbar; if ed is given in mm Hg, multiply by $\frac{1013}{766}$ = 1.33 to find mbar.

EXAMPLES:

for all cases altitude is 0 m;

I Given:	tmax = 35°C; tmin = 22°C; RHmax = 80%; RHmin = 30%;		
Calculation:	tmean	= 28.5°C	(35 + 22)/2
	RHmean	= 55 %	(80 + 30)/2
	ea at tmean = 28.5°C	= 38.9 mbar	from Table 7
	ed = ea x $\frac{\text{RHmean}}{100}$	= 21.4 mbar	38.9 x 0.55
	(ea-ed)	= 17.5 mbar	38.9 - 21.4
II Given	tmax = 35°C; tmin = 22°C; tdrybulb = 25°C; twetbulb = 20°C [1]		
Calculation:	tmean	= 28.5°C	
	ea at 28.5°C	= 38.9 mbar	from Table 7
	ed	= 20 mbar	from Table 8a
	(ea-ed)	= 18.9 mbar	(aspirated psychrometer)
III Given:	tmax = 35°C; tmin = 22°C; tdewpoint = 17.5°C		
Calculation:	tmean	= 28.5°C	
	ea at 28.5°C	= 38.9 mbar	from Table 7
	ed	20.0 mbar	from Table 8c at dewpoint of 17.5°C
	(ea-ed)	= 18.9 mbar	

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[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 8a and 8b to be used respectively.

DO NOT USE

IV Given: tmax = 35°C; tmin = 22°C; RHmax = 80%; RHmin = 30%;

Calculation:
ea at tmax = 56.2 mbar from Table 7
ed at tmax = 16.9 mbar $56.2 \times \frac{RH}{100} = 56.2 \times 0.3$

(ea-ed) at tmax = 39.3 mbar
ea at tmin = 26.4 mbar from Table 7
ed at tmin = 21.1 mbar $26.4 \times \frac{RH}{100} = 26.4 \times 0.8$

(ea-ed) at tmin = 5.3 mbar
(ea-ed) mean = 22.3 mbar $\frac{39.3 + 5.3}{2}$

because recommended wind function f(u) was derived using (ea-ed) as obtained in case I, II and III and does not correspond to example in case IV, much greater divergence will occur in mean (ea-ed) between the first cases and the 4th for situations other than evident here and errors could result if case IV was used.

b) Wind function f(u)

The term f(u) is a wind related function; the effect of wind on ETo using the modified Penman method has been defined in this publication as:

$$f(u) = 0.27 \left(1 + \frac{U2}{100}\right)$$

where U2 is total 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 in the last paragraph.

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

Factors for correcting wind speed at heights other than 2 meter

Measurement height, m	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	10.0
Correction factor	1.35	1.15	1.06	1.00	0.93*	0.88	0.85	0.83	0.77

EXAMPLE

Given: wind speed at 3 m height is 250 km/day

Calculation:
U2 = 0.93 x 250 = 232 km/day
$f(u) = 0.27 \left(1 + \frac{232}{100}\right) = \underline{0.90}$ (from Table 9)

The given wind function applies to most commonly found conditions where average wind speed during the day-time period, i.e. from 07.00 till 19.00 hr local standard time, for mid summer midlatitude climates is double the average speed during the remaining or night-time hours; in other words, where some two thirds of the total windrun occurs during day-time hours. Under some conditions where strong winds or exceptionally calm conditions prevail at nighttime, with abnormal high or low relative humidity values, corrections in predicted ETo* must be applied as given at the end of the subchapter on calculation procedures.

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) as related to temperature and elevation are given in Table 10. For temperature use $\frac{tmax + tmin}{2}$

EXAMPLE

Given: elevation 95 m; tmax = 35°C and tmin = 22°C

Calculation: tmean = 28.5% (1-W) = 0.23 from Table 10

d) Weighting factor, W

W is weighting factor for the effect of radiation on ETo*. Values for W as related to temperature and elevation are given in Table 11. For temperature use $\frac{tmax + tmin}{2}$

EXAMPLE:

Given: elevation 95 m; tmax = 35°C and tmin = 22°C

Calculation: tmean = 28.5°C W = 0.77 from Table 11

e) Net radiation, Rn

Rn, net radiation, or difference between all incoming and outgoing radiation, can be measured, but such data are seldom available. Rn can be calculated if measured sunshine hours (or degree of cloud cover), temperature and humidity data are availblable. Calculations will be simplified and more reliable if solar radiation is known.

In Figure 3 different portions of the radiation balance are shown. The amount of radiation received at the top of the atmosphere is equal to extra-terrestrial radiation, Ra. Ra is dependent on latitude and the time of the year only; its values are given in Table 12. 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 cloud cover and length of day. 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 percent for water and around 20-25 percent for most crops. That which remains is net shortwave solar radiation (Rns).

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

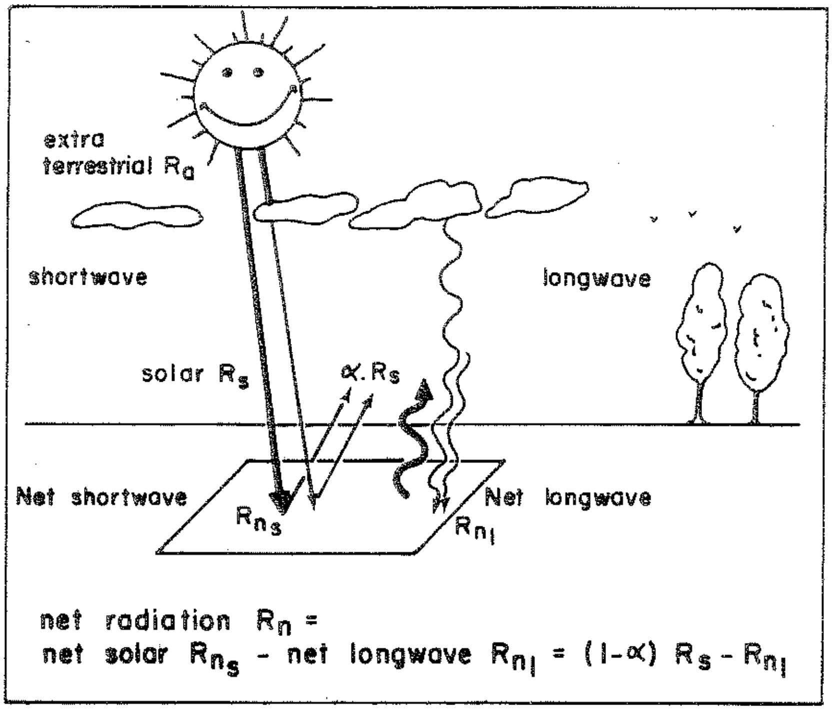


Fig. 3 Illustration of the radiation balance

Additional loss at the earth's surface normally exists since the earth radiates part of the absorbed energy into 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 longwave radiation, Rnl represents an energy loss.

Total net radiation Rn is equal to the difference between net shortwave solar radiation Rns, and net longwave radiation Rnl, or Rn Rns - Rnl. It is expressed in mm/day.

To calculate Rn the different steps involved are:

i. If solar radiation Rs is not available select Ra value from Table 12 for given month and latitude in mm/day.

ii. To obtain solar radiation Rs, correct Ra value for ratio of actual (n) to maximum possible (N) bright sunshine hours; Rs = (0.25 + 0.50 n/N) Ra 1/. Values for N for a given month and latitude are given in Table 13. Both n and N are expressed in 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) or tenths (0 to 10) which must first be converted into equivalent values of n/N. The following table can be used:

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 IV.

Cloudiness (tenths)	0	.2	.4	.6	.8
0	.95	.9	.9	.9	.9
1	.85	.85	.85	.85	.8
2	.8	.8	.8	.75	.75
3	.75	.7	.7	.7	.65
4	.65	.65	.6	.6	.6
5	.55	.55	.5	.5	.5
6	.5	.45	.45	.4	.4
7	.4	.35	.35	.3	.3
8	.3	.25	.25	.2	.2
9	.15	.15	.15	-	-
10	-	-	-	-	-

Cloudiness (oktas)*	0	.2	.4	.6	.8
0	.0	.9	.9	.85	.85
1	.85	.85	.8	.8	.8
2	.75	.75	.75	.7	.7
3	.65	.65	.65	.6	.6
4	.55	.55	.5	.5*	.45
5	.45	.4	.4	.35	.35
6	.3	.3	.25	.25	.2
7	.15	.15	-	-	-
8	-	-	-	-	-

* oktas: a scale where 8.0 is full cloudiness

EXAMPLE: Cloudiness is 4.6 oktas; equivalent value of n/N is 0.5 [1/]

iii. To obtain net shortwave radiation, Rns, the solar radiation must be corrected for reflectivity of the crop surface, α, or Rns = $(1-\alpha)$ Rs = (1-0.25) Rs, in equivalent evaporation in mm/day. Table 14 can be used to calculate Rns from the ratio n/N and the reflection coefficient $\alpha = 0.25$ multiplied by the extra terrestrial radiation Ra.

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 15, 16 and 17, respectively.

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

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

EXAMPLE:

Given: Cairo; July, latitude 30°N; altitude 95 m.
tmean = 28.5°C (Rs = 633 cal/cm^2/day or 11.24 mm/day evap.)
RHmean = 55 percent
sunshine n = 11.5 hr

Calculation:

Ra extra-terrestrial radiation	lat. 30°N, July	Table 12	Ra	16.8 mm/day
Rns net shortwave radiation	lat. 30°N, July	data	n	= 11.5 hr
Rns = $(1 - \alpha)(0.25 + 0.50\ n/N)$ Ra	$\alpha = 0.25$	Table 13	N	= 13.9 hr
= c. Ra 1/		calc	n/N	= 0.83
		Table 14	c	= 0.5
		calc	Rns	= 8.4 mm/day
Rnl net longwave radiation				
Rnl = f(t).f(ed).f(n/N)	tmean = 28.5°C	Table 15	f(t)	= 16.4
	ed = 21.4 mbar 2/	Table 16	f(ed)	= 0.13
	n/N = 0.83	Table 17	f(n/N)	= 0.85
		calc	Rnl	= 1.8 mm/day
Rn net radiation				
Rn = Rns - Rnl		calc	Rn	= 6.6 mm/day

f) Calculation of unadjusted ETo*

Reference crop evapotranspiration ETo* unadjusted for day and night-time weather conditions can be calculated using ETo* = W.Rn + (1-W). f(u).(ea-ed) in mm/day.

EXAMPLE:

Given: Cairo, July
W = 0.77; Rn = 6.6; (1-W) = 0.23; f(u) = 0.90; (ea-ed) = 17.5;

Calculation: ETo* = 0.77. 6.6 + 0.23. 0.90. 17.5 = 8.7 mm/day

g) Adjustment of calculation Penman ETo* data

For many locations the use of the approach given will provide adequate ETo values for weekly or longer periods. The conditions generally found include a wind run or mean wind speed during daytime hours averaging about twice that occurring during the night hours, and highest relative humidity values during the night (RHmax) of 60 percent or more. Wide variations in measured and calculated ETo* may result in some conditions not representative of the averages assumed in the approach outlined thus far. However, these variations are more rare than common. Any adjustments of ETo* necessary should be made for the following general climatic conditions which are given in Figure 4:

1/ 0.25 and 0.50 represent average conditions; for local coefficients see Appendix IV. If cloudiness data are available first convert these data to n/N; if measured solar radiation data, Rs, is available use Rns = $(1-\alpha)$ Rs, or in this example Rns = (1-0.25) 11.24 = 8.4 mm/day.

2/ From vapour pressure calculation under (a) case I, II, or III.

Eto ~ 1.2 ETo*

Important in areas with moderate to high radiation (> 8 mm/day) during summer months, which consistently have low-humidity winds during much of the day (⩾ 4 m/sec) and calm night-time conditions with high night humidity values approaching 100%. Curve 1 in Fig. 4 applies for day-night wind ratios of about 3 to 4 with very high RHmax.

ETo ~ 1.05 to 1.10 ETo*

Applies in areas where daytime winds are < 4 m/sec and nights are very calm and humid, i.e. RHmax > 75%. The daily wind distribution should give a day-night ratio of 3 or more. To adjust ETo*, curve 2 in Fig. 4 should be used.

ETo = ETo*

Daytime wind speeds of about twice those during the night-time are generally found and maximum relative humidity ⩾ 60%. No adjustment of Penman ETo* is required.

ETo ~ 0.75 to 0.95 ETo*

ETo will be slightly over predicted in areas with moderate to high radiation and with wind speeds < 4 m/sec but about equal during the day and night. When relative humidity during night-time is ⩾ 60% curve 4 in Fig. 4 applies.

ETo ~ 0.65 to 0.80 ETo* 1/

Relatively rare but applies for spring, summer and autumn conditions with moderate to high radiation and when wind speeds during the day and night are between 5 and 8 m/sec with maximum relative humidity < 40%. Curve 5 in Fig. 4 should be used.

ETo ~ 0.55 to 0.65 ETo* 1/

Also rare, but applies during spring, summer and autumn with moderate to high radiation and when wind speeds during day and night are > 8 m/sec and with relative humidity day and night < 40%. See curve 6 in Fig. 4.

ETo ~ 0.30 to 0.35 ETo* 1/

Very rare, but will apply under very strong winds of > 8 m/sec during both day and night, while relative humidity, day and night, is low and < 40%. Curve 7 in Fig. 4 will apply but only when radiation is low, i.e. during late autumn and winter (Rns < 4 mm/day).

1/ These cases seldom occur; very windy conditions accompanied by low relative humidity necessitating drastic corrections would persist for only a few days in most climates.

Using mean daily data for each month a summary of calculation of ETo is given indicating for each month of the year the mean daily ETo value in mm/day.

EXAMPLE: Cairo 197-; latitude 30°N; altitude 95 m.

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
t mean $^\circ$C	14	15	17.5	21	25.5	27.5	28.5	28.5	26	24	20	15.5
RH mean	65	65	63	50	45	50	55	57	60	64	68	68
n hr	9.4	8.0	8.9	9.7	10.8	11.4	11.5	11.1	10.4	9.6	8.6	7.5
U_2 km/d	173	181	207	207	232	251	232	181	164	190	164	155
ETo* mm/day	3.0	4.0	5.7	7.0	8.9	9.4	8.7	7.5	6.0	5.0	3.4	2.6

Adjusted ETo

Based on available weather data and general climatic descriptions for Cairo, adjustments of calculated ETo* are to be made using the correction relationship indicated by curve 4 in Fig. 4. Corrections to ETo* values are needed because of the day-night wind ratio of around 1.0 to 1.3 produced by rather calm morning and mid-day conditions with the onset of breezes in late afternoon and evening hours; an exception would be the ''Khamaseen'' winds of April and May which blow day and night but still have a ratio of about 1.0 to 1.5

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
ETo* mm/day	3.0	4.0	5.7	7.0	8.9	9.4	8.7	7.5	6.0	5.1	3.4	2.6
ETo mm/day	2.4	3.3	4.8	6.0	8.1	8.6	7.9	6.6	5.1	4.3	2.8	2.1

Table 7 SATURATION VAPOUR PRESSURE ea IN mbar AS FUNCTION OF MEAN AIR TEMPERATURE t IN °C

Temperature 0°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	9.4	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 0°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

Table 8a 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												dry bulb	Depression wet bulb t °C, altitude 1 000-2 000 m											
0	2	4	6	8	10	12	14	16	18	20	22	t °C	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 8b 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												dry bulb 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	19.6	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 8c **VAPOUR PRESSURE ed FROM DEWPOINT TEMPERATURE**

temp °C	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
ed mmbar	6.1	7.1	8.1	9.3	10.7	12.3	14.0	16.0	18.2*	20.6	23.4	26.4	29.8	33.6	37.8	42.4	47.5	53.2	59.4	66.3	73.8

Table 9 VALUES OF WIND FUNCTION, $f(u) = 0.27 \left(1 + \frac{U2}{100}\right)$

FOR WIND RUN AT A 2m HEIGHT IN KM/DAY

Wind in 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	1.39	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	1.80
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	2.65	2.65
900	2.70									

Table 10

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	.18	.17	.16	.15
500	.56	.52	.49	.46	.43	.45	.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 11

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	.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 12

EXTRA-TERRESTRIAL RADIATION Ra EXPRESSED IN EQUIVALENT EVAPORATION IN MM/DAY

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	15.2	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Table 13

MEAN DAILY MAXIMUM DURATION OF BRIGHT 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	12.9	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 14 CONVERSION FACTOR FOR EXTRA-TERRESTIAL RADIATION TO NET SOLAR RADIATION Rns FOR A GIVEN REFLECTION α OF 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	1.00
$(1-\alpha)(0.25 + 0.50\ n/N)$	0.19	.21	.22	.24	.26	.28	.30	.32	.34	.36	.37	.39	.41	.43	.45	.47	.49*	.51	.52	.54	.56

Table 15 CORRECTION FOR TEMPERATURE f(t) ON LONGWAVE RADIATION Rnl

$t\,^{\circ}C$	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 16 CORRECTION FOR 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
humid climates $f(ed) = 0.56 - 0.079\sqrt{ed}$	0.37	.34	.31	.29	.26	.24	.23	.21	.19	.17	.16	.14	.13	.11	.10	.09	.07	.06
dry climates $f(ed) = 0.34 - 0.044\sqrt{ed}$	.23	.22	.20	.19	.18	.16	.15	.14*	.13	.12	.12	.11	.10	.09	.08	.08	.07	.06

Table 17 CORRECTION FOR 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
$f(n/N) = 0.1\ 0.9\ n/N$	.10	.15	.19	.24	.28	.33	.37	.42	.46	.51	.55	.60	.69	.73	.78	.82*	.87	.91	.96	1.00	

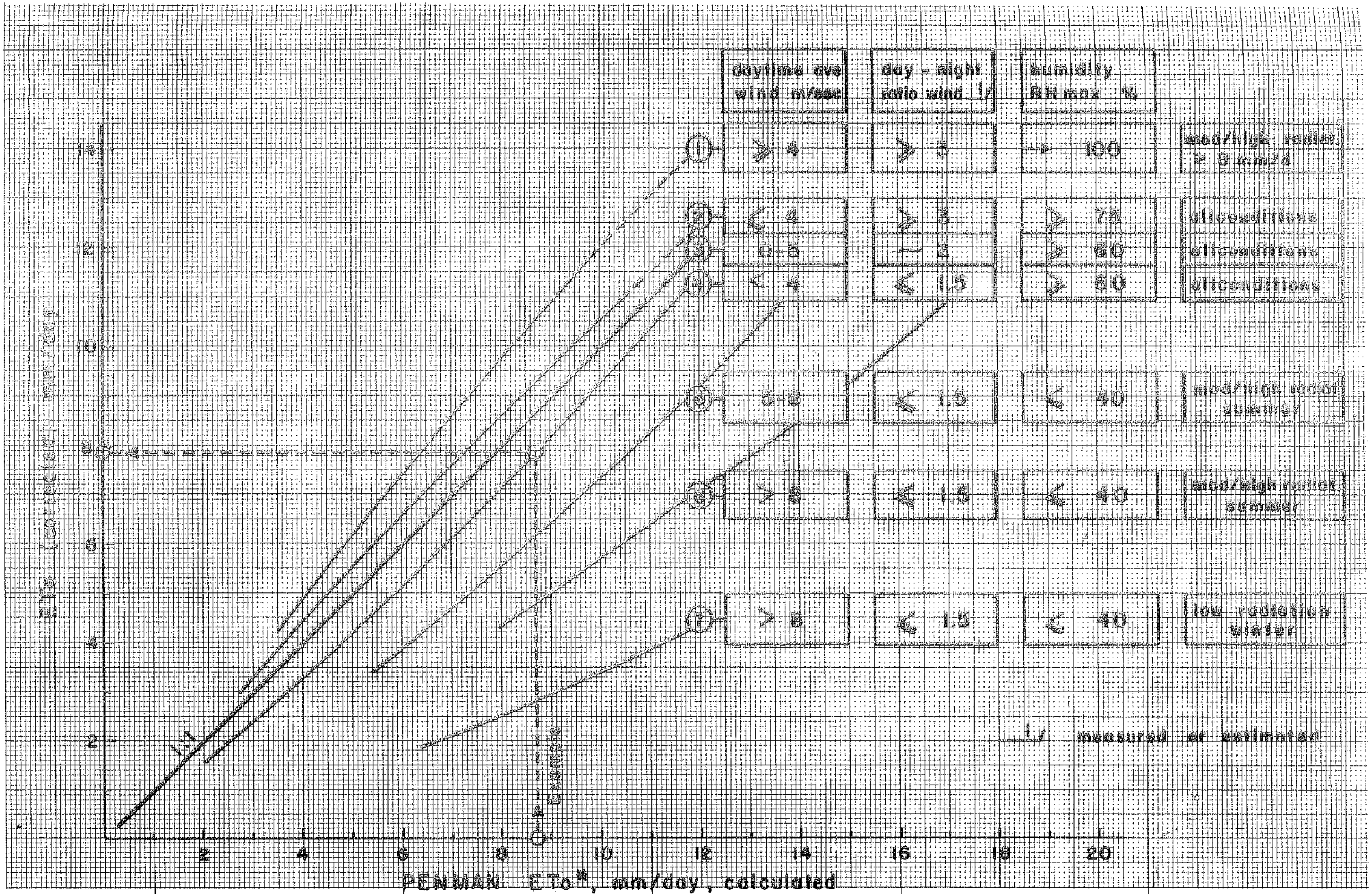
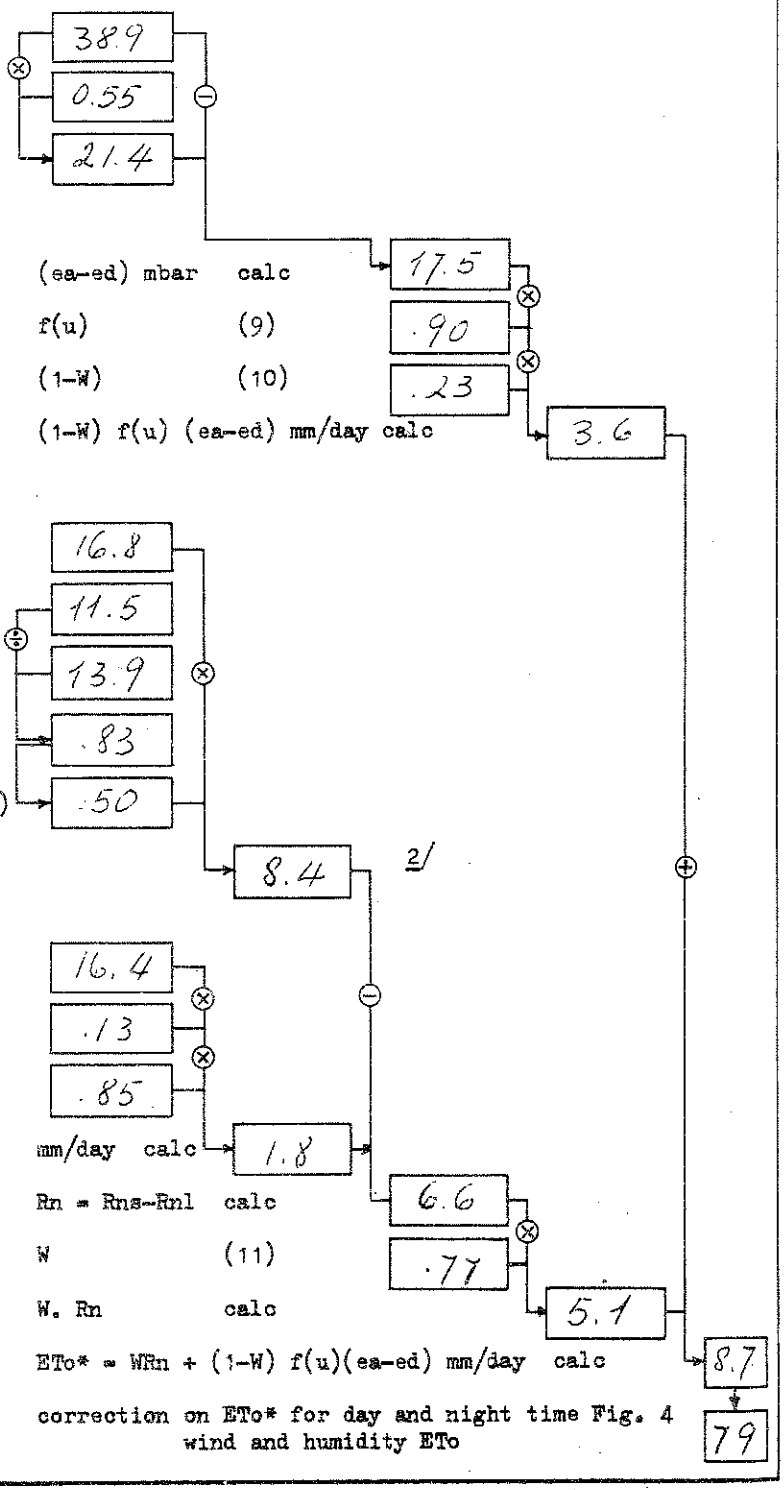


Fig. 4 Correction on calculated ETo* (Penman) for day and night time wind and humidity condition.

FORMAT FOR CALCULATION OF PENMAN METHOD

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

Country: UAR
Period : July 1972
Place: Cairo
Latitude : 30°N
Longitude: 30°
Altitude: 95 m



DATA			
t mean = 28.5°C	ea mbar	(7) 1/	38.9
RH mean = 55 %	RH/100	data	0.55
or t wet bulb depress. or t dewpoint	ed mbar	calc or (8a)(8b) or (8c)	21.4
	(ea-ed) mbar	calc	17.5
u_2 = 232 km/d t = 28.5 °C alt = 95 m	f(u)	(9)	.90
	(1-W)	(10)	.23
	(1-W) f(u) (ea-ed) mm/day	calc	3.6
month = July lat. = 30°N	Ra mm/day	(12)	16.8
n = 11.5 month = July lat. = 30°N	n hr/day	data	11.5
	N hr/day	(13)	13.9
	n/N	calc	.83
α = 0.25	(1-α)(0.25-0.50 n/N)	(14)	.50
	Rns mm/day	calc	8.4 2/
t = 28.5°C	f(t)	(15)	16.4
ed = 21.4 mbar	f(ed)	(16)	.13
n/N = 0.83	f(n/N)	(17)	.85
	Rnl = f(t). f(ed). f(n/N) mm/day	calc	1.8
	Rn = Rns-Rnl	calc	6.6
t = 28.5°C alt = 95 m	W	(11)	.77
	W. Rn	calc	5.1
	ETo* = WRn + (1-W) f(u)(ea-ed) mm/day	calc	8.7
day/night U2.RH	correction on ETo* for day and night time Fig. 4 wind and humidity ETo		79

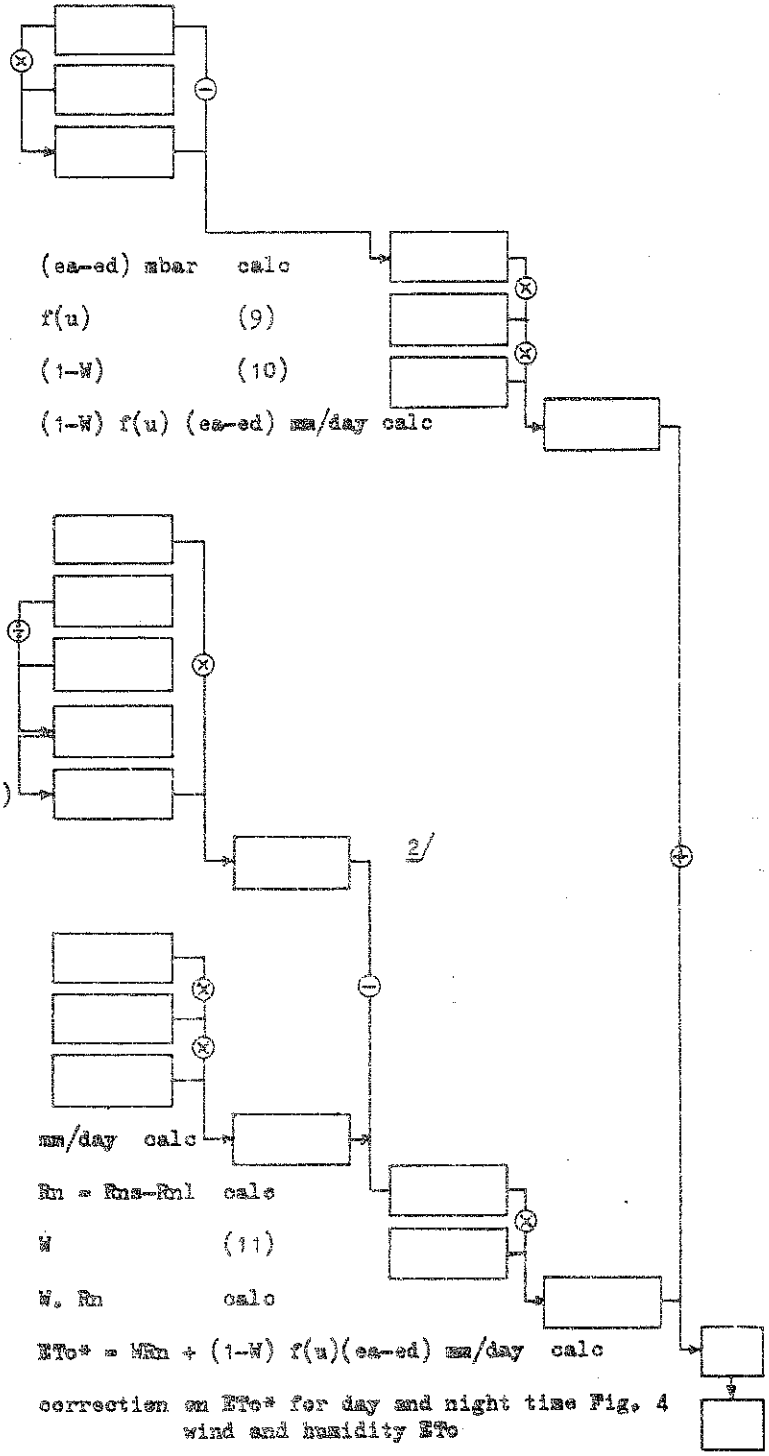
1/ Numbers in brackets indicate Table of reference.

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

FORMAT FOR CALCULATION OF PENMAN METHOD

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

DATA	Country: Period :	Place:	Latitude : Longitude:	Altitude: m
t mean = °C	ea mbar	(7) 1/		
RH mean = %	RH/100	data		
or t wet bulb depress. or t dewpoint	ed mbar	calc or (8a)(8b) or (8c)		
	(ea-ed) mbar	calc		
u2 = km/d t = °C alt = m	f(u)	(9)		
	(1-W)	(10)		
	(1-W) f(u) (ea-ed) mm/day	calc		
month = lat. =	Ra mm/day	(12)		
n = month = lat. =	n hr/day	data		
	N hr/day	(13)		
	n/N	calc		
α = 0.25	(1-α)(0.25-0.50 n/N)	(14)		
	Rns mm/day	calc		
t = °C	f(t)	(15)		
ed = mbar	f(ed)	(16)		
n/N =	f(n/N)	(17)		
	Rnl = f(t). f(ed). f(n/N) mm/day	calc		
	Rn = Rns-Rnl	calc		
t = °C alt = m	W	(11)		
	W. Rn	calc		
	ETo* = WRn + (1-W) f(u)(ea-ed) mm/day	calc		
day/night U2.RH	correction on ETo* for day and night time Fig. 4 wind and humidity ETo			



1/ Numbers in brackets indicate Table of reference.

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

METHOD IV - PAN EVAPORATION

Evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from an 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. Reflectivity of radiation from a water surface is only 5-8%, while that from most vegetative surfaces is 20-25% of solar radiation received. Daytime storage of heat within the pan can be appreciable and may cause almost equal distribution of evaporation between night and day, while most crops lose 95% or more of their 24-hour loss during daytime hours. Also a great difference in water losses from pans and from crop covers can be caused by the variance in air turbulence just above the surfaces and in the temperature and humidity of the air immediately adjacent to these surfaces. For both above-ground and sunken pans heat transfer through the sides of the pan can occur; this may be severe for sunken pans in fallow ground. Also the colour of the pan and use of screens to protect it against birds will affect the measurement. The siting of the pan and the pan environment influence the measured results, especially when the pan is placed in cropped rather than fallow fields. The importance of siting and environment of the pans will be shown later. 1/

Notwithstanding these deficiencies, with proper siting, maintenance of a standardized environment and condition of pans, their use to predict crop water requirements for periods of 10 days or longer is still warranted. To relate pan evaporation to reference crop evapotranspiration ETo empirically derived coefficients are suggested which take into account climate, type of pan and pan environment. Of the many different types of pans, the U.S. Class A pan and the Colorado sunken pan have been selected. A description of these pans is given below.

The pan coefficients, Kp, presented together with measured pan evaporation data, Epan, reflect the effect of climate on reference crop evapotranspiration ETo which was defined in Part I. To arrive at this relationship use has been made of detailed climatic and grass evapotranspiration data from research stations and literature mentioned in the Appendices.

Similar to the previous methods, the effect of crop characteristics on crop water requirements is represented by the crop coefficients given in Chapter I.2.

Recommended relationships

Reference crop evapotranspiration (ETo) can be predicted by:

$$ETo = Kp \,.\, Epan$$

where ETo is in mm/day, Epan is pan evaporation in mm/day and represents the mean daily value of the period considered; Kp is the pan coefficient.

1/ For comparison between pan and lake evaporation see C.E. Hounam (1973) WMO Note 126.

Values for Kp are given in Tables 19 and 20 for different conditions of humidity and wind, pan environment and type of pan and should be applied to pans located in an open environment with no crops taller than 1 m within some 50 m of the pan. Except for the bare soil conditions (case B), immediate surroundings, within 10 m, are covered by a green, frequently mowed, grass cover. The pan station is placed in an agricultural area with a cropping density of some 50%. No screens are mounted over the pan.

Nomenclature used to describe general levels of mean temperature, mean relative humidity and wind are given in the Table on Climatic Nomenclature in the introductory pages.

Description of pans

The class A evaporation pan is circular, 121 cm (47.5 in) in diameter and 25.5 cm (10 in) deep. It is made of galvanized iron (22 gage) or monel metal (0.8 mm). The pan is mounted on a wooden open frame platform with its bottom 15 cm above groundlevel. 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 in) square and 46 cm (18 in) deep. It is made of galvanized iron, set in the ground with the rim 5 cm (2 in) above the groundlevel. The water level inside the pan is maintained at or slightly below groundlevel.

Additional considerations

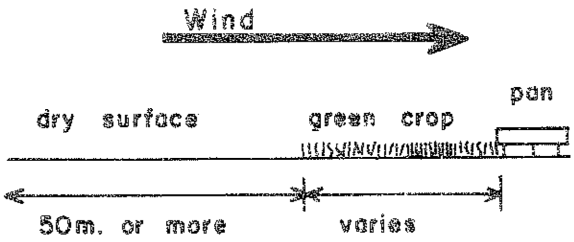
In selecting the appropriate value of Kp to relate Class A and Colorado sunken pan data to ETo, the ground cover of the weather station itself, that of the surroundings outside the station, the effect of day and night weather conditions and the pan conditions need to be considered.

a) In the case of pans located at a weather station with very poor grass cover or 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% lower. Under these rather too commonly found conditions, Epan greatly exceeds ETo. 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 19 and 20. However in cases with no agricultural development and extensive areas of bare soils - as are found, for instance, under desert or semi-desert conditions - the values of Kp given in case B for arid windy areas may need to be reduced by up to 20%; for areas with moderate levels of wind, temperature and relative humidity by 5 to 10%; no or little reduction in Kp is needed in humid cool conditions. It follows that, particularly for truly desert areas, the radiation method of predicting ETo is preferable, since the errors involved may be less severe.

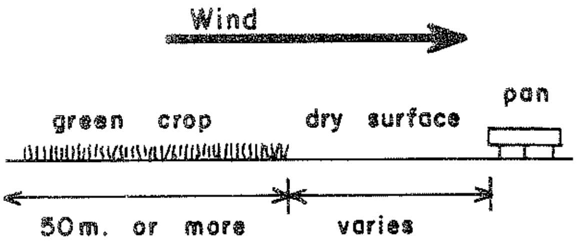
b) Where pans are placed in a small enclosure but surrounded by tall crops, for example 2.5 m high maize, the coefficients in Tables 19 and 20 may need increasing by up to 30% for dry windy climates, whereas only a 5 to 10% increase is required for calm humid conditions.

Epan decreases as pans are placed within increasingly large cropped areas, most of the decrease occuring within the first few tens of metres of upwind cropped fields. This is clearly evident from data in Tables 19 and 20 where 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



c) Since pans lose a significant portion of total evaporation at night, the inclusion of night-time humidity appears desirable. Hence the relative humidity referred to is based on (RHmax + RHmin)/2. The ranges shown for <40% relative humidity thus relate to very dry night-time as well as very dry daytime conditions. The range from 40 to 70% is typical for summertime conditions in drier semi-arid climates although some Mediterranean areas would tend to fall between the 40 to 70 and >70% relative humidity range. Wind is reflected as total daily wind run. Levels of radiation for similar conditions of humidity and wind will affect somewhat the relationship between Epan and ETo, particularly in very dry and windy conditions. The coefficients presented for such conditions reflect a linear relationship as the possible error involved in most cases would be little more than 5%.

d) The pan coefficients listed below apply to galvanized pans annually painted with aluminium. While 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% may occur when they are painted black. The material from which the pan is made may account for variations of only a few percent. Turbidity of the water in the pan does not affect Epan data by more than 5%. Overall variation in Epan is not constant with time because of ageing, deterioration and repainting. The level at which the water is maintained in the pan is very important; resulting errors may be up to 15% 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%. 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.

e) The various types of evaporation pans in use differ in size, shape and installation method. Even for the same crop environments the relationship between evaporation from any two types of pan is acutely dependent upon weather conditions; no constant ratio in measurement can be expected. Caution should therefore be exercised in applying the ratios shown in Table 18 between evaporation for the unscreened sunken pans mentioned and Colorado sunken pans if the two pans are placed in similar environments. The pan area of the Colorado sunken pans is 3 ft square or 0.84 m^2.

Table 18 RELATION BETWEEN EVAPORATION FROM SUNKEN PANS MENTIONED AND FROM COLORADO SUNKEN PAN FOR DIFFERENT CLIMATIC CONDITIONS AND PAN ENVIRONMENTS. COEFFICIENTS GIVEN CAN SERVE AS MULTIPLYING FACTOR TO OBTAIN ESTIMATED COLORADO PAN EVAPORATION.

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	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 E pan sunken Colorado is 1.25 x 8 = 10 mm/day.

Sample calculations

First, using mean daily Epan data, an example shows the procedure to obtain the mean daily value of ETo in mm for a given month. Then mean daily data for each month for the whole year are given to illustrate the selection of relationships between prevailing climatic and environmental conditions and Kp for each month using Tables 19 and 20.

EXAMPLE:

Given: Cairo, July; Epan = 11.1 mm/day from class A pan.
RH mean = medium; wind = moderate
Pan is located in 20 x 20 m bare soil plot with surrounding crops of berseem or wheat in autumn and winter, and cotton in spring and summer; the pan is not screened.

Calculation: Monthly data: since pan is surrounded by 10 m of dry fallow land case B applies.

From Table 19 for moderate wind and medium humidity while upwind distance of dry fallow is 10 m, value of Kp = 0.65.

Reference crop evapotranspiration ETo in July = Kp x Epan
0.65 x 11.1 = 7.2 mm/day

Yearly data: class A pan;

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Wind	Light to moderate		moderate						light to moderate			
RH mean	Medium to high		medium								medium to high	
Surrounding	bare fallow land, 20 x 20 m, surrounded by irrigated crop; Case B with 10 m upwind distance applies for all months.											
Kp	.7	.7	.65	.65	.65	.65	.65	.65	.65	.65	.7	.7
Epan mm/day	3.3	4.5	6.4	8.5	11.2	12.8	11.1	9.7	8.9	6.9	4.5	3.3
ETo mm/day	2.3	3.1	4.2	5.5	7.3	8.3	7.2	6.3	5.8	4.5	3.2	2.3

Table 19 PAN COEFFICIENT Kp FOR CLASS A PAN FOR DIFFERENT GROUND COVER AND LEVELS OF MEAN RELATIVE HUMIDITY AND 24 HOURS WIND

Class A Pan	Case A Pan surrounded by short green crop				Case B 1/ Pan surrounded by dry-fallow land			
RH mean %		low <40	medium 40-70	high >70		low <40	medium 40-70	high >70
Wind km/day	Upwind distance of green crop m				Upwind distance of dry fallow m			
Light <175	0	.55	.65	.75	0	.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	0	.5	.6	.65	0	.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	0	.45	.5	.60	0	.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	0	.4	.45	.5	0	.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

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

Table 20 PAN COEFFICIENT Kp FOR COLORADO SUNKEN PAN FOR DIFFERENT GROUND COVER AND LEVELS OF MEAN RELATIVE HUMIDITY AND 24 HOURS WIND

Sunken Colorado	Case A Pan surrounded by short green crop				Case B 1/ Pan surrounded by dry-fallow land			
RH mean %		low < 40	medium 40-70	high > 70		low < 40	medium 40-70	high > 70
Wind km/day	Upwind distance of green crop m				Upwind distance of dry-fallow m			
Light < 175	0	.75	.75	.8	0	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	0	.65	.7	.7	0	.95	.95	.95
	10	.85	.85	.9	10	.75	.75	.75
	≥100	.95	.95	.95	100	.65	.65	.70
					1 000	.6	.6	.65
Strong 425-700	0	.55	.6	.65	0	.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	0	.5	.55	.6	0	.7	.75	.75
	10	.65	.7	.7	10	.55	.6	.65
	≥100	.7	.75	.75	100	.5	.55	.6
					1 000	.45	.5	.55

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

CHAPTER I.2 : SELECTION OF CROP COEFFICIENT, kc

The four methods described in Chapter I.1 predict the effect of climate on crop water requirements. Each method is calibrated against 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 ET(crop) . The kc value represents evapotranspiration of a crop grown under optimum conditions producing optimum yields. ET(crop) can be found by kc.ET(crop). As each of the four methods predicts ETo only one set of crop coefficients kc is required.

Procedures for selection of appropriate kc values are presented, which take into account the crop characteristics, time of planting or sowing, and stages of crop development. General climatic conditions, especially wind and humidity, still need to be considered, particularly as after temperature, it is the wind conditions which will affect the rate of transpiration due to the degree of air turbulence above the rough crop canopy. Furthermore, rate of transpiration is higher under conditions with dry air winds as compared to humid air winds.

Crop coefficients published elsewhere relating ET(crop) directly to the original prediction formulae should not be used if the approach presented in this publication is followed because the kc values relate to ETo. The crop coefficients suggested here may still contain inaccuracies due to the many factors involved and the problems that plague present day applied research on crop water use, such as sampling errors, deep percolation losses or supply from groundwater, size of experimental plot, lysimeter and other problems. Much data from many sources representing experience covering many climatic, crop and growing conditions had to be considered and may account for some of the author's bias in the selection or rejection of the assembled data.

Local conditions, including agricultural and irrigation practices that affect ET(crop) are discussed in Chapter I.4.

General considerations

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

The effect of crop characteristics on the relationship between ET(crop) and ETo is shown in the conceptual diagram in Fig. 5. The wide variations between major groups of crops are largely due to the difference in plant mechanisms for resisting transpiration, such as closed stomata during the daytime (pineapple) and waxy leaves (citrus). Also difference in crop height, crop roughness, reflection and ground cover produce the illustrated variation in ET(crop). For high evaporative conditions, i.e. hot, strong winds and low humidity, ETo values of up to 12 to 14 mm/day and ET(crop) values of up to 15 to 17 mm/day may be realistic, particularly for small fields reacting in somewhat similar fashion as laundry on a clothesline. However, wilting of crops often occurs under such conditions as is shown for sugarbeets in Fig. 5.

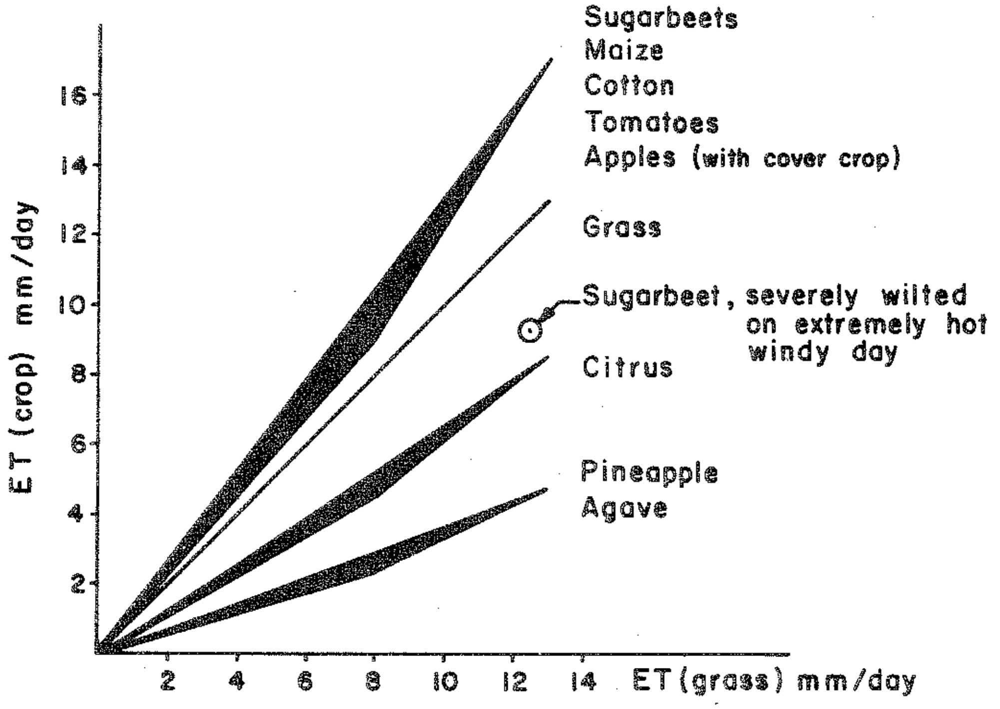


Fig. 5 Magnitudes of ET(crop) as compared to ET (grass)

The crop planting or sowing date will affect the length of the growing season, the rate of crop development to full ground cover 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 Fig. 6 for surgarbeets the time needed to reach full development or maximum water demand varies from up to 60 percent to the total growing season for an autumn sown crop to about 35 percent for an early summer sowing 1/. In selecting the appropriate crop coefficient, kc, for a given crop for each month in the growing season, the rate of crop development must be considered.

1/ This indicates that, when calculating water requirements, the commonly used presentation of kc values as a function of percentage of total growing season (USDA-SCS Release No. 21, 1967) will not suffice when attempting to include all possible variations of growing seasons.

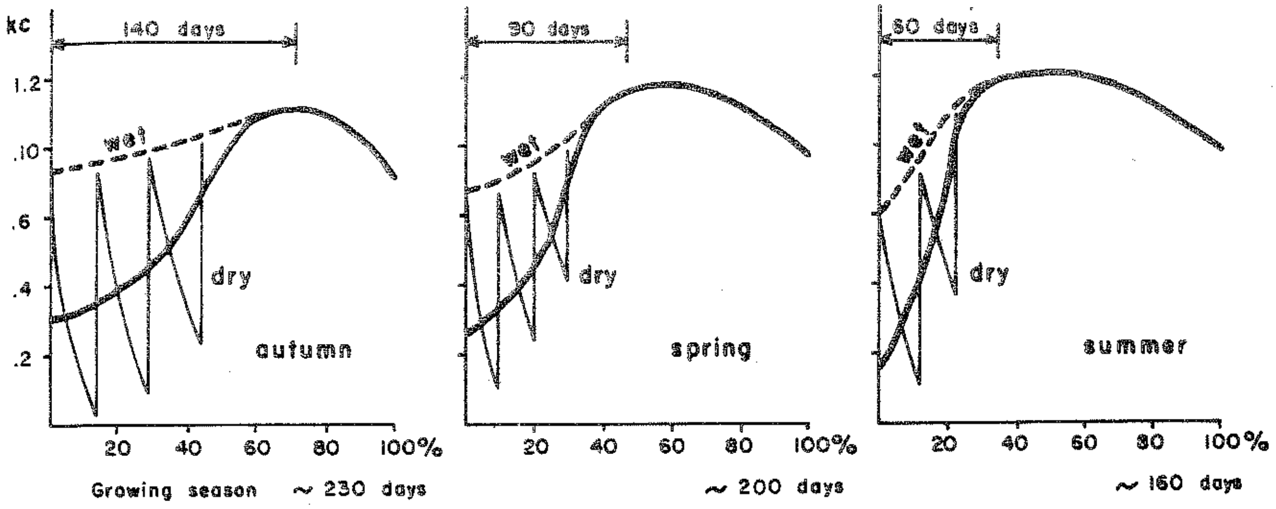


Fig. 6 Sugarbeets; k_c for different sowing dates and irrigation and rainfall frequency.

For the same crop, fully developed, the ratio ET(crop) and ETo or the value of kc is not constant but changes with climatic conditions. In relation to ETo, crop evapotranspiration is higher in hot, windy and dry climates as compared to cool, calm and humid climates. This is clearly reflected in the kc values presented for different climatic conditions.

The nomenclature used in describing general levels of the climatic variables involved has been given in the introductory pages.

ET(crop) is the sum of transpiration by the crop and evaporation from the soil surface. Whereas during full ground cover 1/ evaporation is negligibly small, during the early growing period evaporation from the soil surface may be considerable, particularly when the soil surface is wet for most of the time from irrigation and rain. Hence the great range of kc values during early season growth as shown in Fig. 6 for dry and wet soil surface conditions. The smooth curves are obviously idealized since each irrigation or rain would produce a sharp increase in kc with a less sharp but marked dropping off afterwards, until the next irrigation or rain. The practical significance in terms of field irrigation water management are described in Chapter I.4.

1/ Ground cover is expressed in percentage of soil surface shaded by the crop when the sun is directly overhead; full ground cover is frequently assumed when ground cover as defined in some 80 percent.

For ease of reference, approximate ranges of seasonal ET(crop) for different crops are given in Table 21. The magnitudes shown will change according to the factors discussed, i.e. mainly crop characteristics, climate, length of growing season, time of planting; other factors include size of fields, soil water levels and agricultural practices. Also, approximate comparative values are given where 100 is for grass with a 12 month growing season in frost free areas.

Table 21 APPROXIMATE RANGE OF SEASONAL ET(CROP) IN MM AND IN COMPARISON WITH ET(GRASS)

ETC(crop) seasonal	mm	%		mm	%
Alfalfa	600 - 1 500	90 - 105	Onions	350 - 600	25 - 40
Avocado	650 - 1 000	65 - 75	Orange	600 - 950	60 - 75
Bananas	700 - 1 700	90 - 105	Potatoes	350 - 625	25 - 40
Beans	250 - 400	20 - 25	Rice	500 - 800	45 - 65
Cocoa	800 - 1 200	95 - 110	Sisal	550 - 800	65 - 75
Coffee	800 - 1 200	95 - 110	Sorghum	300 - 650	30 - 45
Cotton	550 - 950	50 - 65	Soybeans	450 - 825	30 - 45
Dates	900 - 1 300	85 - 110	Sugarbeets	450 - 850	50 - 65
Deciduous			Sugarcane	1 000 - 1 500	105 - 120
trees	700 - 1 050	60 - 70	Sweet potatoes	400 - 675	30 - 45
Flax	450 - 900	55 - 70	Tobacco	300 - 500	30 - 35
Grains(small)	300 - 450	25 - 30	Tomatoes	300 - 600	30 - 45
Grapefruit	650 - 1 000	70 - 85	Vegetables	250 - 500	15 - 30
Maize	400 - 700	30 - 45	Vineyards	450 - 900	30 - 55
Oil seeds	300 - 600	25 - 40	Walnuts	700 - 1 000	65 - 75

Recommended values

a) Field and vegetable crops

Values of kc for the different stages of crop development are given below. The crop growing season is divided into four stages. For each stage, crop coefficients kc for different climatic conditions are presented in Table 22. For reference, length of crop development stages and total growing season for selected crops and climate are given in Table 23. The need to collect data locally on growing season and rate of crop development cannot be overstressed.

The four stages in crop development are:

- initial stage : germination and early growth when the soil surface is not or hardly covered by the crop;
- crop development stage : from end of initial stage to attainment of effective full ground cover 1/;
- mid-season stage : from attainment of effective full ground cover 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 ET(crop) is induced to increase yield and/or quality (sugarcane, cotton, some grains);
- late season stage : from end of mid-season stage until full maturity or harvest.

The steps needed to arrive at the kc values for the different stages to be plotted for simplification as straight lines are indicated in Fig. 7:

(1) establish planting or sowing date from local information or from practices in similar climatic zones;

(2) determine total growing season and length of crop development stages from local information (for approximations see Table 23);

(3) initial stage: predict irrigation and/or rainfall frequency; for predetermined ETo value, obtain kc from Fig. 8 and plot kc value as shown in Fig. 7;

(4) mid-season stage: for given climate (humidity and wind), select kc value from Table 22 and plot as straight line;

(5) late-season stage: for time of full maturity or harvest, select kc value from Table 22 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;

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

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

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 Fig. 7 although this may have little effect in terms of accuracy added.

EXAMPLE:

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

(1) Planting date	local information (or Table 23)	Late spring, early summer
(2) Length of growth stages		
initial		20 days
crop development		35 days
mid-season		40 days
late season		30 days
		125 days
(3) Plot periods as indicated	Fig. 7	
(4) kc initial stage ETo = 8.4 mm/day irrig. frequency = 7 days	Fig. 8	kc initial = 0.35
kc mid-season stage wind = light/moderate humidity = low	Table 22	kc mid-season = 1.15
kc late season stage (end) wind = light/moderate humidity = low	Table 22	kc end of season = 0.6
(5) Plot kc value and connect values with straight lines	Fig. 7	kc development stage = 0.35-1.15 kc late season stage = 1.15-0.6
(6) Read kc value from prepared graph for each selected period at mid point of 10 to 30 day period.		

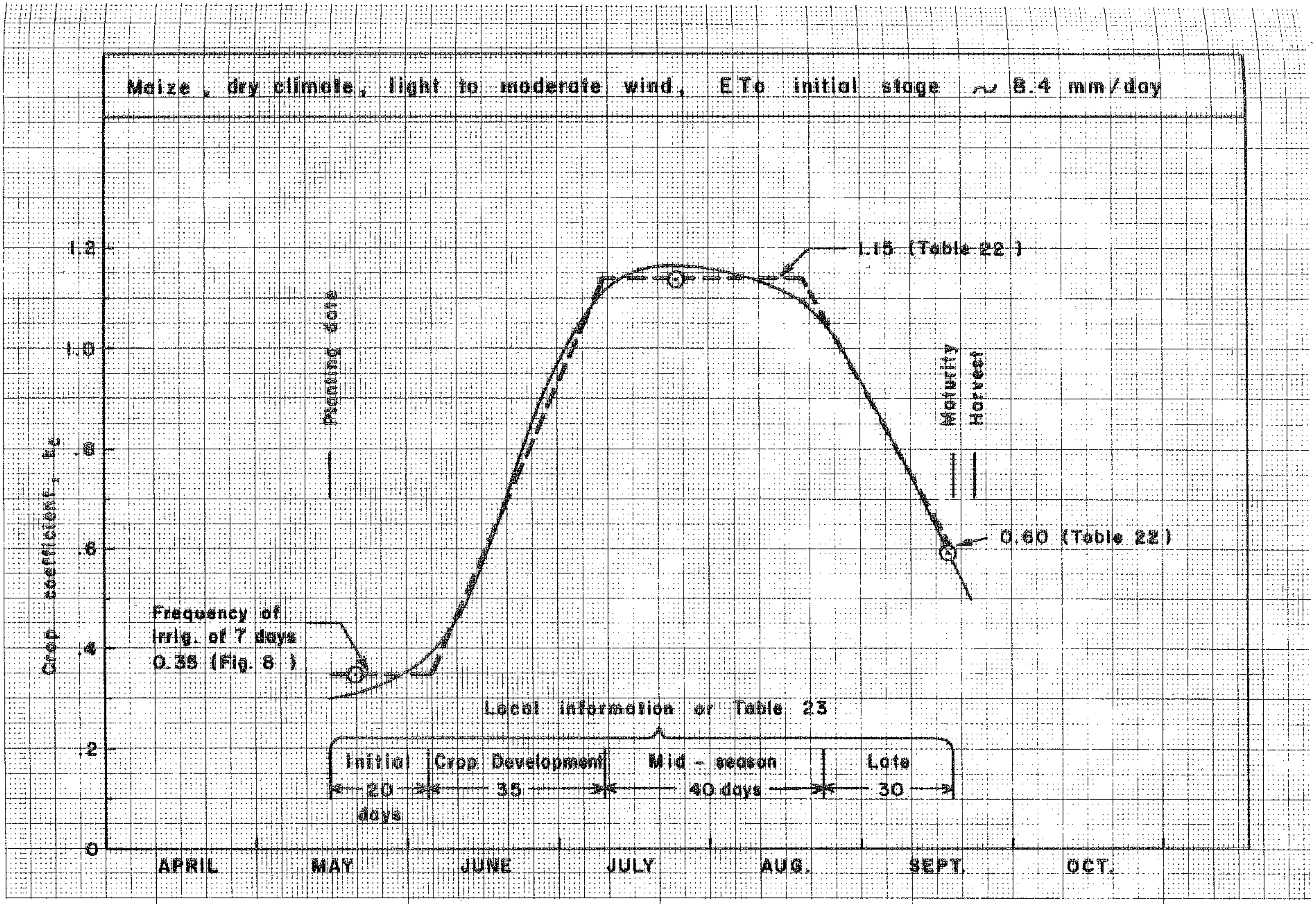


Fig. 7 Example of crop coefficient curve (for maize) Cairo

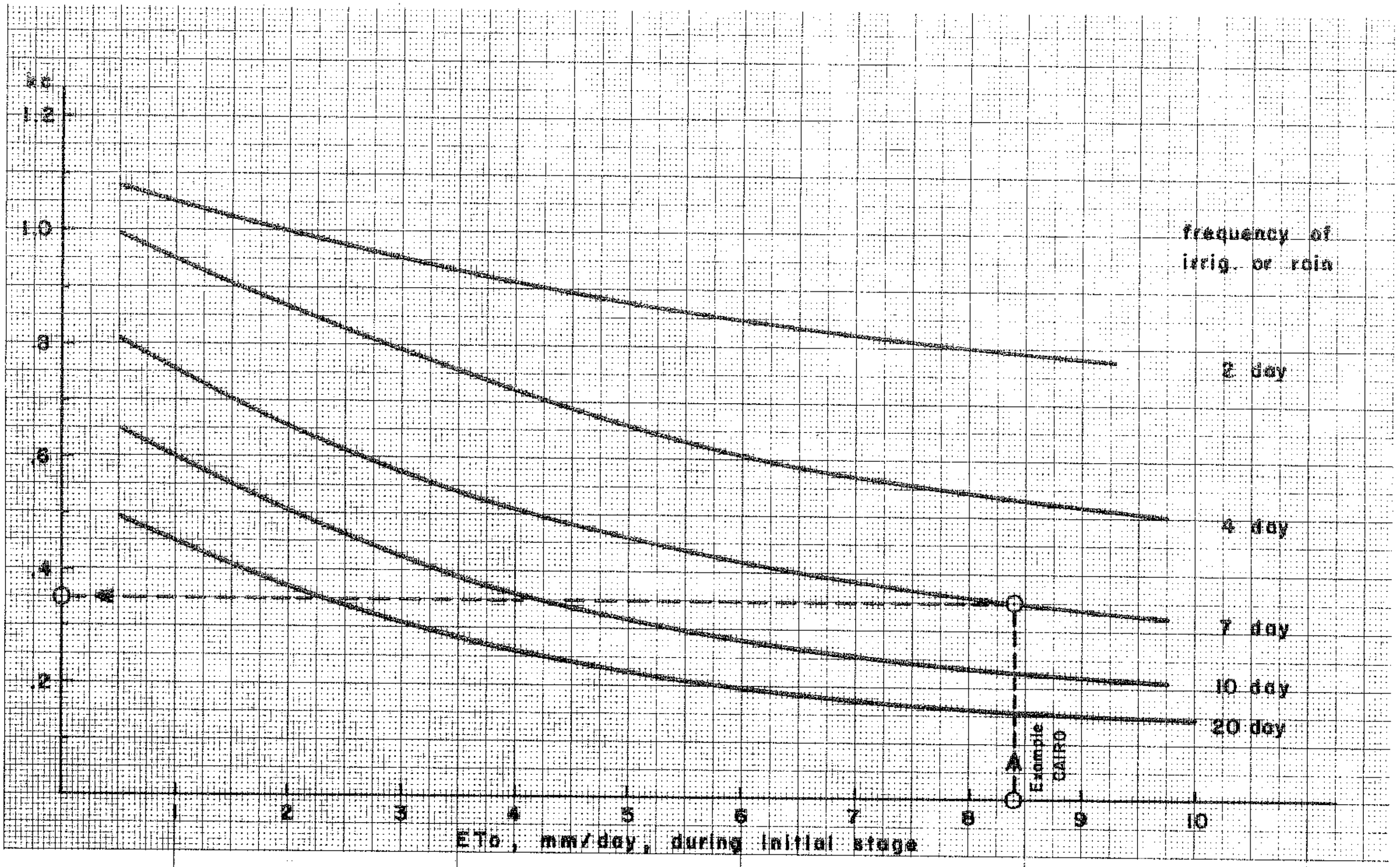


Fig. 8 Average k_c for initial stage as a function of average ETo level (during initial stage) and frequency of irrigation or of significant rain.

Table 22 CROP COEFFICIENT kc FOR FIELD AND VEGETABLE CROPS FOR DIFFERENT STAGES OF CROP GROWTH AND PREVAILING CLIMATIC CONDITIONS

Crop	Humidity	RH min >70%		RH min <20%	
	Wind m/sec	0-5	5-8	0-5	5-8
	Crop stage				
All field crops	initial 1	Use Fig. 8 by interpolation			
"	crop dev. 2				
Artichokes (perennial-clean cultivated)	mid-season 3	.95	.95	1.0	1.05
	at harvest 4	.9	.9	.95	.10
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	mid-season 3	1.0	1.05	1.1	1.15
	at harvest 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

Crop	Humidity	RH min > 70%		RH min < 20%	
	Wind m/sec	0-5	5-8	0-5	5-8
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
Oats	3	1.05	1.1	1.15	1.2
	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	0.95	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
Soyabeans	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	mid-season 3	.9	.9	.95	1.0
	at harvest 4	.7	.7	.75	.8
Sugarbeet	3	1.05	1.1	1.15	1.2
	4	.9	.95	1.0	1.0
	no irr. 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

N.B. 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 23 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 groundlevel in late spring each year at end of harvest or 20/40/220/30 and (310).
Barley	Also wheat and oats; varies strongly with variety; wheat Central India November planting 15/25/50/30 and (120); semi-arid, 35°-45° latitudes early spring sowing and South Korea November planting 20/25/60/30 and (135); wheat in East African highlands at 2 500 m altitude sown in July and South 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 (160); 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 30/40/45/15 and (125).
Corn (maize) (sweet)	Philippines, early March planting (late dry season) 20/20/30/10 and (70); 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 Sevilla Spain 30/40/50/30 and (150).

1/ 40/40/250/30 and (360) stands for respectively 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	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 30/40/25/10 and (105); early cool season low desert climates from 25/35/30/10 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 (110); mid-winter planting 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 - Resp. 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).
Soyabeans	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).
Spinach	Spring planting Mediterranean, 20/20/15/5 and (60), Sept-Oct. 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 (110).
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 (150); spring planting Mediterranean climates 30/40/45/30 and (145).
Wheat	See Barley.

b) Rice

For submerged rice kc values are given in Table 24 for different geographical locations and for different seasons including wind conditions. Relative humidity during dry season may be important; where minimum relative humidity is more than 70% during the dry season, 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.

As the plant cover spreads with time, the average reflectivity of the surface increases from low values for free water surface (5%) to high values for vegetative surface (25%). For humid areas with light to moderate wind this may tend to produce slightly lower kc values in the succeeding months. For dry conditions with light to moderate wind this trend is reversed due to the increased influence of the roughness of the surface. This is even more marked under very strong winds. Therefore, little difference in kc value between the first and second months can be noted.

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 submerged rice will apply since recommended practices involve the maintaining of top soil layers very close to saturation. Only during initial crop stage will kc need to be reduced by 15 to 20% .

It should be added that efforts to predict accurately the kc and ET(crop) values needed to determine irrigation water requirements,are wasted when water loss through deep percolation is not determined with equal accuracy.

Table 24

kc VALUES FOR RICE

	Planting period	Harvest period	First month	Second month	Mid-season	Last 3-4 weeks
Humid Asia						
Wet season (monsoon)	June-July	Nov-Dec				
light to moderate wind			1.1	1.1	1.05	.95
strong wind			1.15	1.15	1.1	1.0
Dry season 1/	Dec-Jan	mid-May				
light to moderate wind			1.1	1.1	1.25	1.0 1/
strong wind			1.15	1.15	1.35	1.05
Humid Australia						
Wet season	Dec-Jan	Apr-May				
light to moderate wind			1.1	1.1	1.05	.95
strong wind			1.15	1.15	1.1	1.0
Humid S. America						
Wet season	Nov-Dec	Apr-May				
light to moderate wind			1.1	1.1	1.05	.95
strong wind			1.15	1.15	1.1	1.0
Europe (Spain, southern France and northern Italy)						
Dry season	May-June	Sept to early Oct				
light to moderate wind			1.1	1.1	1.2	.95
strong wind			1.15	1.15	1.3	1.0
U.S.A.						
Wet summer (southern states)	May	Sept-Oct				
light to moderate wind			1.1	1.1	1.1	.95
strong wind			1.15	1.15	1.15	1.00
Dry summer (Calif.)	late Apr to early May	late Sept to early Oct				
light to moderate wind			1.1	1.1	1.25	1.0
strong wind			1.15	1.15	1.35	1.05

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

c) Sugarcane

Crop coefficients kc 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. Total growing season for virgin plantings 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 or normal rate of development under similar climatic conditions is essential. Also, attention must be given to cane variety. Data provided refer to a ratoon crop for the 12-month crop and to a virgin cane for the 24 month period. Irrigation application usually ceases 4 to 6 weeks before harvest.

Table 25 kc VALUES FOR SUGARCANE

Crop age		Growth stages	RH min > 70 %		RH min < 20%	
12 month	24 month		light to moderate wind	strong wind	light to moderate 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

d) Alfalfa, clover, grass-legumes, pastures

Alfalfa

The kc values vary similarly to those for field crops except that the initial stage to harvest is repeated 2 to 8 times a year. Fig. 9 shows expected variation of kc values for alfalfa for the total growing season under dry, and light to moderate wind conditions. To obtain mean ET (alfalfa) for design purposes, kc(mean), shown as the smoothed curve in Fig. 9, would generally suffice. This value should be selected rather than the higher kc values of the 3 to 4 week period before cutting. Only for irrigation depth and frequency determinations will the variation of kc over the irrigation interval need to be considered, that is from kc (low) to kc(peak). During full cover until the middle of full bloom, alfalfa grown for seed production will have a kc value equal to kc(peak) just before cutting. Values of kc are given in Table 26.

Grasses

Grasses grown for hay reach kc(peak) values within 6 to 8 days after cutting. The kc(low) values are 10 to 20% 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) for clover and grass-legume mixture 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 for pastures 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.

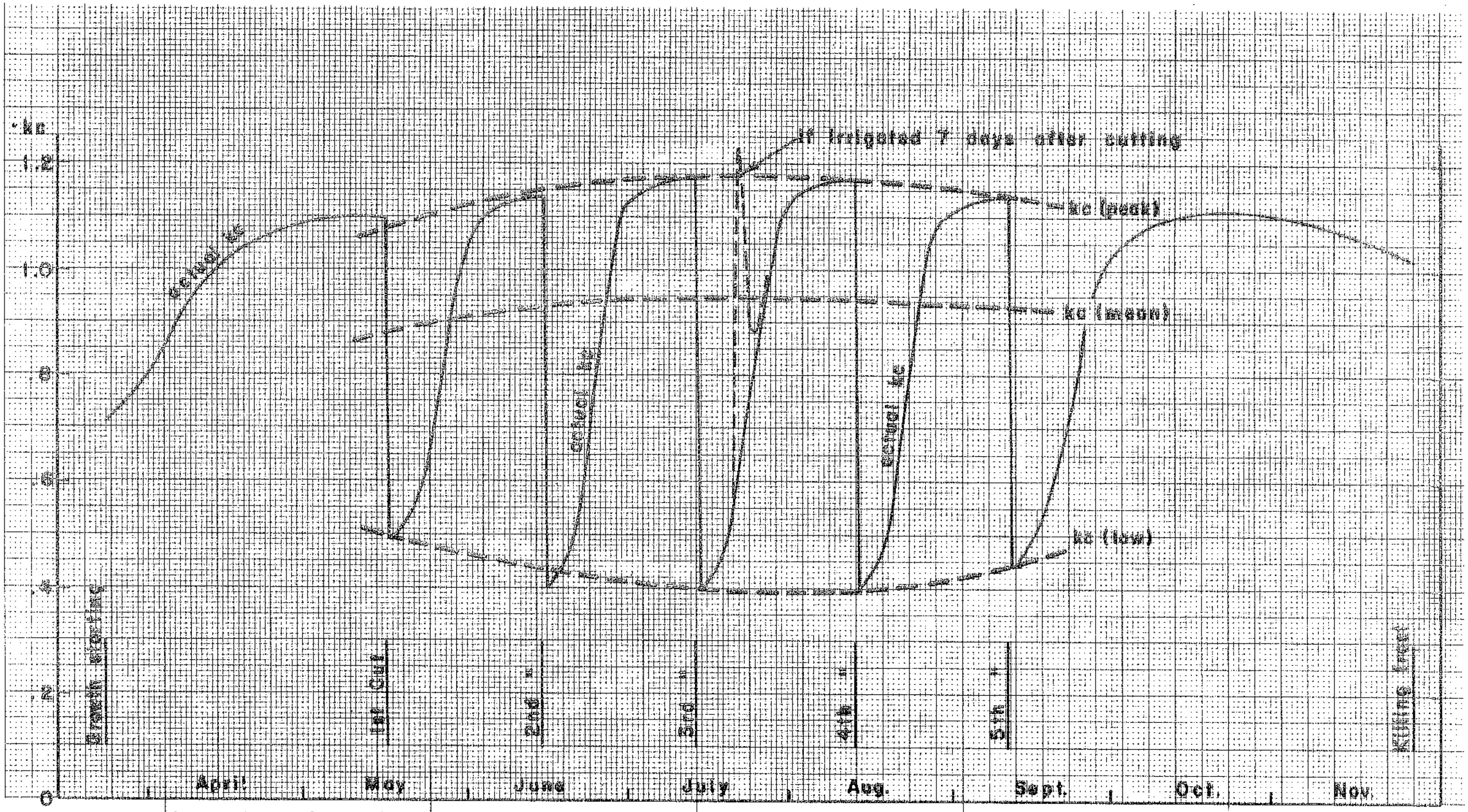


Fig. 9 kc values for alfalfa grown in dry climate with ligth to moderate wind with cuttings every 4 weeks. One heavy irrigation per growth period, a week before cutting, is assumed.

Table 26 CROP COEFFICIENT kc(mean) FOR ALFALFA, GRASS FOR HAY, CLOVER AND GRASS-LEGUME MIXTURE AND PASTURE, AND kc(peak) JUST BEFORE HARVESTING AND kc(low) JUST FOLLOWING HARVESTING

	kc(mean)			kc(peak)			kc(low) 1/		
	Humid, light to mod.wind	Dry, light to mod.wind	Dry, strong winds	Humid, light to mod.wind	Dry, light to mod.wind	Dry, strong winds	Humid, light to mod.wind	Dry, light to mod.wind	Dry, strong winds
Alfalfa	.85	.95	1.05	1.05	1.15	1.25	.3	.4	.3
Grass for hay	.8	.9	1.0	1.05	1.1	1.15	.6	.55	.5
Clover, grass-legume mixture	1.0	1.05	1.1	1.05	1.15	1.2	.55	.55	.55
Pasture	.95	1.0	1.05	1.05	1.1	1.15	.55	.5	.5

1/ Under dry soil surface conditions; under wet conditions increase values by 25 % or more.

e) Deciduous fruits and nuts

Values of kc for deciduous fruit and nut crops for clean cultivated and for cover-crop conditions are presented in Table 27. Coefficients given relate to full-grown trees with spacings that provide about 70 % ground cover. Examples are given for 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 others involve lower latitude and warm winter conditions (e.g. Mediterranean). In the former case and at altitudes of >1 200 m in lower latitude areas, trees have leaves for some 5 1/2 to 6 months, with the 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 a 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.

Also indicated in Table 27 is a variation of crop coefficients with climatic variables in particular, humidity and wind.

Table 27

kc VALUES FOR FULL GROWN DECIDUOUS TREES 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																		
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. 8 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 case of frequent irrigation for March, April and November adjust using Fig. 8; 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.

f) Citrus

The kc value for citrus, large mature trees, include different tree ground cover conditions with clean cultivation and no weed control programme. 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. For young orchards with a low percentage of tree ground cover, kc values given for 20% and 50% tree ground cover may be assumed. For frequent rain or irrigation, kc values for clean cultivation will approach those for no weed control programme. It should be added that certain studies have indicated somewhat higher kc values, up to 10-15% for grapefruit and lemons compared with those given. Months mentioned refer to northern hemisphere; for southern hemisphere add 6 months.

Table 28 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	.5	.5	.55	.55	.55	.6	.6	.6	.6	.6	.55	.55
No weed control programme	.75	.75	.8	.8	.8	.85	.85	.85	.85	.85	.8	.8
Trees providing ~50% tree ground cover												
Clean cultivated	.45	.45	.5	.5	.5	.55	.55	.55	.55	.55	.5	.5
No weed control programme	.75	.75	.8	.8	.8	.85	.85	.85	.85	.85	.8	.8
Trees providing < 20% tree ground cover												
Clean cultivated	.4	.4	.4	.4	.4	.45	.45	.45	.45	.45	.4	.4
No weed control programme	.85	.85	.9	.9	.9	.95	.95	.95	.95	.95	.9	.9

g) Grapes

The kc values for grapes will vary considerably with cultural practices such as vine and row spacing, pruning, trellicing 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% ground cover. Also there maybe a somewhat greater degree of stomatal control of transpiration compared to many other crops.

In Table 29 the kc values for grapes are presented for cold winter, light winter and hot, dry 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 those used for light winter and hot dry conditions. In the last two cases kc values need to be reduced when ground cover is less than 35%. For all cases infrequent irrigation and dry soil surface during most of the time are assumed. Months mentioned in Table 29 refer to northern hemisphere; for southern hemisphere add 6 months.

Table 29 kc VALUES FOR GRAPES (INFREQUENT IRRIGATION, SOIL SURFACE DRY)

	Jan	Feb	Mar	Apr	May	Jun	Jul	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; clean cultivated												
Humid, light to moderate wind	-	-	-	-	.5	.6	.7	.7	.6	.5	-	-
Humid, strong wind	-	-	-	-	.5	.6	.75	.75	.65	.55	-	-
Dry, light to moderate wind	-	-	-	-	.45	.65	.8	.85	.75	.6	-	-
Dry, strong wind	-	-	-	-	.5	.7	.85	.9	.85	.65	-	-
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; clean cultivated												
Humid, light to moderate wind	-	-	-	.5	.55	.6	.6	.6	.55	.4	.35	-
Humid, strong wind	-	-	-	.5	.55	.65	.65	.65	.6	.45	.35	-
Dry, light to moderate wind	-	-	-	.45	.6	.7	.7	.7	.65	.5	.3	-
Dry, strong wind	-	-	-	.45	.65	.75	.75	.75	.7	.55	.3	-
Mature grapes grown in hot dry areas; initial leaves late February-early March, harvest last half of July; ground cover 30-35% at mid-season; clean cultivated												
Dry, light to moderate wind	-	-	.25	.45	.6	.7	.7	.65	.55	.45	.35	-
Dry, strong wind	-	-	.25	.45	.65	.75	.75	.7	.55	.45	.35	-

h) Bananas

Values of kc for bananas are given in Table 30 for different climates, 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 development, especially in the first year, kc values reflect a considerable lack of ground cover and a climate where rainfall is presumed to occur at 5-7 day intervals. For less frequent rain, lower kc values should be used; in humid tropical zones with more frequent rain, coefficients close to 1.0 would be likely even during the crop development stage. Fig 8 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 of kc, with subsequent recovery to high levels 4-5 months later, or as ground cover again approaches 70-80% . Recovery time may be considerably shorter than 4-5 months in warm or hot humid climates. Figures given in Table 30 reflect the effect of the climate on the eastern coast of the Mediterranean Sea. Months mentioned in Table 30 refer to the northern hemisphere; for the southern hemisphere add 6 months.

Table 30 kc VALUES FOR BANANAS

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
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

i) 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 ET(reeds) can be expected to be considerably lower. Water loss by fully submerged weeds is equal to that of open water evaporation Eo. In Table 31 the kc values of 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, a higher reflectance of the green plants and their internal resistance to transpiration. The conflicting data found in literature which show ET(aquatic 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 31. 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% lower and due to heat release during late summer and early autumn 20 to 30% higher.

Table 31 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)	1.10	1.15	1.15	1.2
Floating (duck weed)	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	.9	.9	.95	1.0
moist soil	.7	.7	.8	.85
Open water	1.1	1.15	1.15	1.2

j) Coffee

Two species of coffee provide the bulk of the world's supply, Coffea arabica and Coffea robusta. The former only 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.

k) Tea

No direct comparison of evapotranspiration by tea with that by grass could be found in literature. The water requirement of tea bushes in full production can be assumed to be close to ETo. Hence, crop coefficients kc of around .95 to 1.0 are suggested for non-shaded plantations where more than 70% ground cover exists. Where grown under shade trees, kc values of 1.5-1.10 would be more appropriate for more humid periods, and perhaps 1.10-1.15 for dry periods.

l) Non-cropped or bare soils

To determine the water balance, particularly after winter rains, estimation of evaporation losses from the soil surface E(soil) are 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. E(soil) will be greatly affected by the water content of the soil surface, and frequency and depth of rain, type of soil and level of evaporative demand. To determine kc Fig. 8 should be used; the prediction of E(soil) follows closely the method shown for field crops, initial stage. Data presented in Fig. 8 assume a medium-textured soil. For light and heavy-textured soils kc values may need a downward adjustment by some 30% and upward by some 15% respectively. Only a short period following the rain should be considered since top soil may soon dry out and, particularly for sandy soil, soil evaporation will be severely restricted.

EXAMPLE:

Estimation of E(soil) from fallow, essentially weed-free soil.

Given: Cairo; ETo as given and obtained from Method III of Chapter I.1; ficticious rainfall data on frequency.

Calculation: from ETo in mm/day and data on frequency of rainfall, select kc value from Fig. 8.

	Nov.	Dec.	Jan.	Feb.	March	
ETo, mm/day	2.8	2.1	2.4	3.3	4.8	Method III
Frequency of rain, days	7	7	5	7	10	Data
kc factor	.6	.65	.75	.55	.35	Fig. 8
E(soil) mm/day = kc x ETo	1.7	1.4	1.8	1.8	1.7	Calc.

CHAPTER I.3

CALCULATION OF ET(crop)

As stated in the introduction ET(crop) reflects the rate of evapotranspiration of a disease-free crop, growing in a large field (one or more hectares) under optimal soil conditions including sufficient water and fertility and achieving full production potential of that crop under the given growing environment.

The methods of calculating crop evapotranspiration have been detailed and include the effect of climate on crop water requirements as the mean daily value of ETo in mm for the period considered. The effect of crop characteristics on water requirements is represented by the crop coefficient kc and its values can be obtained from the information outlined in Chapter I.2. For a given crop, planting date, growing season and length of crop development, ET(crop) can be determined by ET(crop) = kc . ET(crop) for each 30 to 10 day period.

EXAMPLE:

Given: Cairo; maize; sown in mid May

total length of growing season	125 days
initial stage	20 ,,
crop development stage	35 ,,
mid-season stage	40 ,,
late season stage	30 ,,

Calculation:

	May	June	July	Aug	Sept	
ETo, mm/day	8.1	8.6	7.9	6.6	5.1	Method III
kc	0.35	0.60	1.12	1.08	0.75	Fig. 7
ET(crop) mm/day	2.8	5.2	8.8	7.1	3.8	Calc.

Mean 10 daily ET(crop) can be obtained from reading kc from Fig. 7 for each 10 day period.

CHAPTER I.4 CONSIDERATION OF FACTORS AFFECTING ET(crop) UNDER PREVAILING LOCAL CONDITIONS

Actual ET(crop) depends to a marked degree on local conditions including variation in climate, size of fields and nature of surrounds, advection, altitude, soil-water availability, salinity, method of irrigation, methods of cultivation and some of these factors are in turn partially dependent on the farming and irrigation practices followed. The prediction methods described so far do not cover all possible factors prevailing under local conditions which may have a distinct effect on ET(crop). Some additional considerations are therefore given in order to alert and orient the user of data when particular conditions occur. Where possible, factors and processes are formulated in quantitative terms; others are formulated in qualitative terms only since the present lack of data hinders adequate quantification of the complex phenomena involved.

I.4.1 CLIMATE

a) Variation with time

For a given location ET(crop) will vary from year to year and for each period within the year.

Total annual ET(crop) on the other hand, will vary little from year to year for many climates since it is largely dependent on the input of solar energy which, outside the atmosphere, may be considered as a constant on a yearly basis. The variation in annual total ET(crop) may be as low as about 10% for the humid tropics, and as high as about 25% for midcontinental climates, depending mostly on the degree of cloudiness.

Compared with the annual variation, monthly ET(crop) values for a given month and location will tend to be larger, the nature of distribution being closely related to typical variations in weather conditions. For mid-latitude continental climates the variability in net radiation can be extreme for a given calendar month. Normal transition months for areas having distinct dry and wet seasons also show significant changes for the same month from year to year; when rains arrive either exceptionally early or exceptionally late the monthly ET(crop) values of that month may vary from one year to the next by 50% or more.

Daily ET(crop) may vary drastically, with low ET(crop) values registered on days that are rainy, humid, cloudy and calm and with high values on dry, sunny, windy days.

As shown in Fig. 10, the wide range of daily, 10-day or monthly ET(crop) values clearly demonstrates that ET(crop) for a given period should be calculated for each year of record rather than using mean climatic data to derive mean values for ET(crop). Not only are extremes of high and low ET(crop) data revealed, but also the expected variation in it allows a better selection of the level of ET(crop) for design purposes. When sufficiently long climatic records are available a frequency distribution analysis should preferably be made. The methodology for making such an analysis is similar to that presented for rainfall (Chapter II.1.2).

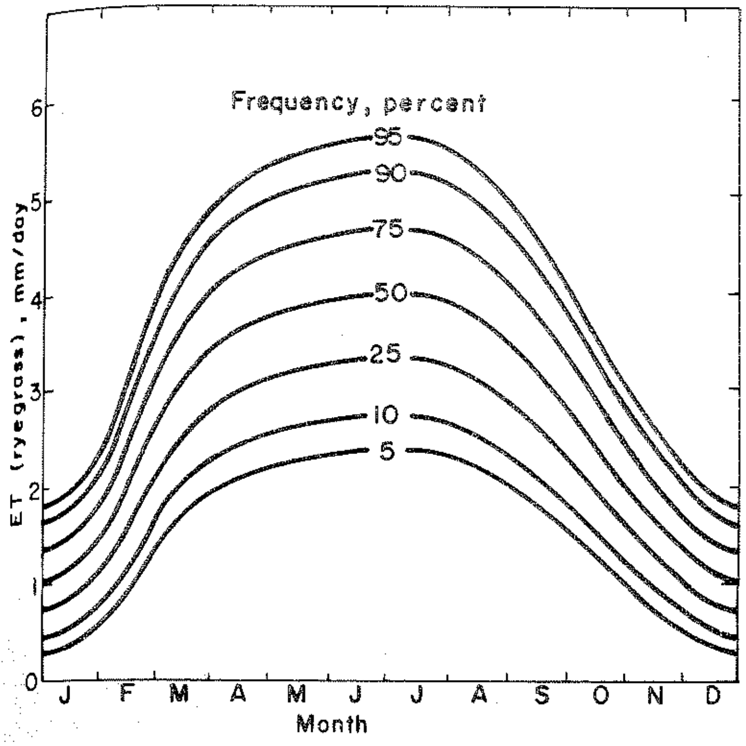
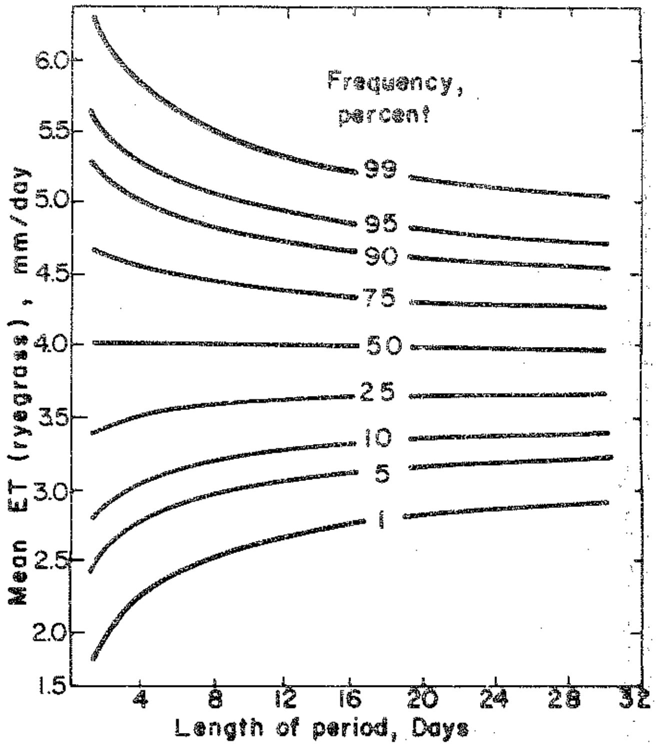


Fig. 10 - Frequency distribution of mean daily ET (ryegrass) for each month in coastal California Valley (Source: Nixon et al. 1972)



Frequency distribution of 1-30 day mean ET (irrigated ryegrass) during peak period June-July (Source: Nixon et al. 1972)

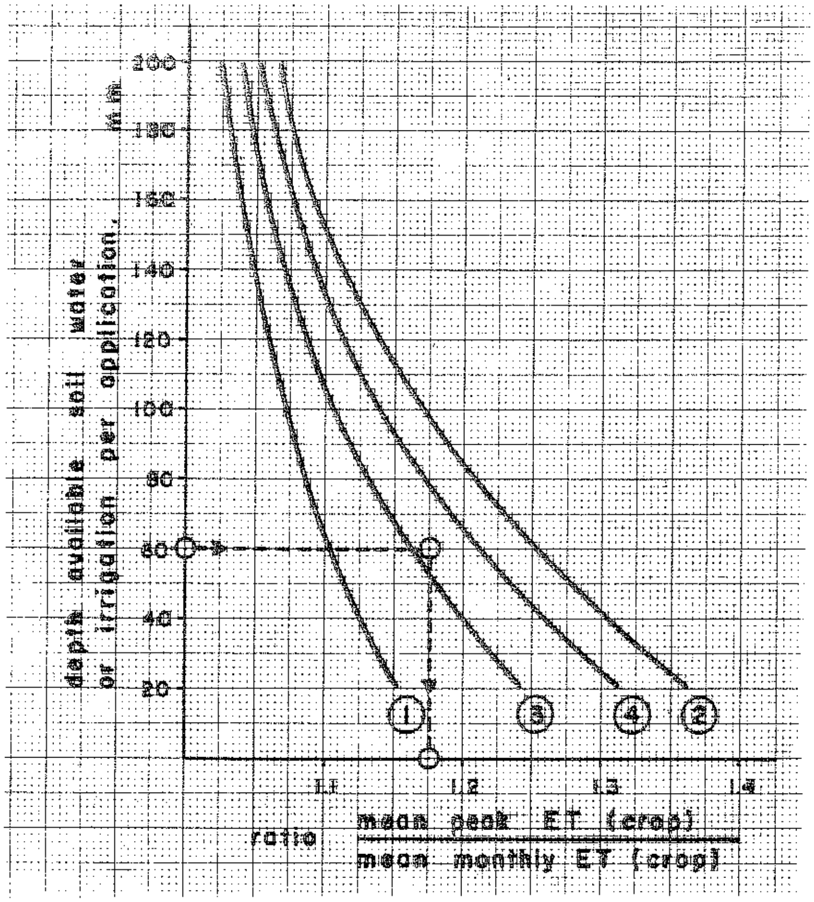
Long ET(crop) records will be needed when analysing the magnitude and frequency of ET(crop) extremes but these are often not available. An irrigation system should have the capacity to meet the adopted levels of peak ET(crop) of the crops it is to serve. Peak ET(crop) will vary with the length of time considered or for any given month or

$$\frac{\text{Peak ET(crop) daily}}{1} > \frac{\text{Peak ET(crop) 10-daily}}{10} > \frac{\text{Peak ET(crop) monthly}}{30}$$

To allow a first estimate of maximum crop water requirements from mean monthly ET(crop) data, consideration must be given to the degree to which ET(crop) may vary during that period, the possible duration of peak ET(crop) within that period and the length of time for which peak ET(crop) can be met from available soil water. In Fig. 11 generalized curves are given for two climatic extremes showing the ratio of average daily peak ET(crop) to average daily ET(crop) for the month of maximum ET(crop) and level of soil water availability.

From Fig. 11 a first approximation can be made of average peak ET(crop) when only mean monthly ET(crop) data are available. Especially when soils are shallow and light, a correction is thus made which allows full water supply to the crop during peak demand.

EXAMPLE: for mid-continental climate with variable cloudiness, mean monthly ET(crop) is 6 mm/day;
depth of available soil water or irrigation per application is 60 mm;
peak period ET(crop) is 6 x 1.175 = 7.1 mm/day.



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

Fig. 11 - Determination of peak period ET(crop) from mean monthly ET(crop) data and depth of available soil water

b) Variation with distance

Weather stations located at some distance from the area under study are frequently the only source of meteorological data. No set of general instructions can be developed on the use of such data. In many locations similar conditions may extend for hundreds of kilometers allowing the use of data collected at distant stations. It is obvious that in zones with rapid changes in climate across comparatively short distances extreme caution should be used; an example is the case of semi-arid and arid areas just inland from large bodies of water, such as Lake Nasser, Aswan, where Epan at an inland distance of only 250 m from the shore is up to double Epan at the shore line of the lake. In areas where the air mass is forced upward as mountain ranges are approached, extreme variations in radiation can be expected. Possible changes in climate over short distances should therefore always be considered before applying data collected in adjacent zones. This is shown by ETo data for California for distances of 5, 40 and 120 km from the coast. See Fig. 12.

Where available, use should be made of climatic surveys already carried out and of publications containing the results of calculations of derived data. A careful check should always be made that available meteorological data used in ET(crop) prediction are representative of the area under investigation.

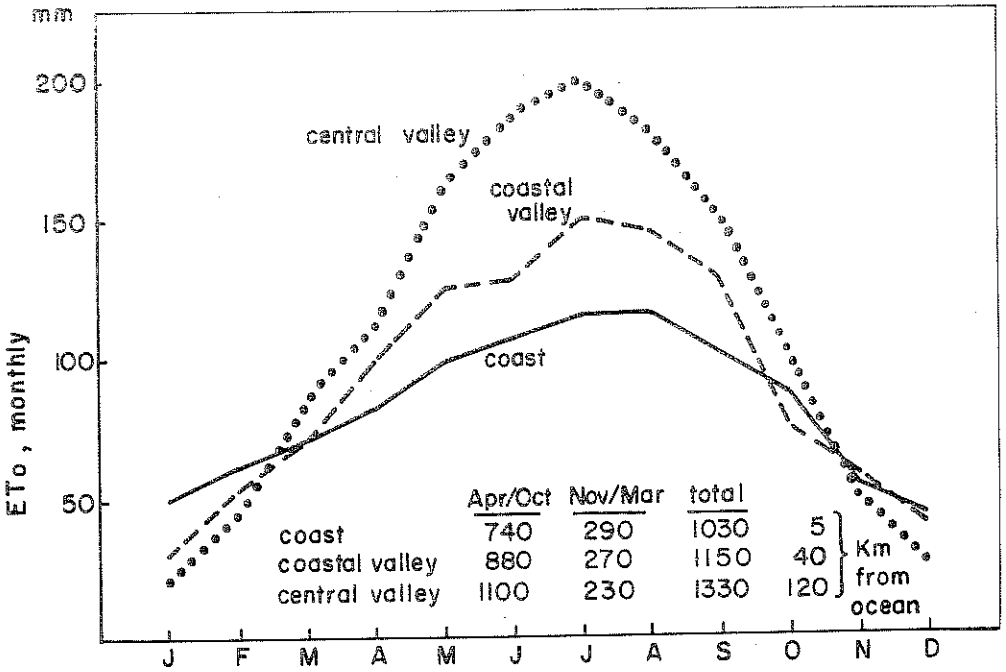


Fig. 12 Change in ETo with distance from ocean, California
(Source: State of California, (1967) Bulletin 113-2)

c) Variation with size of irrigation development: advection

Most of the raw data used in predicting ET(crop) are collected on sites located in rainfed or uncultivated areas, or even on rooftops or at airports. Irrigated fields will produce a different microclimate and ET(crop) may not be equal to predicted values based on meteorological data from sites outside of or collected prior to the development of large irrigation projects. The different microclimate induced by irrigated agriculture will depend mostly on the aridity of the surroundings, wind, size of the irrigated area and distribution and density of irrigated cropped and fallow fields.

Crops grown in arid and semi-arid climates but surrounded by large dry fallow areas are subject to advection by which air masses greatly warmed while passing over such areas will give up heat as they pass over the irrigated fields. Advective energy resolves into the ‘‘clothesline’’ effect at the edge of the field and into the ‘‘oasis’’ effect inside the large irrigated field. Appreciably higher ET(crop) can be expected on the upwind edge of the field and can be as much as double the predicted value for large fields. With increasing distances downwind from the upwind border the air becomes cooler and more humid.

As is shown in Fig. 13, the high ET(crop) values near the edge will fall off sharply followed by a more gradual general decrease. The ‘‘clothesline’’ effect may become negligible with distance from the border where the change of temperature, humidity and wind profiles is complete and a near-equilibrium of air temperature, and humidity is reached. This distance will depend on initial temperature, humidity and wind speed, and may extend in dry hot climates for 100 to 400 m from the leading edge for wind speeds greater than 5 m/sec, 50 to 100 m for speeds of 2 to 5 m/sec and 10 to 25 m for speeds of 0 to 2 m/sec. This aspect is of considerably less importance in humid areas.

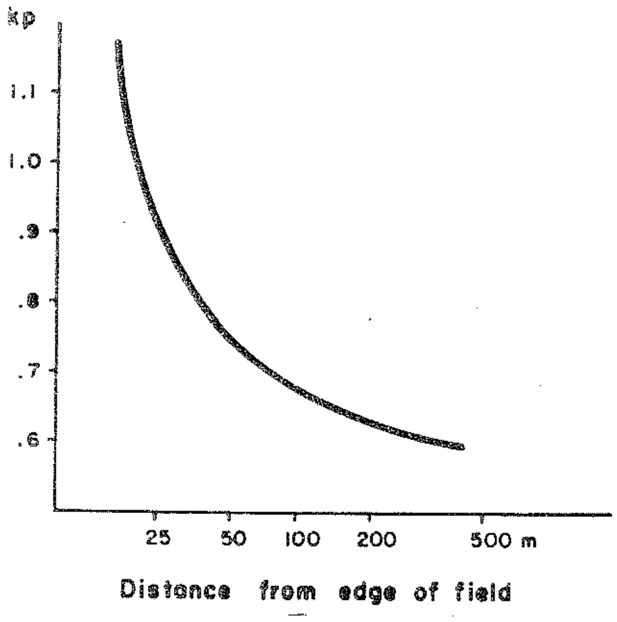


Fig. 13 Value of pan coefficient Kp under arid windy conditions at various distances from upwind edge of the field; A-pan is located in upwind dry fallow field.

It follows that caution should be applied when extrapolating measured ET(crop) data from irrigation experiments carried out on small plots and located in dry surroundings to large irrigation projects. The ''clothesline'' effect on the patchwork of different crops and treatments within small irrigation experimental plots of 0.01 to 0.5 ha can be considerable. With such small plots, especially when surrounded by several hectares of dry surface area, measured experimental results may predict up to double irrigation requirements of a future large irrigation development.

The ''oasis'' effect per se will result in higher ET(crop) values for irrigated fields surrounded by large dry fallow areas compared to irrigated fields in extensive vegetated areas. However, in arid and semi-arid climates, inside the irrigated fields temperatures are generally lower and humidity higher compared to outside the scheme. Therefore, when ET(crop) is predicted from data collected before irrigation development, ET(crop) could be over-predicted by 5 to 15% for fields of 5 to 20 ha and 10 to 25% for large irrigation schemes with a cropping density close to 100%.

In Fig. 14 approximate values for the effect on ET(crop) of size of the irrigated area located in dry fallow surrounds is given for arid hot conditions with moderate winds. Values shown are coefficients for correcting ET(crop) values determined from climatic data from non-irrigated areas.

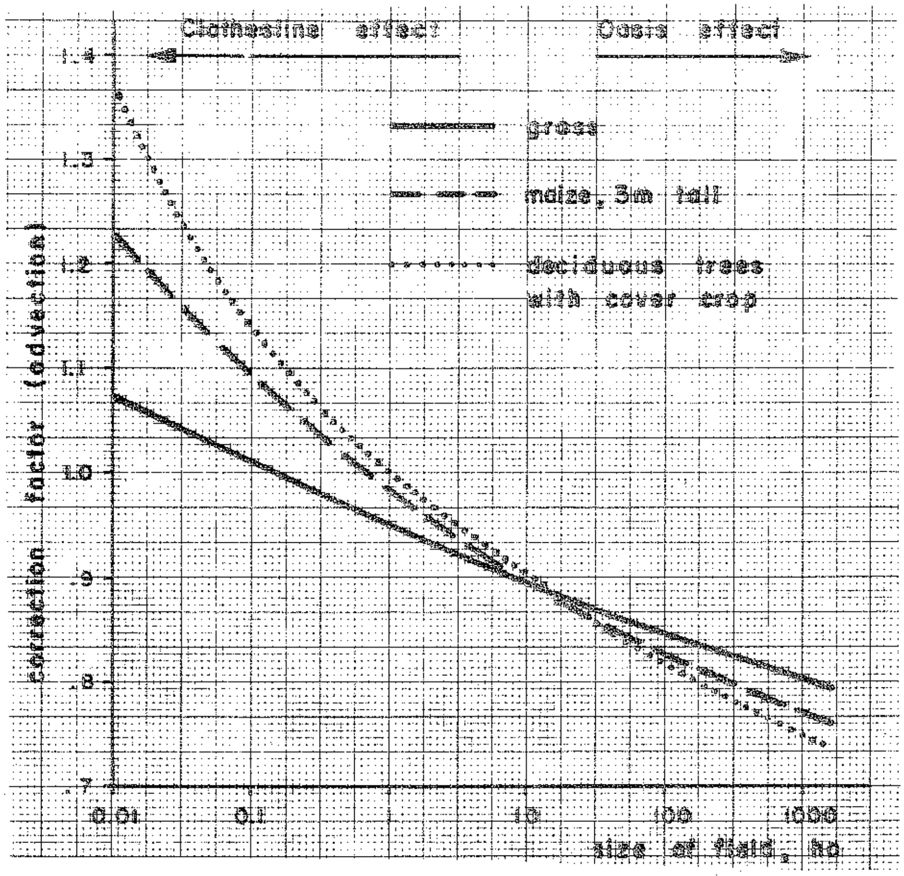


Fig. 14 Correction factors for ET(crop) determined from climatic data collected outside or prior to irrigation development for different size irrigated fields under arid, hot, moderate wind conditions.

<u>EXAMPLE</u>: Crop is maize, climate is arid, hot and wind is moderate; ET(maize) from early data is 10 mm/day. ET(maize) corrected for ''oasis'' effect for a 100 ha continuous cropped field is 10 x .85 = 8.5 mm/day.

The decrease in ET(crop) over long distances is partly offset by uneven distribution of fallow and cropped irrigated fields. This is shown in Fig. 15 presenting Epan data (Hudson) for a given cross section over irrigated cotton and fallow fields in the Gezira scheme, Sudan.

Given an irrigation scheme where the size of the individual cropped field varies from 5 to 20 ha with an overall cropping density of some 50%, ET(crop) has been shown to be as much as 10 to 20% higher than ET(crop) for intensely cropped schemes where cropping densities are close to 100%. Using ET(crop) values determined from areas previous to irrigation development the reduction in ET(crop) over distance will thus be much less drastic as compared to large continuous cropped areas. Apart from other considerations, overall ET(crop) will be reduced by arranging cropped fields as much as possible in large continuous blocks rather than in interspersed small fields.

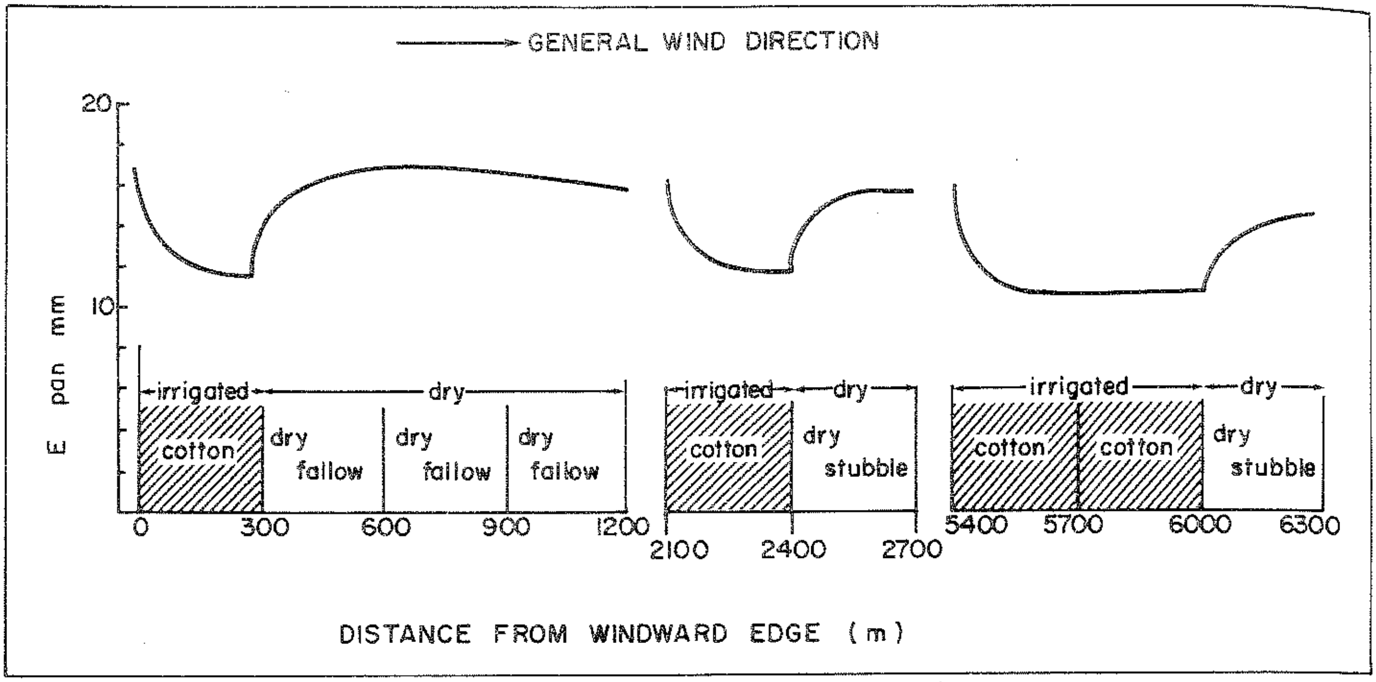


Fig. 15 Changes in Epan (Hudson) data for cross-section over irrigated cotton and fallow fields (Source: Hudson, 1964)

Only approximate values for the effect of advection are presented and these only for arid, hot, moderate wind conditions. Advection is much less important under cool, humid conditions. There is no simple way of evaluating the effect of advection on ET(crop).

d) Variation with altitude

ET(crop) changes significantly with altitude in a given climatic zone. These differences are not caused by variations in altitude as such but mainly by changes in temperature, humidity and in the day-night distribution of wind from areas near the coast to high mountain valleys. Also radiation at high altitudes may be rather different than in low-lying areas. The use of the ET(crop) prediction methods presented will remain problematic for high altitude areas with the possible exception of the Penman and Pan method.

I.4.2 SOIL WATER

a) Level of available soil water

ET(crop) prediction methods presented in Chapter I.1 and I.2 take into account climatic conditions and crop characteristics and assume soil water in ample supply. In the absence of appreciable drainage losses, after irrigation or rain, the soil water content will be reduced primarily by evapotranspiration. As the soil dries out, the rate of water transmitted through the soil and supplied to the roots will reduce and consequently the rate of water uptake by the plant will be affected. ET(crop) will fall at some stage below its predicted level or

$$p = ETa(crop) / ET(crop)$$

where $p \leqslant 1$ and ETa(crop) and ET(crop) are respectively actual and predicted evapotranspiration.

The value of p is dependent on the level of available water in the soil to the crop and on the level of the evaporative demand of the air and will vary with type of crop and soil. The level of available water in the soil can be described as the force or tension at which water is held by the soil at a given soil water content; in common usage soil water tension is expressed in atmospheres (1 atm $\simeq$ 1 bar $\simeq$ 100 centibars $\simeq$ 1000 cm of water). For ease of reference, soil water tension and corresponding available water content in volume percentage are given below. Available water is defined here as the difference in soil water content at field capacity (soil water tension of some 0.2 to 0.3 atm) and at wilting point (16 atm)1/.

Soil water tension	0.2	0.5	2.5	16.	0.2	0.5	2.5	16.
Heavy clay	18	15	8	0	0	17	55	100
Silty clay	19	17	10	0	0	10	45	100
Loam	20	15	7	0	0	25	65	100
Silt loam	25	19	5	0	0	25	80	100
Silty clay loam	16	12	7	0	0	25	55	100
Sandy clay loam	14	11	6	0	0	20	55	100
Sandy loam	13	8	3	0	0	40	75	100
Loamy fine sand	14	11	5	0	0	20	65	100
Medium fine sand	6	3	2	0	0	50	65	100
	Available soil water in volume %				Available soil water depletion in volume %			

For conditions where evaporative demand by the air is high, the point at which soil water supply to the roots becomes insufficient to meet predicted ET(crop) is reached at a lower soil water tension compared to conditions where evaporative demands by the air are low. This will be even more pronounced in heavy textured soils compared to light textured ones since water can be transmitted more rapidly and removed more easily from a light textured soil than a heavy one. Due to differences in plant characteristics, the value of p will vary with crop species. Also the value of p is not constant over the entire irrigation period; p will be equal to unity during days just following irrigation and will gradually decrease until next irrigation.

1/ The concepts of field capacity and wilting point assume static soil water conditions and represent an equilibrium value on soil water content; in fact, soil water through continuous redistribution in the soil profile under both saturated and unsaturated conditions is a dynamic process and in a physical sense no static levels can be assumed. Despite this, the mentioned concepts are, for practical reasons here, still considered as useful criteria for determining the soil water available.

Idealized curves are presented in Fig. 16 indicating the relative decrease in ET(crop) which occurs in a drying soil for both a heavy and a light textured soil at a given soil water tension. The effect of evaporative conditions on the decrease in ET(crop) in a drying soil is shown for ET(grass), adapted from Rijtema, 1965. For well established grass, grown on a deep clay or loamy sand, under low evaporative demand - 2 to 4 mm/day - ET(grass) starts to decrease at soil water tensions of 5 and 8 atmospheres respectively or, correspondingly, available soil water depletion of some 70% for clay and about 99% for loamy sand. Under conditions of high evaporative demand - 8 to 10 mm/day - ET(grass) starts to decrease at a soil water tension of 1.5 and 3 atmospheres or at available soil water depletion levels of 35 and 75% respectively.

Timing and magnitude of ET(crop) reduction are important criteria for predicting crop yield and for recommending irrigation practices. In Table 32, adapted from Rijtema (1965), data are presented on the amount of soil water available since last irrigation for a number of soil types and climatic conditions; soil water depletion in excess of the indicated amount will result in a decrease in predicted ET(crop). Data in Table 32 assume a rooting depth of of 1 m; interpolation can be used to derive estimates for different rooting depths for crops given. With ET(crop) known, a first approximation can be made on the length of time after irrigation that ET(crop) will be maintained at the predicted level. Since higher levels of soil water are found during infiltration and water distribution in the soil profile during and immediately following irrigation, one or two days can be added. Table 32 clearly indicates that under conditions of high evaporative demand the predicted ET(crop) is maintained for a relatively short period following irrigation. Also, total amount of soil water available until ET(crop) begins to reduce varies with the type of crop and type of soil.

<u>EXAMPLE</u>: Alfalfa grown in a medium textured soil;
ET(alfalfa) is 9 mm/day; rooting depth is 1.50 m.
Available soil water after irrigation before ET(alfalfa) will start to reduce is 1.5 x 50 = 75 mm; ET(crop) will start to reduce (75 ÷ 9) + 2 = 10 to 11 days following the last irrigation.

The rate of decrease in ET(crop) is shown in Fig. 17 for cotton grown in Egypt on a fine textured soil (Rijtema and Aboukhaled, in press). Different levels of ET(crop) are assumed. When ET(cotton) is 8 and 12 mm/day, it will remain at this level for some 12 and 8 days respectively. For longer periods since the last irrigation, ET(cotton) is shown to decrease more rapidly under high evapotranspiration conditions compared to lower ones. The value of p will decrease with time; the mean value of p over a period exceeding 24 days since the last irrigation becomes more or less independent of the evaporative conditions. Whether the reduction in ET(cotton) is permissible during part or all of the growing season can only be determined if sufficient data on the effect of soil water stress on yield during the various stages of growth are available. This is discussed in the chapter on crop yields.

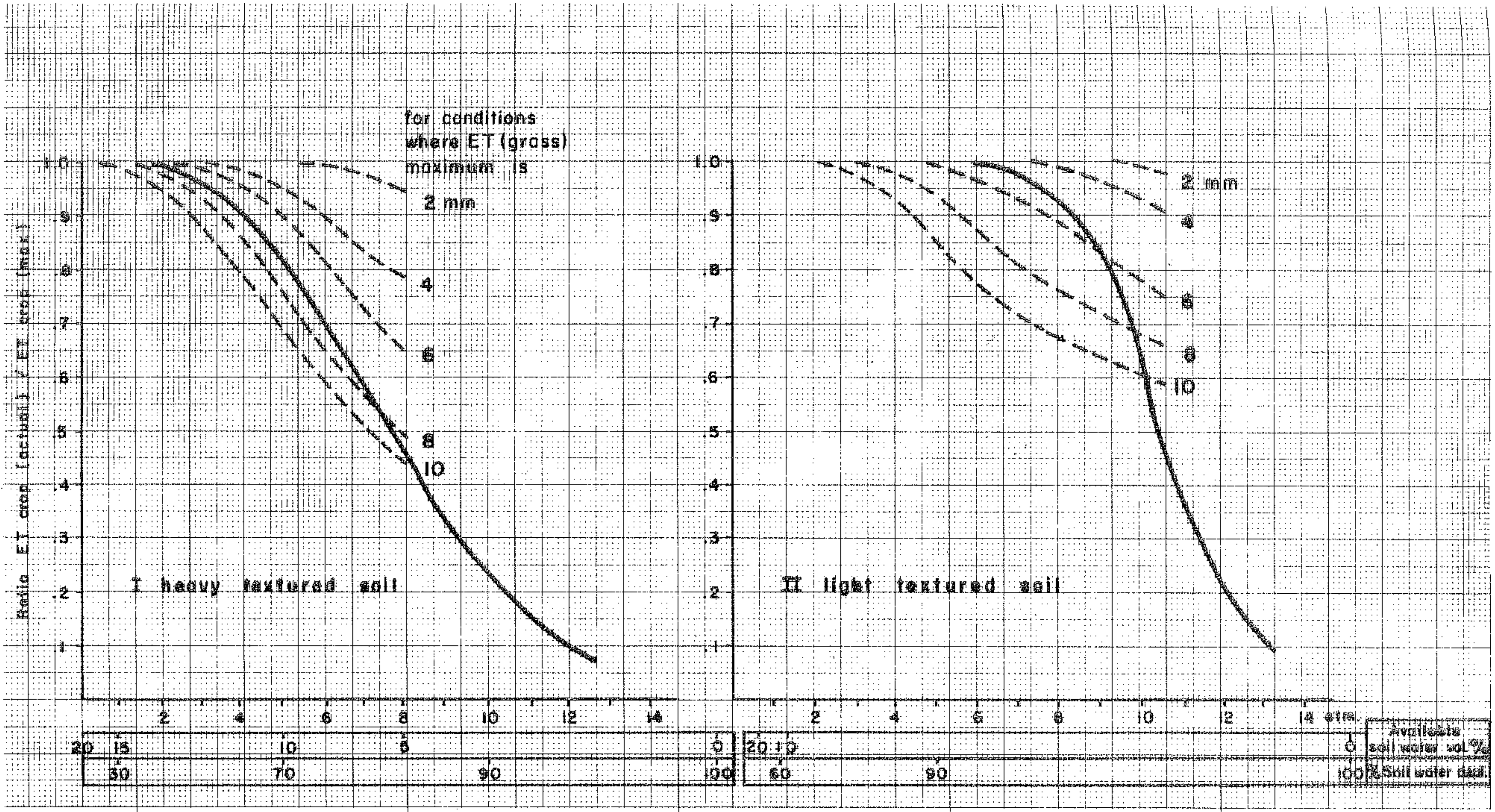


Fig. 16 Ratio ET (crop) actual to ET (crop) maximum for different levels of available soil water for a heavy and a light textured soil.

——— for ET (grass) under different evaporative demand levels - adapted from Rijtema (1965)

Table 32 DEPTH OF SOIL WATER AVAILABLE IN mm FOR DIFFERENT SOIL TEXTURES AND LEVELS OF ET(crop) AT WHICH ET(crop) IS MAINTAINED AT ITS PREDICTED MAXIMUM LEVEL; SOIL DEPTH 1 m

Soil texture	Predicted ET(crop)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Fine (loam - clay)	Cotton	200	190	170	155	140	125	110	100	95	90	80	75	70	65	60	60	55	50	50	50
	Cereals, alfalfa clover, grass	190	165	150	135	115	100	90	80	75	70	65	60	60	55	55	50	50	45	45	
	Sunflower	170	145	125	110	95	80	75	65	60	55	55	50	50	45	40					
	Pepper, potatoes	125	95	75	60	55	45														
Medium (sandy loam - sandy clay loam)	Cotton	130	125	110	100	90	80	70	65	60	55	50	50	45	40	40	35	35	30	30	30
	Cereals, alfalfa clover, grass	125	110	100	85	75	65	60	55	50*	45	40	40	35	35	35	30	30	30	25	
	Sunflower	110	95	85	70	60	55	50	40	40	35	35	30	30	30	25					
	Pepper, potatoes	80	60	50	40	35	30														
Coarse (loamy sand - sand)	Cotton	60	55	50	45	40	35	30	30	25	25	25	20	20	20	20	15	15	15	15	15
	Cereals, alfalfa clover, grass	55	50	45	40	35	30	25	25	20	20	20	15	15	15	15	15	15	15	10	
	Sunflower	50	45	35	30	25	25	20	20	15	15	15	15	15	10	10					
	Pepper, potatoes	35	25	20	15	15	10														

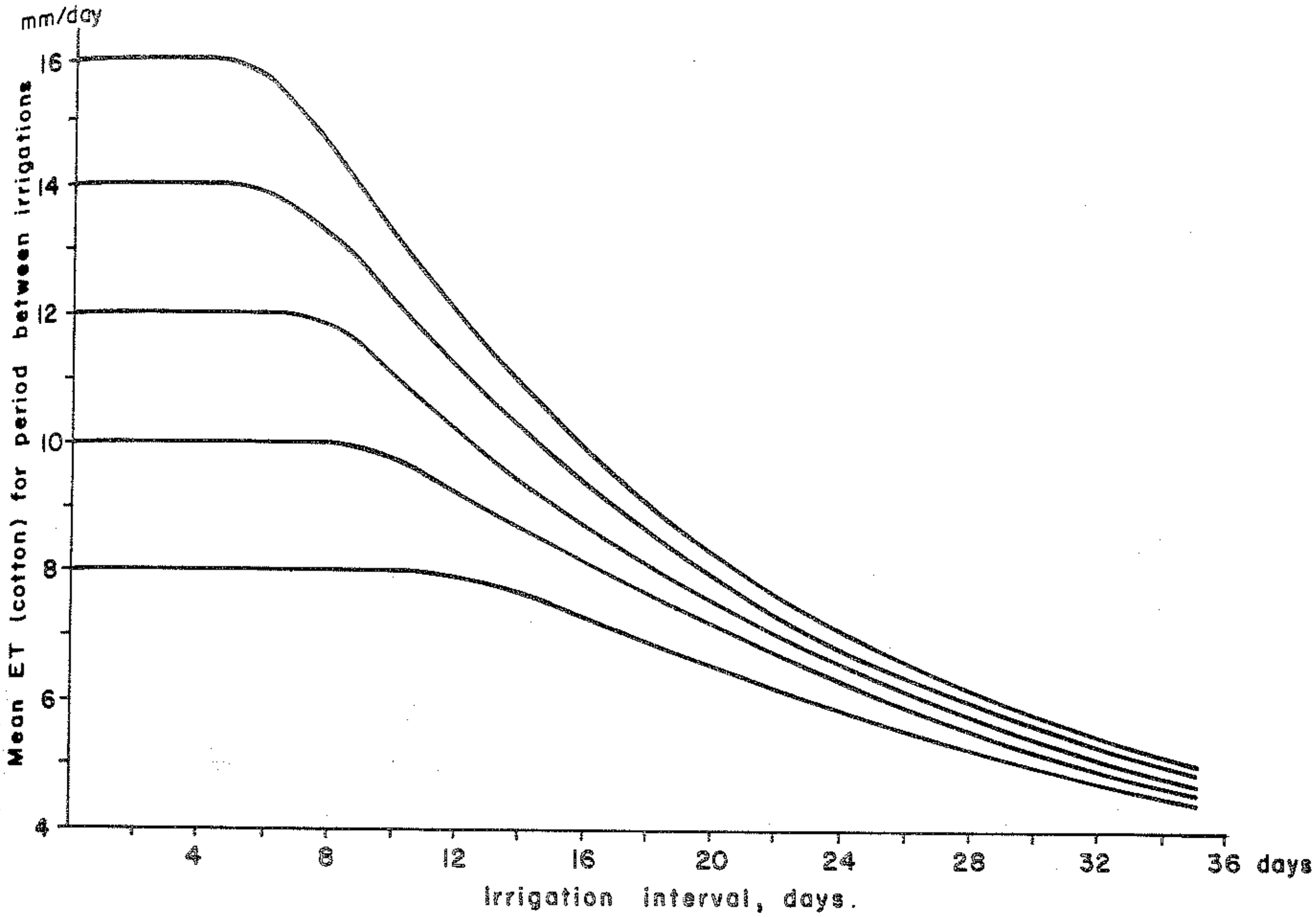


Fig. 17 Mean ET (cotton) and length of irrigation interval for a fine textured soil where ET (cotton) predicted is 16,14,12,10, and 8 mm/days

The above examples show that no generalization can be made on the relation between ET(crop) and soil water tension; its effect will vary with the type of crop, soil type and level of evaporative demand of the air. Stated very generally, under moderate evaporative conditions and if ET(crop) does not exceed approximately 5 mm/day, a reduction in ET(crop) for most crops may be expected at a soil water tension exceeding 1 atmosphere (corresponding approximately to available soil water depletion of some 30 volume % for clay, some 40% for loam, some 50% for sandy loam and some 60% for loamy sand). The relation between soil water and ET(crop) under high evaporative conditions becomes rather complex with wilting and stomatal closure becoming more pronounced.

Information on soil water tension and corresponding soil water depletion levels tolerated by different crops without causing an unacceptable reduction in ET(crop) or, even more important, in yield, is given in Table 36 in the chapter on crop yields (I.4.5).

b) Soil water uptake

Apart from the level of soil water available to the crop, actual soil water uptake is also conditioned by the type and depth of crop root system. Rooting depth and lateral extent are mostly determined by the genetic character of the crop but also by soil texture and structure, presence of impervious layers, depth of groundwater table, level of available soil water at the time of root development and by low soil temperature, particularly in early periods of root development. Poor soil aeration also decreases the rate and extent of root development.

If plants are sufficiently anchored and there are proper growing conditions (water and nutrient availability, soil density, soil temperature), ET(crop) will hardly be affected even when effective rooting depth is severely restricted. However, the danger of drought damage (wilting) will increase and reduced utilization of the subsoil fertility may lead to poor plant development which may subsequently affect ET(crop).

The water uptake pattern over the soil profile has been expressed as 40% of total water uptake over the first one-fourth of total rooting depth, 30% over the second one-fourth, 20% over the third and 10% over the last one-fourth of the total rooting depth. However, horizontal and vertical movement of water will take place in the soil profile when portions become dry. Also, appreciable water can be supplied to the roots from moist soil layers below the root zone. Many scattered data are available on the depth over which the crop extracts most of its water and over which an adequate level of soil water should be maintained. The effective rooting depth over which the plant will extract water from the soil is given in Table 33. A range of depths for each crop is given since effective rooting depth will vary with soil water levels maintained during early growth or high groundwater tables and other factors.

Table 33 EFFECTIVE ROOTING DEPTH FOR VARIOUS CROPS AT MATURE GROWING STAGE GROWN IN HOMOGENEOUS DEEP SOILS

Alfalfa	90-180 cm	Grains	60-150 cm	Safflower	90-180 cm
Beans	50- 90	Grapes	75-180	Soyabeans	60-125
Citrus	120-150	Legumes	50-125	Strawberries	20- 30
Cotton	75-170	Maize	75-160	Sugarbeet	60-125
Crucifers	30- 60	Olives	100-150	Sugarcane	75-180
Cucurbits (cucumbers)	75-125	Onions	30- 75	Tomatoes	40-100
Dec. orchards	100-200	Pastures	60-100	Tobacco	45- 90
Egg plant (aubergine)	75-120	Peppers	40-100	Vegetables	30- 60
		Potatoes	30- 75		

c) Groundwater tables

Soils which are too wet can be just as harmful to plant growth as soils which have little water in the root zone. When groundwater tables are high and soils saturated, the growth and consequent ET(crop) of most crops will be reduced. Wet soils in cooler climates are slow to warm in spring thus causing delays to seed germination and plant development. Also, land preparation and use of farm machinery may have to be restricted resulting in later planting and consequently different ET(crop) rates during the remainder of the season.

The relative tolerance of some crops to oxygen deficits in the root zone, to high groundwater levels and to waterlogging is summarized in Table 34.

Table 34 TOLERANCE LEVELS OF CROPS TO HIGH GROUNDWATER TABLES AND WATERLOGGING

	O_2 deficit	Groundwater tables at 50 cm	Waterlogging
High tolerance	conc. O_2 0-1% rice willow sugarcane various grasses	yield 80-100% sugarcane potatoes broad beans	strawberries various grasses plums
Medium tolerance	conc. O_2 2-5% oats barley onions cotton citrus soyabeans apples	yield 60-80% sugarbeet wheat barley oats peas cotton	citrus banana apples pears blackberries
Sensitive	conc. O_2>10% maize peas beans tobacco	yield < 60% maize	peach cherry date palm olives

Source: International Sourcebook on Irrigation and Drainage of Arid Lands, FAO/Unesco, 1973.

Higher groundwater tables are generally permitted in sandy soils than in loam and clay soils since the latter have very limited air-filled pores in the capillary fringe above the groundwater table. In sandy soils, more pore space will contain air in comparable conditions. This effect of soil type has been expressed as minimum depth of groundwater table required for maximum yields for most crops as follows:

sand, rooting depth + 20 cm
clay, rooting depth + 40 cm
loam, rooting depth + 80 cm

d) Salinity

ET(crop) can be affected by soil salinity which is partly caused by reduction in water availability due to salinity, by reduced growth due to nutritional imbalances and by toxic effects of specific ions in solution. Uptake of soil water by the plant can be drastically reduced due to the higher osmotic pressure of the saline soil water 1/. An additional factor causing poor plant growth may be the poor physical characteristics of some soils due to sodium associated with soluble salts which causes low water transmission and lack of aeration. It is impossible to distinguish the relative extent to which each of these factors affects ET(crop). The composition of salts contained in the soil water has an effect on plant growth (specific ion toxicity); crops like citrus and most fruit trees are very sensitive to sodium and/or chloride. Chlorides may cause a sharper drop in ET(crop) than an equivalent amount of sulphate.

Reduced water uptake by the plant under saline conditions is shown by symptoms similar in appearance to those of drought such as early wilting, leaf burning, a bluish-green colour in some plants, reduced growth and small leaves. Certain shallow rooted crops require high soil water levels for best production, e.g. potatoes and onions, may be particularly sensitive to reduced availability of free water. It follows that high evaporative conditions accentuate the effect of salinity on water uptake by the plants and consequently the effect on ET(crop) is evidenced more rapidly. The same level of soil salinity can be expected to cause more damage under hot conditions than under cool weather unless water management can be adjusted to meet the added ET demand. The detrimental effect of soil salinity on the water uptake by the crop can be partly off-set by maintaining a high level of soil water in the root zone.

1/ High salt concentration will increase total soil water tension as exerted by both the soil and the salt solution. The approximate relation between salt content or the soil solution and osmotic pressure is:

Conductivity mmhos	Salt content ppm	meq/1	Osmotic pressure atm
1	650	10	0.3
2.5	1 600	30	0.9
5	3 300	60	1.9
7.5	5 000	90	2.9
10	6 600	125	3.9
20	13 000	270	8.2

The osmotic effect (atmospheres) can be added to usual soil water tension (atmospheres) to obtain approximate net effect on water availability.

I.4.3 METHOD OF IRRIGATION

ET(crop) is little affected 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 are met. Selection of the method is generally determined by the cost of water application, water use efficiency, simplicity of the system, soil erosion and deterioration, salinity of irrigation water and perhaps other factors.

Different methods of irrigation generally imply different rates of water application. In experiments to evaluate and compare the various methods in terms of water efficiency, 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. There are several sources of information for practical considerations on irrigation methods and practices 1/.

A number of practices which may directly affect ET(crop) are mentioned briefly below.

a) Surface irrigation

The practice of reducing the area wetted by alternate furrow irrigation for row crops generally has little effect on the total quantity of irrigation water needed. The positive effect on crop growth of alternating furrow irrigation which has sometimes been noticed should therefore be ascribed to other factors such as better soil aeration. Only in the case of incomplete crop cover - less than 60% - and of a relatively small wetted area - less than 30% - will there be a noticeable reduction in evaporation from the soil surface. This practice is often followed in orchards and vineyards by means of irrigating furrows and basins near the stems of fruit trees and vines; the net reduction in seasonal ET(crop) generally will not be more than 5%.

b) Sprinkler irrigation

ET(crop), including the direct evaporation of water from wet leaves, of recently sprinkled crops with full crop cover does not greatly exceed predicted ET(crop) rates. Transpiration by the crop may be greatly reduced during application but will be compensated by increased evaporation from the wet leaves and soil surface. However, the higher evaporation from wet leaves does not lead to a significant increase in water loss. 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 under severe hot dry conditions; a temperature drop of up to 10°C and a humidity increase of up to 30% has been noted. The effect of irrigation on micro-climatic modification is however relatively short lived and little effect on ET(crop) will be observed.

1/ For surface irrigation Booher (1974) and Merriam (1968); for basin irrigation Slabbers (1971); sprinkler irrigation Pillsbury (1968); and trickle irrigation in FAO Irrigation and Drainage Paper No. 14 (1973) and Keller and Karmeli Trickle Irrigation Design (1974).

Evaporation losses occur from the spray, their magnitude depending on climate (wind, temperature, humidity) and spray characteristics such as radius of spray and size of drops. Such losses have been estimated to range from 2 to possibly 8% of the water discharged by the sprinklers. Strong winds will result in poor water distribution. Depending on sprinkler system design, sprinkler irrigation should not be used when windspeeds are over 5 m/sec.

c) Drip or trickle irrigation

Drip irrigation systems allow frequent application of small quantities of water which closely follow the rate of soil water uptake by the crop. A well operated drip system can provide a nearly constant low tension soil water condition in major portion of the plant root zone. The high water use efficiency can be attributed to improved water conveyance and water distribution to the root zone. Evapotranspiration of a crop with near or full ground cover such as vegetables and closely spaced mature tree crops should be affected little by this method of irrigation unless under-irrigation is practised. It is only with widely spaced crops and young orchards that ET(crop) will be reduced since a small proportion of the soil surface will be wetted and evaporation from it will be restricted to that area kept moist near the individual plant or tree. For young orchards with 20 to 30% groundcover on light sandy soils and under conditions of high evaporation requiring very frequent irrigations, a reduction in ET(crop) of up to possibly 60% as compared to surface and sprinkler irrigation has been observed. This reduction in ET(crop) would be considerably lower for medium to heavy textured soils or for conditions with low evaporative demands requiring much less frequent irrigation applications. For closely spaced crops the crop water requirements under drip irrigation can be predicted using the methods described without applying any reduction factor.

d) Subsurface irrigation

When meeting crop water demands with a subsurface water distribution system, depending on the adequacy of the water supply through upward water movement to the root zone, ET(crop) should be affected little except for the early stage of growth of some crops which require frequent irrigation.

I.4.4 CULTURAL PRACTICES

a) Fertilizers

The use of fertilizers to promote maximum plant growth and crop yields gives only a slight affect on seasonal ET(crop), if any, unless crop growth was previously severely affected by low soil nutrition. Lower water uptake is experienced during early stages of crop growth as poor fertilization will retard vegetative growth and full crop cover is attained at a later date. In well-fertilized soil the crop may be somewhat less susceptible to droughts due to a better developed root system. 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 plant are thus highly dependent on method and frequency of irrigation. The effect of fertilizer on crop yields and the relation between wateruse and yield for different fertilizer applications are shown in Figs. 18 and 19 for wheat and maize respectively.

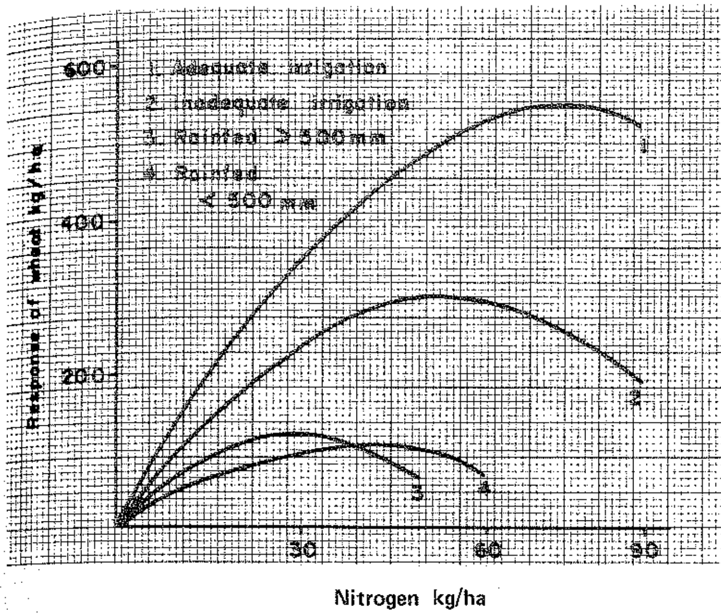


Fig. 18 Effect of water supply on response of wheat to nitrogen (Source: E.W. Bolle-Jones and M. Rezania, Soil Institute of Iran, Teheran, 1969).

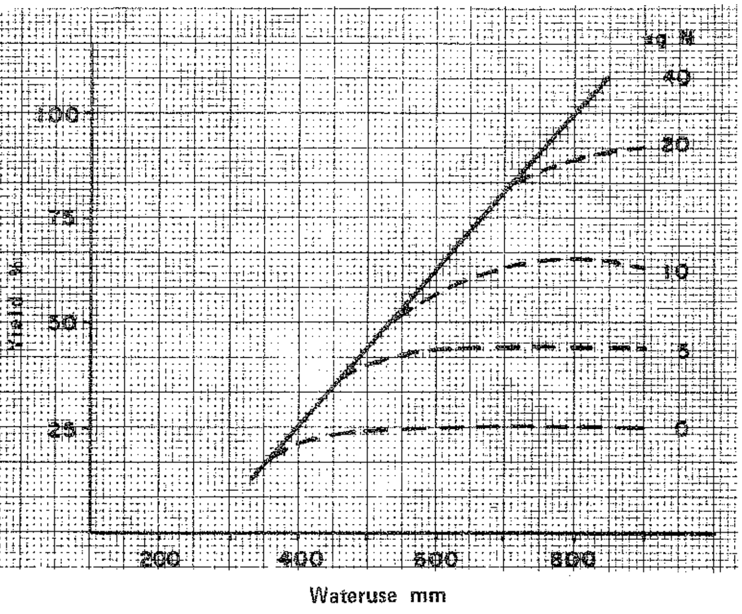


Fig. 19 Relation between wateruse and kernel yield of maize at 5 nitrogen fertilizer levels (Shimshi 1967).

b) Plant population

The effect of plant population or plant density on ET(crop) is similar to that of percentage of groundcover. Under conditions where the soil surface is kept wet and crop cover is less than about 60%, the total amount of water transpired by the plant and evaporated from the soil surface may even exceed the ET(crop) of high population crops due to greater overall roughness and lower reflectivity of moist soil. When top soils are relatively dry, evaporation from the soil surface is sharply reduced and ET(crop) will be less for low population crops than for high population crops.

The effect of population on ET(crop) and in particular the increased sensitivity of high population crops to droughts has received much more attention in rainfed agriculture. Few data are available for dense, irrigated crop populations since in irrigated agriculture this aspect has been considered to have little importance in terms of total water needs. For a given crop, a high population planting would normally require more water in the early stages of crop development than a low density planting due to quicker development of full groundcover.

c) Tillage

Except for soils which tend to form deep cracks, tillage produces little if any effect on ET(crop) unless a significant quantity of weeds is eliminated. Rough tillage will accelerate evaporation from the plough layer; deep tillage may increase ET(crop) when the land is fallow or when the crop cover is sparse. However other factors such as higher infiltration rates may decide in favour of tillage. On some soils tillage may be required to break up sealed furrow surfaces in order to achieve adequate infiltration. Soil ripping between crop rows may result in temporarily higher infiltration rates but the crop could be slightly set back due to root pruning.

d) Mulching

Except for specific purposes such as a reduction in erosion by wind and in water runoff, the use of a mulch of crop residues in irrigated agriculture to reduce ET(crop) is often considered of little net benefit. 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 reflective 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, possible slower plant development due to lower soil temperatures, and problematic water distribution from surface irrigation.

However, a major advantage of mulching using organic plant material is the protection of the soil surface, preventing soil capping or sealing and it may produce a higher infiltration rate which results in greater storage of rainfall in the soil.

Polyethylene and perhaps also asphalt mulches are the most effective. A net reduction in ET(crop) using waterproof covers is however largely dependent on the percentage of land covered as well as on the percentage of crop cover. The method is most effective when mulch covers more than 80% of the soil surface and crop cover is less than 50% of the total cultivated area. For instance, positive results have been obtained in Tunisia on strawberries where plants grow through holes in plastic sheets and the soil is kept relatively wet. Wead control and little rotting of the fruit added to the successful use of plastic.

e) Windbreaks

Due to a reduction in wind velocities produced by artificial and vegetative windbreaks, ET(crop) may be reduced under windy, warm, dry conditions by about 5% at a horizontal distance equal to 25 times the height of the barrier downwind from it, increasing to 10 and sometimes up to 30% at a distance of 10 times this height. However, ET(crop) as determined by the overall climatic conditions is not altered. In most cases shrubs and trees are used and thus, due to the transpiration of the vegetative windbreak, overall ET may be more.

Regardless of the benefits of reduced ET(crop), wind damage to crops, such as by the mistral in southern France, may be far more serious than the increase in total water loss. A productive, low water consuming windbreak, for example citrus, or an artificial wind barrier might be considered in order to eliminate even this last negative effect. Recent studies have shown in Nebraska (U.S.A.) that due to the protective physical effect of artificial wind barriers, crop yields of maize can be increased by from 10 up to 30% without an increase in ET(crop).

f) Anti-transpirants

The use of anti-transpirant, natural or artificially induced variations in plant foliage properties and soil conditioners to reduce ET(crop), continues to interest many investigators, but so far is still in the experimental stage.

I.4.5 CROP YIELDS

Knowledge of the relationship between crop water requirements and crop yields is needed to predict levels of production that can be achieved by varying the allocation and use of available water for irrigation. Whether or not ET(crop) is to be fully met by adequate irrigation water supply depends on set objectives such as maximum production in relation to investment, greatest yield per unit of water when water is short, greatest yield per unit of land when land is short, in assuring the greatest number of farmers to benefit from irrigation when socio-economic factors are most pressing, or in assuring a high net income for the farmers. Also, in project operations, particularly during periods of water shortage, decisions need to be made on the best use of available water and how to minimize reduction in crop yields due to drought. Much of the information required concerns the relation between periods when the crop is most sensitive to reduced water uptake associated with soil water stresses.

The relation between crop yields and water seems confusing due to the many factors involved. Earlier investigations suggested that for most crops a linear relationship exists between seasonal ET(crop) and dry matter production. The slope of the linear relationship varies with each crop species. For instance, to obtain the same dry matter yield, total seasonal ET(alfalfa) may be four times that of sorghum, and twice that of wheat. ET(rice) of high-yielding varieties is similar to that of traditional rice varieties but yields can be fourfold provided good water management is practised and other agricultural inputs are supplied at the correct time. In addition, climate also affects the relationships as shown in Fig. 20 for dry matter production of grass.

The linear relationshp between dry matter production and seasonal ET(crop) seems to be valid only when other growth factors such as fertilizers, temperature, sunshine and soil depth are not limiting. However, for most crops dry matter production does not determine the actual yield as this depends on the harvested part of the plant which can be either a chemical constituent (e.g. sugar, oil) or reproductive (apples, grain). Additional consideration will be needed to express the relationship between harvested yield and ET(crop).

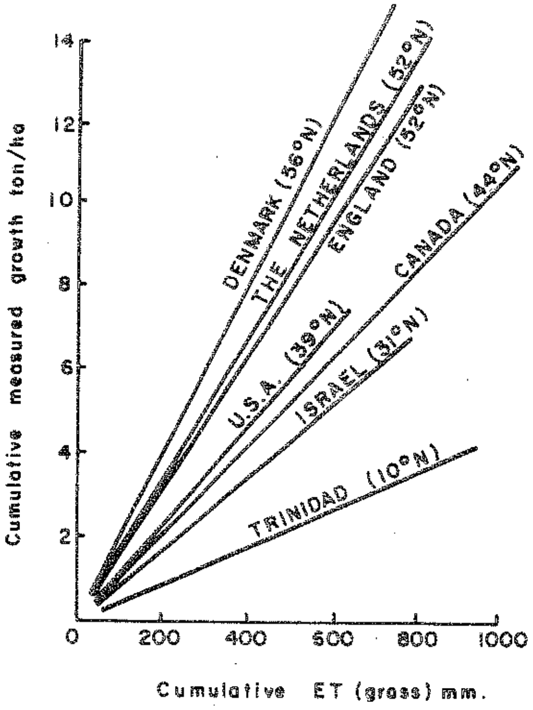


Fig. 20 Relation between ET(grass) and dry matter production from pastures at different latitudes (Stanhill 1960)

Recently developed concepts seem to show that for harvested yields the ratio of relative yield to relative ET(crop) may be assumed to be constant or nearly constant for a given variety provided specific crop characteristics and growth stage effects are controlled, and growth factors other than water are not limiting. If this is so, knowledge of the slope of the two parameters considered, that is actual ET(crop)/maximum ET(crop) versus actual yield/maximum yield, combined with the quantitative prediction of maximum yield and maximum ET(crop), would enable a quantitative prediction to be made of yields to be obtained with the selected water supply for any given location with a suitable climate (Stewart and Hagan, 1973, 1974). This assumption seems to be supported by Downey (1972) who provides data on 14 non-forage crops including wheat, potatoes, cotton, beans, maize, drawing these data from a variety of sources. Figure 21(1) shows that for dotted envelope curves representing 86% of the results analysed, yields decrease by 80% when actual ET(crop) is allowed to drop to 0.5 ET(crop) maximum; yields decrease by 50% when actual ET(crop) is 0.7 ET(crop) maximum. These data apply for conditions where soil water is available at a fairly constant reduced rate for most of the growing season. It should be noted that the curve does not begin at the origin; there is a threshold value below which production is negligible.

The effect of water shortage on yield is very pronounced during periods when the plant is particularly susceptible to water stress. This is shown for maize in Fig. 21(2) for which yields are negligible when limited soil water sharply reduces ET(crop) during the tasselling stage. Figure 21(3) shows a generalized relationship between yield and actual ET(sugarcane) in Hawaii. Prolonged reduction in ET(cane) during the period of active growth from

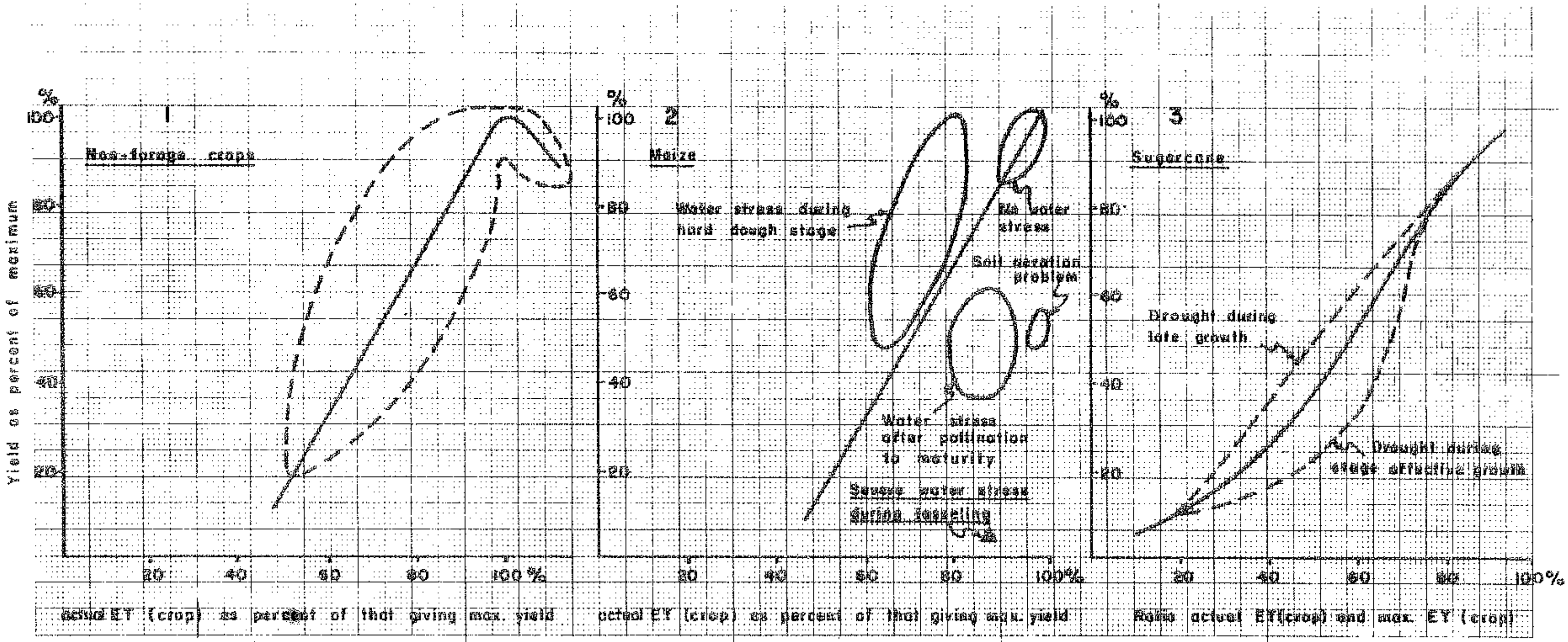


Fig. 21 Relationships between relative yield and relative ET (crop) for non-forage crops, maize, and virgin cane (Downey (1972), Chang (1963)).

12 to 14 months after planting virgin cane will have a much greater negative effect on yields than if the reduction in ET(cane) is experienced during the late growth period.

Reducing ET(crop) by decreasing the irrigation supply or by extending the irrigation interval beyond the period during which soil water is freely available to the crop is thus particularly critical during times when the crop is sensitive to soil water stress; at that time any soil water stress may have a lasting effect and could drastically reduce yields. Critical stages of crop growth for most field crops can be considered as any changes from vegetative to reproductive growth-heading and flowering to fruit setting. However some crops have no specific critical stage, for example such vegetables as potatoes, bananas and other crops grown for fresh weight production, but they are sensitive in any period to prolonged water stress conditions. Critical stages for soil water of some crops are given in Table 35.

In order to produce high yields, crops have different requirements as to maximum soil water tension or degree of depletion between irrigations. Some crops will only produce an acceptable yield when soil water is kept at a high level, usually well above 50% of available soil water. Crops requiring relatively wet soils include most vegetables, potatoes, bananas, etc. Yields from other crops including deciduous fruits, barley and sugarbeet, normally do not respond when water is applied above the 50% depletion level. Moreover, soil water deficits can sometimes have a positive effect on the quality of yields; slight deficits may improve the quality of apples, peaches and plums, and increase the aromatic quality of tobacco and the oil content of olives. An induced reduction in ET(crop) before harvesting may also increase the sugar content of sugarcane. Irrigations should therefore be scheduled to bring about the specific soil water levels required by the crops.

Information on soil water tension tolerated by different crops without causing an unacceptable reduction in ET(crop) or, even more important, an unacceptable reduction in yield, is given in Table 36. The corresponding level of available soil water depletion should not be exceeded, particularly during critical periods. Lower values apply to high and higher values apply to low evaporative conditions; values given in the table represent mostly vegetative periods and may not apply during critical periods where plants are sensitive to soil water stress. A comprehensive review of the subject of crop responses to soil water deficits at different stages of crop growth including the critical stage for soil water stress can be obtained from the references given [1]

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[1] R.O. Slatyer, Plant-Water Relationships, Academic Press, 1967.
R.M. Hagan, H.R. Haise and T.W. Edminster, Irrigation of Agricultural Lands, ASA No. 11, 1967.
T.T. Kozlowski, Water Deficits and Plant Growth I, II and III, Academic Press, 1968.
P.J. Salter and J.E. Goode, Crop Responses to Water at Different Stages of Growth, Commonwealth Agricultural Bureau, 1967.
Y.F. Vaadia et al, Plant Water Deficits and Physiological Processes, American Review of Plant Physiology, 12: 265-292, 1961.

Table 35 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.

Table 36 SOIL WATER DEPLETION LEVELS, EXPRESSED IN SOIL WATER TENSIONS, TOLERATED BY DIFFERENT CROPS FOR WHICH ET(crop) REMAINS AT PREDICTED LEVEL AND MAXIMUM YIELDS ARE OBTAINED

Alfalfa	0.8 - 1.5 atm 1/	Onions	0.4 - 0.7
Banana	0.3 - 1.5	Peas	0.3 - 0.8
Beans	0.6 - 1.0 1/	Potatoes	0.3 - 0.7
Cabbage	0.6 - 1.0	Rice	at or near saturation
Carrots	0.5 - 0.7	Safflower	1.0 - 2.0 1/
Citrus	0.5 - 1.0	Small grains	0.4 - 1.0 1/
Clover	0.3 - 0.6	Sorghum	0.6 - 1.3 1/
Cotton	1.0 - 3.0	Soybeans	0.5 - 1.5
Cucumber	1.0 - 3.0	Strawberries	0.2 - 0.5
Deciduous fruits	0.6 - 1.0	Sugarbeet	0.6 - 0.8
Flowers & ornamentals	0.1 - 0.5	Sugarcane	0.8 - 1.5 1/
Grapes	0.4 - 1.0	Tobacco, early	0.3 - 0.8
Grass	0.4 - 1.0	,, late	0.8 - 2.5
Lettuce	0.4 - 0.6	Tomatoes	0.5 - 1.5
Maize	0.5 - 1.5 1/	Wheat	0.8 - 1.5
Melons	0.3 - 0.8	,, ripening	3.0 - 4.0

1/ Higher values than those shown apply during ripening period.

Source: Taylor 1965, Hagan and Stewart 1972, Salter and Goode 1967, and others.

PART II CALCULATION OF FIELD IRRIGATION REQUIREMENTS, If

INTRODUCTION

Field irrigation requirement is the amount of water and timing of its application needed to compensate soil water deficits during the growing season of a given crop. Irrigation requirements are determined by crop evapotranspiration minus the water contributed from precipitation, groundwater, carryover of soil water from earlier precipitation or flooding, and surface and subsurface in flow. It is expressed in mm per growing period (season or one month or less) for the purpose of overall planning and evaluation of the field, project or basin water balance. Summarized over the entire cultivated area, it forms the basis for determining the necessary supply and the adequacy of available water resources. It is expressed in the form of an irrigation schedule in depth of an interval between irrigation for the purpose of project operations (mm and days).

Irrigation is never 100 percent effective and allowance must be made for unavoidable and avoidable losses including deep percolation, surface runoff and other managerial or technical faults. Irrigation application efficiency Ea is normally expressed in fraction or percentage of In or field irrigation requirement If = In/Ea where In is the net irrigation requirement and If is the gross field irrigation requirement.

In is based on the field water balance which for a given crop and period can be expressed as:

$$In = [ET(crop) + F + R] - [Pe + Ge + N + \Delta W]$$

$$= \quad \text{losses} \quad - \quad \text{gains}$$

where Pe and Ge are the effective contribution to the rootzone by rainfall and groundwater respectively; surface and subsurface in and outflow, N and R can be of local significance; deep percolation F which takes place after the soil has attained field capacity following irrigation is generally but incorrectly accounted for in the correction of Ea, the field application efficiency; ΔW is the change in soil water content in the effective root zone which, under irrigation, should vary between field capacity and maximum available soil water depletion for a given soil and crop. All variables can be expressed in units of depth of water (mm). Depending on data available and accuracy required, In can be predicted for seasonal, monthly or 10 day periods.

Of importance is the period or time interval over which the field water balance is made. Too long periods may obscure the occurrence of short duration water shortages. For instance, when using monthly data, monthly effective rainfall may be shown to meet monthly ET(crop) but since rainfall is normally not distributed evenly over the month, short duration water deficits may occur. Too short periods may be impractical. It should be realized that when using a monthly rather than a daily balance this may produce results acceptable for overall planning purposes but these results may be far from realistic for use in detailed design and operation of irrigation works, and in scheduling field application.

In most cases, calculation of the field water balance will have to be made for alternative cropping patterns in order to find the optimum solution between irrigation requirements and water supply available at source.

CALCULATION PROCEDURES

When determining field irrigation requirements for a selected crop and cropping pattern for overall planning purposes certain data are required and to obtain it procedures are suggested. Determine:

1. for alternative crops, cropping patterns and intensities the variables composing the field water balance for the growing season and for shorter periods:
   crop evapotranspiration, ET(crop)
   effective precipitation, Pe
   groundwater contribution, Ge
   surface and subsurface in and outflow, N and R
   deep percolation from rootzone, F
   changes in stored soil water, ΔW
2. from field water balance the seasonal and monthly net irrigation requirements In;
3. for the month of maximum net irrigation requirements, the peak period net irrigation requirements Inpeak;
4. after selecting field irrigation application efficiency, the gross field irrigation requirements If;
5. the water requirements for cultural practices and leaching of salts;
6. the irrigation schedules from field water balance, taking also into account water storage capacity of the soil and level of soil water required by the crop.

CHAPTER II.1 FIELD WATER BALANCE

To calculate net irrigation requirements for seasonal, monthly or shorter periods the variables composing the field water balance must be determined first.

II.1.1 Crop evapotranspiration, ET(crop)

Crop evapotranspiration, ET(crop) can be determined using one of the four prediction methods given in Chapter I.1 and selecting an appropriate crop coefficient kc from Chapter I.2. At this point of investigations data on ET(crop) for different crops and cropping periods should be available, taking into account also the considerations given in Chapter 1.4. Expected crops yields, agricultural inputs, soil improvements and sometimes other opposite facets should have been investigated.

Depending on local weather conditions, ET(crop) will vary from year to year and for each period therein; ET(crop) should then preferably be calculated for each year for which climatic records are available. A probability analysis may be made from which ET(crop) value can be selected.

When mean climatic data from available years of record are used to predict ET(crop), a correction factor on ET(crop) to account for the year to year variation in it for the given period will be required. For overall planning this correction is normally applied only for the month of maximum irrigation requirements in order to derive peak water requirements. Details are described in Chapter I.4.1.

When climatic data have been used collected outside or prior to large scale irrigation development, a correction of the effect of advection may be required - as given in Chapter I.4.1.

To reduce the risk of crop failure due to water shortages or drought, in overall planning an ample supply of soil water to the crop is normally assumed. Only in the case that detailed data on the relation between ET(crop) and level of production have been locally determined, and when water is short in supply or expensive, should a reduction in the predicted ET(crop) and a level of production below maximum be considered. This is discussed in Chapter 1.4.5.

EXAMPLE: semi-arid, hot and moderate winds during July and August; crop is maize sown mid May, harvested end September; size of fields is 10 ha and cropping intensity is 50%; surrounds are dry fallow lands; irrigation depth of application is 80 mm; climatic data are collected before irrigation development in non-agricultural area,

	May	June	July	Aug.	Sept.
ET(maize) mm	2.8	5.2	8.8	7.1	3.8 (Chap. I.1 and 2)
Correction factor advection	0.95	0.95	0.9	0.9	0.95 (Chap. I. 4.1)
Correction peak month			1.09		(Chap. I. 4.1)
ET(maize) mm	2.7	4.9	8.6	6.4	3.6 (calc.)

II.1.2 Effective precipitation, Pe

a) Rainfall

Vital to irrigation planning is knowledge of the frequency and amount of rainfall. Since rainfall for a given period can be expected to vary considerably from year to year, mean rainfall based on short records can at best be considered a very gross approximation and subject to large errors. Also, not all rainfall is effective; part is lost by runoff, by deep percolation or by evaporation. Methods are given below to estimate the percentage of effective rainfall which will be available to the crop.

Future rainfall can be projected through statistical analysis of past rainfall records. Rainfall probabilities derived from historical data will show the amount which can be expected in any percentage of time and from this a dependable level of rainfall can then be selected. A practical and realistic value of dependable rainfall frequently used is mean monthly rainfall that occurs on a probability basis three years out of four; however, this also means a shortage one year out of four. To allow proper evaluation of dependable rainfall the degree of shortage and the expectable frequency during the driest years should preferably also be given. The resulting loss in yields during driest years may be of significant importance in the economic viability of the project.

Furthermore, the time of deficient rainfall periods is important. Some crops, as indicated in Table 34, are particularly sensitive during certain stages of crop growth and all crops are during germination. Water shortage during these periods may well have a marked negative effect on crop yields; a higher level of dependable rain should be selected for these periods.

For large scale irrigation development or where mountains or other physiograpic features greatly influence rainfall and the occurrence of storms, the spatial distribution of rainfall must be evaluated. Methods for interpreting areal rainfall are described in detail in most textbooks on hydrology 1/.

i) Method for computing rainfall probabilities

There are several methods for determining the frequency distribution of rainfall; most will produce similar results at or near the middle of the distribution, but different values for high and low extremes. The selection of method should thus depend on the purpose for which the data are going to be used. For detailed analysis the references given should be consulted. Computer calculation may often be required for detailed analysis.

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

A simple method to provide rainfall probability data is given below. From the results a selection of the probability level and corresponding likely depth of rainfall can be made; the probability level must be based on the crop to be grown in the area and on the crop growing stage.

EXAMPLE:

Computing rainfall probabilities

1) Point rainfall frequency:

Steps involved:

- tabulate rainfall totals for given period/line 2
- for number of records or items (N) arrange rainfall in order of magnitude and give rank number (m)/lines 3 and 4
- tabulate plotting position (Fa) using for instance Weilbull formula $100m/(N + 1)$. (N is total number of items, m is number of items arranged in descending magnitude, thus m=1 is the largest item)/line 5
- prepare vertical scale and plot rainfall according to Fa position on log-normal probability paper/Fig. 22

Line																
(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	5.9	11.8	17.6	23.5	29.4	35.3	41.2	47.0	52.9	58.8	64.7	70.6	76.4	82.3	88.2	94.1

From Fig. 22: dependable rainfall 3 out of 4 years, or 75% probability, for given month is 36 mm.

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 distributed in such a way as to allow simple statistical analysis. This last factor can be overcome to some extent by either:

- plotting on probability paper the square root of the same rainfall data or
- particularly for periods with spells of 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.

2) Rainfall duration frequency:

Rainfall values over consecutive days are found by moving totals, i.e. for a period of say 5 consecutive days the totals of rainfall from 1-5 May, 2-6 May, 3-7 May ... 27-31 May are computed. In this way 27 values of 5 day-totals of rainfall for the month of May are obtained. Then out of the 27 values the highest is selected. For a recording period of say 30 years, this gives 30 values of highest rainfall on 5 consecutive days in May. Frequency distribution of these values is made following the step method given before. The same procedure can be repeated for different numbers of consecutive days. Rainfall duration curves are obtained by plotting, for a given frequency of rainfall occurrence, the number of days against depth of rainfall. Curves of equal probability are drawn through the points.

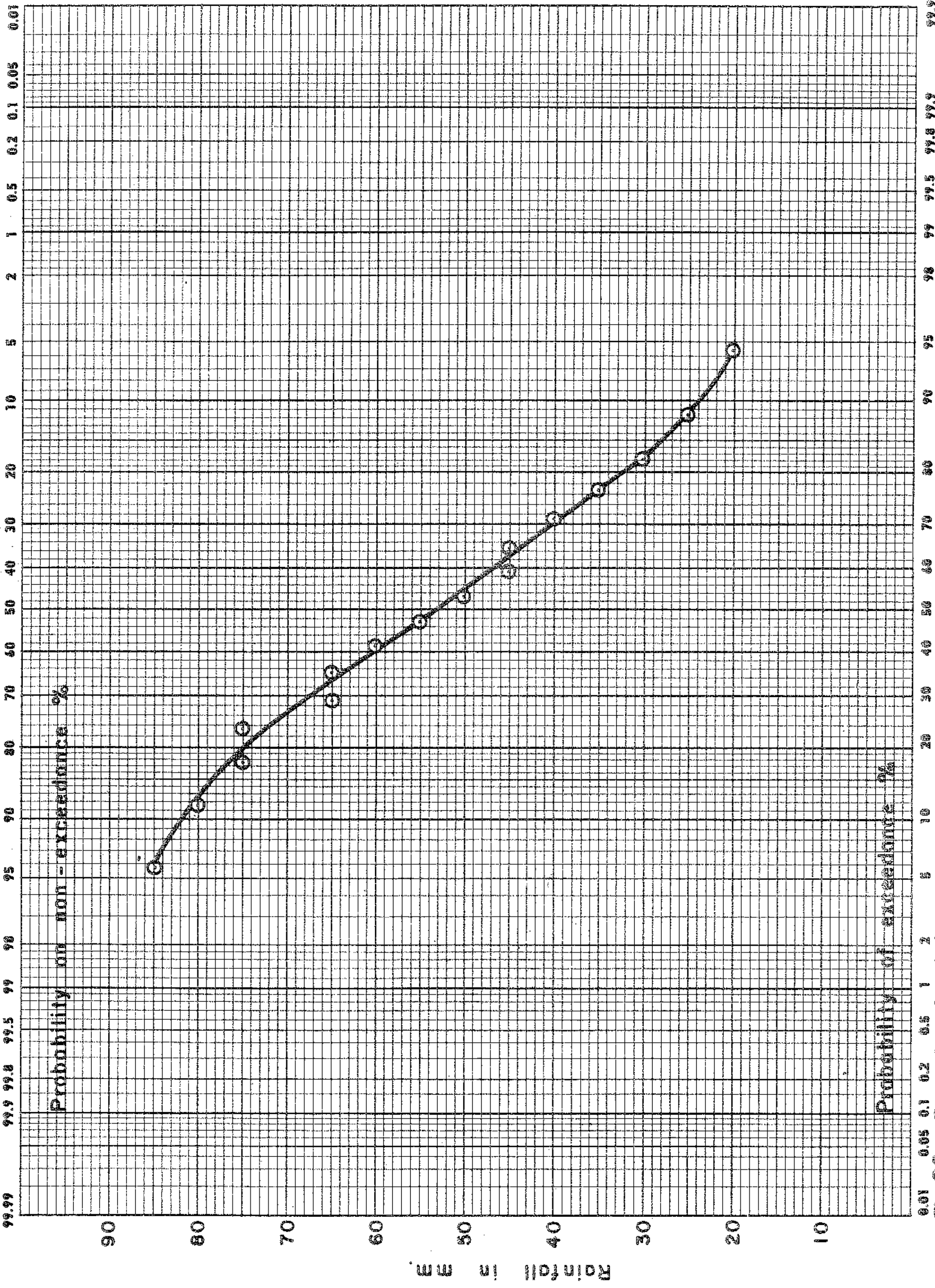


Fig. 2.2 Example of rainfall probability calculation.

3) Drought duration frequency:

Here only the lowest values of rainfall of the moving totals of rain 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.

[illegible]r 2 and 3 machine calculation will be required.

[illegible]ive rainfall

[illegible] rainfall is only a portion of total rainfall. Part of the rain may be lost
[illegible], by deep percolation below the rootzone or by evaporation of the rain
[illegible] plant foliage. In regions with heavy and high intensity rains only a
[illegible] stored in the rootzone and the effectiveness of rain is consequently
[illegible]ns interception by the plant foliage can be important; wet plants
[illegible]hich is off-set by increased evaporation of the rain water inter-
[illegible]ge. In practice, for full ground cover conditions it can be safely
[illegible] light rainfall is close to 100 % effective. Where a high percentage
[illegible] and the soil surface has been dry for some time before
[illegible]rface can be considerable. Rainfall of 6 to 8 mm per
[illegible]ion. Even rains of 25 to 30 mm during initial
[illegible] percentage of ground cover may result in a net

[illegible] tries to estimate effective rainfall as a
[illegible] considers 70% of the average seasonal rainfall
[illegible] taken as the mean rainfall but excluding
[illegible] and in excess of 75 mm in 1 day and
[illegible]er 5 days following irrigation is con-
[illegible] than 12 mm is considered ineffective, while
[illegible] November and 90% of December
[illegible] rice, rainfall is
[illegible] mm is disregarded;
[illegible]xceeds [illegible]0 mm, the surplus
[illegible] above 50 mm is
[illegible] 50 mm is ineffective;

[illegible] monthly rainfall

A more detailed evapotranspiration/precipitation ratio method to determine effective rainfall is given in Table 37 (USDA 1969). It shows the relationship between average monthly effective rainfall and mean monthly rainfall for different values of average monthly ET(crop). The soil water storage capacity, ΔS, is assumed equal to 75 mm at the time of irrigation, but correction factors are presented where ΔS is either smaller or greater than 75 mm at the time of irrigation. The data presented do not account for variations in soil infiltration rates and rainfall intensity; where infiltration is low and rainfall intensities are high, a considerable percentage of water may be lost by runoff which is not accounted for in this method. The effect of scheduling irrigation or the net depth of irrigation application on the amount of rainfall predicted to be effective, should be considered in relation to the amount of water stored in the soil and available at the time of irrigation.

For a more detailed prediction of effective rainfall from available rain data reference is made to FAO Irrigation and Drainage Paper No. 25 by Dastane (in press).

Table 37 AVERAGE MONTHLY EFFECTIVE RAINFALL AS RELATED TO AVERAGE MONTHLY ET(crop) AND MEAN MONTHLY RAINFALL (ADAPTED FROM USDA, SOIL CONS.SERV., 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 1/															
Average monthly ET(crop) mm	25	8	16	24													
	50	8	17	25	32	39	46										
	75	9	18	27	34	41	48	56	62	69							
	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	12	25	37	50	61	72	84	92	102	112	121	132	140	150	158	167

1/ Where soil water storage at time of irrigation (ΔS) is greater or smaller than 75 mm, the correction factor to be used is:

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

EXAMPLE: monthly mean rainfall is 100 mm; ET(crop) is 150 mm and ΔS is 175 mm, the average monthly effective rainfall is 1.07 x 74 = 79 mm.

b) Dew

The contribution of dew to crop water needs is often considered very small. Sometimes various types of dew formation are distinguished, the main ones being atmospheric moisture condensing on cooler surfaces, or the trapping of fog or cloud droplets by vegetation. For irrigated crops much of the moisture condensed on crops by early morning comes from the re-condensing on leaves of water evaporated from the soil, hence no real change in water budget results.

Measured data from India and Israel show that annually measured dew accumulation is below 30 mm, with possibly a monthly maximum rate of 3 to 7 mm. California data indicate monthly maximum values of only 0.5 mm. Data from Australia show that only about 3% of monthly ET(crop) is met by dew during summer. In arid and semi-arid regions dew deposition is often too small to make any contribution to soil water. In Canada the highest quantity of observed dew on tobacco leaves was only 1.25 mm per night. It is sometimes claimed that dew on leaves is much greater than that actually measured. Examples are found on high mountain ranges and volcanoes (Canary Island) of crop water requirements being met by the interception of fog, but these are very rare. Benefits from dew include delayed warming of leaves and reduction in wilting symptoms in the early morning. Detrimental effects include the spreading of plant diseases (fungi). It should be noted that there has been a strong tendency to over-estimate average dew; impossible amounts have been claimed as researchers overlooked absolute physical limitations involved in the process.

c) Snow

Snow remaining on the soil surface provides a considerable source for storage of water. Normally 10 cm of snow hold approximately 1 cm of water and may hold as much as 1.5 cm but both the amount of snow and the percentage of water content are difficult to measure. The amount of runoff and infiltration into the soil is very dependent upon the rate of snow melt. The contribution of snow toward future crop water requirements should be seen as a contribution of water to the soil-water reservoir similar to winter rains.

d) Carry-over of soil water: winter rains and melting snow may cause the soil profile to be near or at field capacity at the start of the growing season. The contribution of winter rain, which may be equivalent to one full irrigation, is generally deducted when determining seasonal irrigation requirements. An additional benefit of excess winter rain is the leaching of salts accumulated in the root zone in the summer season. Carry-over of soil water is of great importance in rainfed farming in water-short areas.

The amount of winter rain stored in the root zone does not necessarily have to be 100 % effective. Soil water can be lost at appreciable rates from the wet soil surface equal to open-water evaporation, but this decreases as the soil dries. Evaporation losses may remain fairly high due to the movement of soil water by capillary action toward the soil surface. Attempts to control soil surface evaporation include the use of various mulches, but unless complete soil cover is attained, such as by the use of plastic, the reduction in evaporation is often small.

In addition water is lost from the root zone by deep percolation where groundwater tables are low. Deep percolation can persist at an appreciable rate following the attainment of field capacity. Depending on weather, type of soil and time span considered, effectiveness of stored soil water may be as high as 90% or as low as 40% .

II.1.3 Groundwater contribution, Ge

The contribution from the groundwater table is determined by the depth of groundwater below the root zone, the capillary and conductive properties of the soil and the soil water content or soil water tension in the root zone. Both rate and distance of water movement are important criteria; for heavy soils distance of movement is high and the rate low, while for light textured soils distance of movement is low and the rate high. Very detailed experiments will often be required to determine the groundwater contribution under field conditions.

In the absence of impervious layers, the depth of groundwater below the root zone, at which the contribution to the moist root zone is reduced to less than 1 mm/day, may be taken approximately at some 50 to 90 cm for coarse and heavy textured soils and about 120 to 200 cm for most medium textured soils. In Fig. 23 some examples of the contribution of water are given in mm/day for different depths of groundwater below the root zone and various soil types; the soil in the root zone is assumed to be relatively moist or soil water tension equal to about 0.5 atm. It should be added that to obtain lasting benefit from relatively high groundwater tables, their level and fluctuations must be controlled.

II.1.4 Surface and subsurface in and outflow, N and R

Calculation of surface inflow normally does not apply, except for areas subject to occasional flooding. Under good irrigation practices surface outflow should be small; management losses and waste of water due to technical faults should normally be accounted for in irrigation efficiency.

Subsurface inflow is only of local significance in areas where there is upward movement of water from deeper subsoil caused by seepage from reservoirs and canals. Subsurface inflow may also occur locally on or near the toe of sloping lands. Detailed field investigations will be required to determine total depth of water involved.

II.1.5 Deep percolation below root zone, F

Deep percolation or drainage out of the root zone can continue for a long time after field capacity has been reached following irrigation or heavy rain. The rate of deep percolation decreases with time. Total water loss by deep percolation in irrigated conditions can account for 20% or more of the total amount of water applied (Hillel 1972). However, soil water movement in and below the root zone, after an initially net downward outflow, can later be reversed to a net upward inflow from the wet sub-soil to the drying root zone above. Detailed field investigation will be required to determine the net rate of downward flow of water. In calculating monthly irrigation requirements deep percolation is often, but incorrectly, accounted for in irrigation application efficiency.

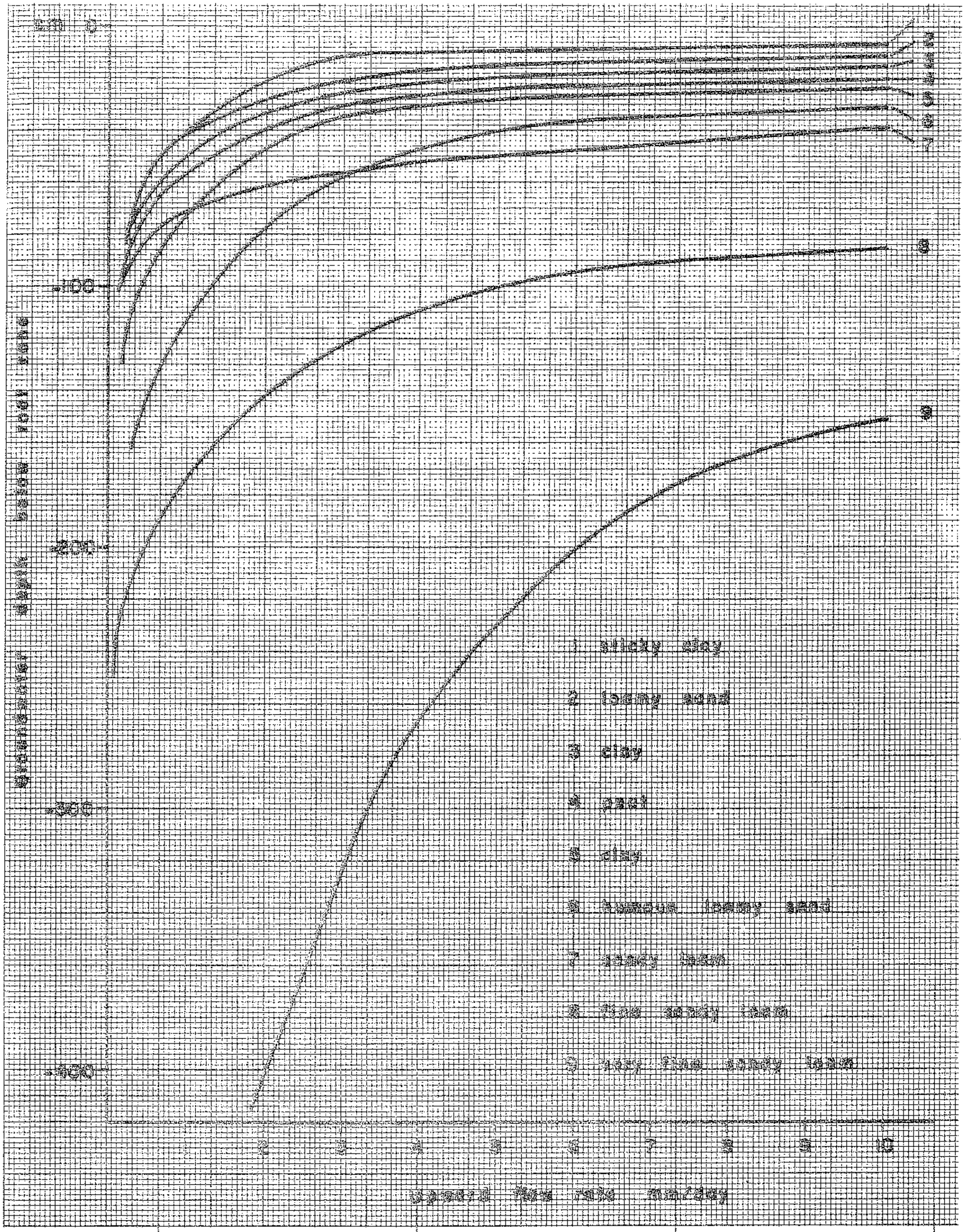


Fig. 23 Contribution of groundwater to root zone in mm/day for different depth of groundwater and soil texture under moist conditions (soil water tension of root zone ~0.5 atm.) source, Wind (1955) Talsma (1963) Rijtema (1965), Feddes (1971), Hillel (1971)

It should be noted that deep percolation will affect the amount of soil water available to the crop between two irrigations. Where the deep drainage component is appreciably high, more frequent irrigation may be required than is indicated by simply dividing the depth of soil water available to the crop between irrigation (mm) by the rate of evapotranspiration (mm/day) under given climatic and crop conditions.

II.1.6 Changes in stored soil water, ΔW

Changes in stored soilwater ΔW may vary between absolute dry soil or $W = 0$ and field capacity or $W = Sfc$. The water storage capacity of the soil reflects the balancing between water outflow (losses) and water inflow (gains). Soil water storage capacity will change with type of soil and depth of root zone. Since soils are rarely homogeneous over the entire root zone, their storage capacity is the sum of the storage capacity of the different layers composing the soil.

For irrigation purposes the water storage capacity of the soil is frequently expressed as total available storage capacity ΔS taking into account only the water that is available to the crop between field capacity Sfc and wilting point Sw. Approximate data on total available soil water are given for different soil textures in Chapter I.4.2.

To calculate available soil water storage at given soil water tension or soil water content the following data should be available:

soil and rooting depth, D

soil texture and structure of soil layers and their depth, D1

soil water content in volume percent at field capacity, Sfc

soil water content in volume percent at given soil water tension, Si

When soil water content is given in weight percentage, the apparent specific gravity of the soil As (ranging from 1.1 to 1.6) should be known to calculate soil water content in volume percent or S in vol% = As x S in weight%.

The available storage capacity of the soil at given soil water tension is the summation of storage capacity of each soil layer or:

$$\Delta Si = \Sigma \left[\frac{Sfc - Si}{100} . As . D1 \right]$$

D is frequently taken as effective rooting depth of the given crop.

EXAMPLE:

Soil depth is >140 cm; crop rooting depth is 140 cm.
Soil texture is sandy loam over first 60 cm and sandy clay loam over next 80 cm;
From measured data or from the table in Chapter I.4.2a, Sfc is respectively 13 and 14 vol% and Si at a selected soil water tension of 1,5 atm. is respectively 5 and 8 vol%.
Available storage capacity at time of irrigation is:

$$\Delta Si = \frac{(13 - 5)60}{100} + \frac{(14-8)80}{100} = 9.6 \text{ cm or } \underline{96} \text{ mm.}$$

Soil data should include a real distribution of the soil type for which a soil survey of the area under investigation will be required. For each soil type the physical soil data need to be determined including field capacity and wilting point, soil apparent specific gravity, infiltration rate and hydraulic conductivity. Such data are essential for selecting the method of irrigation and for determining irrigation schedules.

CHAPTER II.2 NET FIELD IRRIGATION REQUIREMENTS, In

II.2.1 Seasonal and monthly data

In drawing up the seasonal or monthly net irrigation requirements for a given crop or cropping patter the main variables composing the field water balance to be considered include (i) crop water requirements as determined by climate and crop characteristics, (ii) contribution from precipitation, (iii) groundwater and (iv) carry-over of soil water and, where applicable (v) in- and outflow of water, either surface or subsurface. The deficit in the soil water balance is compensated by the net irrigation requirements. For overall planning purposes, examples to predict monthly net irrigation requirements are given in which the balancing effecto of the water storage capacity of the soil is accounted for. Apropos the latter, knowledge of soils found in the area under investigation is essential. A quick approach to determine monthly requirements excluding the balancing effect of the soil water storage is also given. Generally, for planning purposes, mean data are used for a period in which records are available. Where one or more variables may differ significantly from year to year, the monthly field balance should preferably be calculated for each year of record; after which the level of monthly irrigation requirements is selected that will meet water deficits say three out of four or four out of five years.

EXAMPLE:

Given: crop is cotton with effective rooting depth of 140 cm; soil texture 60 cm of sandy loam over sandy clay loam; irrigation is applied at soil water tension of 1.5 atm. or available storage capacity at time of irrigation is some 100 mm; soil assumed to be near field capacity at start of growing season; ET(crop), effective rainfall Pe, and groundwater contribution Ge, have been predetermined from available data.

Calculation:

	Apr	May	June	July	Aug	Total
ΔS initial mm	+ 90	+ 80	+ 30	+ 50	+ 60	
Pe	+ 60	+ 40				
Ge	+ 20					
ET(crop)	- 90	- 190	- 280	- 290	- 150	
In 1/	0	+ 100	+ 300	+ 300	+ 100	800 mm
ΔS end of month	+ 80	+ 30	+ 50	+ 60	+ 10	

1/ In, net irrigation requirement, needed to keep a positive balance at the end of the month; rounded here to net depth per application equal 100 mm

A simplification would be by neglecting the carry-over effect of soil water or

$In = \sum [ET(crop) - Pe - Ge] = 1\,000 - 120 = \underline{880}$ mm/season.

Should it be assumed that soil water content is at field capacity at the time of sowing and at wilting point at the end of the growing season:

$In = 1000 - 120 - 100 = \underline{780}$ mm/season

Net irrigation requirements are computed similarly for fields under different crops. Total net irrigation requirement In for a given cropping pattern is computed for each crop and is then weighted and totalled for each selected period.

EXAMPLE:

Cropping pattern of 100 ha field is wheat (40 ha), maize (60 ha), berseem (60 ha) and cotton (40 ha); crop growing periods are shown below; water balance is computed from predetermined mean ET(crop), effective rainfall, Pe, contribution of groundwater Ge, while taking into account the carry-over effect of soil water all in mm.

	J	F	M	A	M	J	J	A	S	O	N	D	
Pe mm/month	45	23	15						25	50	42	40	
Ge	20	25	10										
wheat 40 ha													
ET(crop)	50	80	160	70							45	45	
In	0	0	140	0							0	0	
maize 60 ha													
ET(crop)					85	150	270	200	110				
In					100	200	300	200	?				
berseem 60 ha													
ET(crop)	65	40								45	40	55	
In	0	0								0	0	0	
cotton 40 ha													
ET(crop)				90	190	280	290	150					
In				100	200	300	300	100					
In, weighted for crop distribution	-	-	56	40	140	240	300	160	-	-	-	-	936

A simplification is introduced by using:

$$In = \frac{1}{A} \left[(ET(crop) - Pe - Ge)_n \, A_n \right]$$

$$= \frac{1}{100} \left[(450 - 220).40 + (815).60 + (245 - 245).60 + (1000).40 \right]$$

wheat + maize + berseem + cotton

$$\doteq \underline{980 \text{ mm}}$$

II.2.2 Peak period irrigation requirements

The peak period irrigation requirement can be obtained by using monthly irrigation requirements computed for the selected cropping pattern for each year that data are available. The month of highest requirements is normally taken. To carry out the computation for this data consideration must be given to climatic extremes during that month affecting the level and duration of peak period ET(crop), to the available stored soil water for meeting short duration peak requirements and to possible critical crop stages for soil- water stress resulting in appreciable yield decreases when water is in short supply. Necessary computations are given in the example below; use is made of the information provided in Chapter I.4.1.

EXAMPLE:

Given: crops include maize, mid May to end September, and cotton, early April to half September; acreages are respectively 60 and 40 ha. Maximum mean monthly ET(crop) in July is 280 and 288 mm or 9.0 and 9.3 mm/day; available soil water storage is 100 mm for both crops; climate is semi-arid with predominantly clear weather conditions.

Calculation: using Fig. 11 of Chapter I.4.1 for given climate and depth of available soil water the ratio between mean peak ET(crop) and mean monthly ET(crop) is 1.075 or ET(maize) = 9.7 mm/day and ET(cotton) = 10 mm/day. Weighted peak period ET(crop) = (9.7 x 0.6) + (10 x 0.4) = 9.8 mm/day

CHAPTER II.3 GROSS FIELD IRRIGATION REQUIREMENTS, If

II.3.1 Irrigation application efficiency, Ea

To account for avoidable and unavoidable inefficiencies in water application, net irrigation requirement, In, needs to be increased by the irrigation application efficiency Ea, or

$$If = In \times \frac{1}{Ea} \quad (\text{or} = In \times \frac{100}{Ea})$$

where If is the gross field irrigation requirement; Ea is commonly expressed in fraction (or percentage) and is the ratio between the amount of water actually stored in the root zone directly available to the crop and the total amount of water applied to the field.

EXAMPLE:

Given: single crop, cotton; data are derived according to Chapter II.2.

	Apr	May	June	July	Aug	Total
In mm	0	100	300	300	100	
Ea fraction		.55	.65	.60	.55	
If mm	-	180	460	500	180	1 320

A simplification is by using:

$$If = \frac{\Sigma[\overline{ET}(crop) - Pe - Ge]}{Ea} = 880 \times \frac{100}{60} = 1\ 470 \text{ mm/season}$$

Gross field irrigation requirement is directly related to irrigation application efficiency Ea which is the fraction of applied irrigation water that is stored in the soil and available to the crop. Low efficiencies will occur when depth of water applied is in excess of the amount that can be stored in the root zone at time of irrigation and the excess water is lost by deep drainage. When the rate of application is in excess of the soil infiltration rate, appreciable run-off and tail-losses will result. Uneven distribution of water applied will normally cause drainage losses in one part and possible under-irrigation in the remaining part of the field.

Apart from avoidable losses due to field layout and water application inefficiencies, there are unavoidable losses. These include deep percolation of stored soil water after attainment of field capacity, losses by evaporation from the soil surface and, for sprinkler irrigation, evaporation losses from the spray. Complete uniformity of water application over a field is hard to obtain. Also, sudden rain may upset pre-determined irrigation schedules and will result in a lower percentage of water being applied that is stored in the root zone. Attainment of 100 percent irrigation efficiency can therefore never be reached.

However, on average, in most schemes irrigation application efficiency does not exceed 0.60 particularly in the early years of the project; much lower efficiencies are frequently found. Some variation over season may be noted with higher efficiencies during peak requirement periods and lower efficiency in the early and late crop seasons.

Data on field irrigation application efficiency is of the utmost importance but is at the same time difficult to estimate. When estimations are too high it results in water deficiencies during average rainfall years and during peak water use periods in most years, and in too low irrigation system capacities. When estimated too low, the result is a reduction in size of the area that can be irrigated, overcapacity of the irrigation system and probably wasteful irrigation practices. However, the former is more commonly the case.

Some indicative data on field irrigation efficiencies are given as they could be considered to apply to a well designed layout, well levelled fields and to optimum irrigation practices achieved after the scheme has been in operation for many years. (See tables 38 and 39)

Table 38 FIELD APPLICATION EFFICIENCY FOR METHOD OF IRRIGATION

	US(SCS)	ICID 1/
Graded borders	0.60 - 75	0.58
Basin and level borders	.60 - 80	.53
Contour ditch	.50 - 55	
Furrows	.55 - 70	.57
Corrugations	.50 - 70	
Subsurface	up to .80	
Sprinkler, hot dry climate	.60	
moderate climate	.70	.67
humid and cool	.80	
Rice		.32

Source: 1/ M.G. Bos and J. Nugteren Irrigation efficency in small farm areas. ICID 1974 or Publication No. 19, International Institute for Land Reclamation and Improvement, Wageningen 1974

Table 39 IRRIGATION APPLICATION LOSSES AS FRACTION OF WATER APPLIED AND FIELD APPLICATION EFFICIENCY FOR DIFFERENT SOIL CONDITIONS

	light	medium	heavy texture
Farm lateral losses, unlined	0.15	.10	.05
Surface runoff loss	.05	.10	.25
Deep percolation loss	.35	.15	.10
Field irrigation efficiency	.45	.65	.60

Source: USDA

Evaporation losses from the soil	25 mm per irrigation
Surface run-off losses	0.1
Drainage losses, except porous soils	0-0.5
Field ditch losses	0.03-0.3 per km
Field application efficiency, common farm crops	0.2-0.5
Field application efficiency, fruit crops	0.35-0.7
Average field application efficiency, large projects	0.3-0.5

Source: Houk (1951)

II.3.2 Other water needs including leaching requirements

Some consideration should be given to the need for water applications for purposes other than just crop water requirements. Water is needed for cultural practices which are linked to specific requirements of certain crops. The fulfilling of these water needs can often be considered as a bonus feature of irrigation; but they are also most desirable even if no irrigation is required for crop growth. To improve the yield and its quality water may be needed for such specific reasons as an aid to germination, land preparation, frost protection, maintenance of crispness of some fresh vegetables, control of certain insects and pests, control of temperature and humidity, and for dissolving fertilizers. Post harvest irrigation is sometimes practised; for example after harvesting groundnuts to induce germination of any nuts left behind so that they can be removed easily from the fields. One other important aspect is the leaching of salts from the root zone.

Except for the last reason, generally no allowance is made during planning for these extra water needs, which may have important local significance in certain cases. Except for salt leaching, which should always be considered in total irrigation requirements, some of these specific demands may also be taken into account when determining irrigation schedules in existing projects.

The level of soil salinity is affected mainly by irrigation, effective rainfall and leaching practices. Salinity varies during the growing season; salts accumulate in the soil profile as the season advances. Leaching of the accumulated salts can be programmed to take place during, before or after the growing season depending on available water, the efficiency of irrigation, leaching practices and the yield reduction the grower will accept due to the accumulation of salts. The effect of salts can be appreciably decreased by maintaining soil water in the root zone in the upper range of availability. Approximate data on upper limits of soil salinity levels for different crops are given in Table 40, where salinity is expressed in electrical conductivity (mmhos/cm) of the soil saturation extract.

Table 40 APPROXIMATE VALUES OF SALINITY LEVELS FOR DIFFERENT CROPS ASSUMING 50% DECREASE IN YIELD

ECe - 4 mmhos		4 - 10		10
Pear	Peas	Fig	Corn (maize)	Date
Apple	Beans	Oats	Flax	Barley
Orange	Sugarcane	Grape	Potato	Sugarbeet
Prune		Wheat	Carrot	Cotton
Plum		Tomato	Onion	Spinach
Apricot		Alfalfa	Cucumber	

Source: Handbook 60, US salinity Laboratory

The yearly leaching requirement can, in a first approximation, be related to the quality of the irrigation water to be used and the quality of the drainage water tolerated by the crop at the bottom of the root zone. Using the quality of the drainage water to be tolerated as 4, 8, 12 and 16 mmhos, the leaching requirement (LR) is then given as a percentage of the total amount for the various qualities of irrigation water, using the formula:

$$LR = \frac{ECirr}{ECdw} \times 100$$

Quality of irrigation and drainage water is given as electrical conductivity in mmhos/cm. Examples are given in Table 41.

Table 41 LEACHING REQUIREMENTS IN PERCENTAGE FOR DIFFERENT SALINITY LEVELS OF IRRIGATION (ECirr) AND DRAINAGE WATER (ECdw) IN mmhos/cm

ECirr	Leaching requirements in % of irrigation requirements for ECd2			
	ECdr - 4	8	12	16
0.1	2.5	1.2	1	0.5
0.25	6	3	2	1.5
0.75	20	10	6	5
2.25	60	30	20	15
5.0		60	40	30

For preliminary planning, the prediction of yearly water demand (If) including need for leaching water can be made by:

$$If = \frac{ET(crop) - Pe}{1 - LR} \cdot \frac{1}{Ea}$$

where LR is the annual leaching requirement in fraction and Pe is effective rainfall.

The above prediction method for annual leaching requirements does not account for the effect of the type of salts on plant growth, type of soil, and restrictive drainage conditions. Also, the variation in salinity level of the soil during the growing season is not reflected. No consideration is given to the method of leaching, i.e. intermittent or continuous. In addition, the leaching requirements are related to the entire root zone although crops can perform well under conditions where part of the root zone only has a high salt content.

For detailed evaluations, including monthly leaching requirements as related to salt tolerance levels during various stages of crop growth and appropriate leaching practices to be followed, there are many sources of reference.1/

1/ FAO/Unesco International Sourcebook on Irrigation and Drainage of Arid Lands. FAO/Unesco 1973; Hagan et al., Irrigation of Agricultural Lands, 1967; Salinity Laboratory Handbook No. 60; FAO Irrigation and Drainage Paper No. 7, Salinity Seminar, Baghdad (1972); Unesco, Final Report of the GRUESI Project, Tunisia, 1971.

CHAPTER II.4

FIELD IRRIGATION SCHEDULING

Depth and frequency of irrigation should conform to the soil replenishment criteria for a given crop, soil and climate. Water scheduling, in depth and time, must be carefully determined throughout the crop season to avoid any decrease in crop yield due to soil water shortage. At the planning stage only approximate rules on irrigation application scheduling can be given. Refinements to water application scheduling will be required after projects have been constructed and been in operation for some time.

Depth and frequency of irrigation will vary with crop, soil, ET(crop), type of harvested yield and level of management and these are shown in qualitative terms in the next Table.

Table 42 QUALITATIVE NORMS ON FREQUENCY AND DEPTH OF IRRIGATION APPLICATION IN RELATION TO CROP, SOIL, CLIMATE, TYPE OF HARVESTED YIELD, AND LEVEL OF MANAGEMENT

Long interval and great depth	Factor	Short interval and small depth
Deep rooted, dense Thick, hairy, waxy leaves Low crop factor (kc) Low percentage of ground cover Early closing of stomata and wilting Main growth during winter periods Accept high soil water depletion rates Smooth crop surface	Plant	Slow growing and shallow rooted Complete ground cover Broad flat leaves Main growth during hot dry periods Drought sensitive period High crop factor (kc) Requiring high level of soil water throughout High-yielding variety High population density Rough crop surface
Medium to heavy textured Deep, wellstructured High water holding capacity Non-saline High groundwater table of good quality	Soil	Light textured Shallow, poor structure Impervious layers, hardpans Low water holding capacity Poor aeration Saline-alkaline Slow infiltration rate, soil crust Root pests and disease Poor soil fertility
Low ETo Frequent rainfall, well distributed Winter rains Closed smooth crop surface	Weather	High Eto High daily variation in ETo Advection No rainfall Low soil temperatures during early growth
Optimum yields Dry weight yields	Product	High water use/crop production ratio Maximum vegetative yields Fresh weight yield High quality of harvested yield
Large continuous fields Dormancy periods Good land preparation Well designed field irrigation distribution system	Management	Small interspersed fields Planting just before hot dry season Poor irrigation methods and practices

II.4.1 Depth of irrigation

Depth of irrigation is the amount of soil water that can be stored between so-called field capacity and, for the given crop, the selected maximum soil water tension or available soil water depletion. Data on type of soil and its available soil water storage capacity should be collected at site. An approximation of the water content at field capacity can be made using the data given in Chapter I.4.2. Selection of the maximum allowable soil water tension and corresponding level of available soil water depletion should be based on crop and soil data discussed in Chapter I.4.5. Depth of application (d) will vary over the growing season and for a given crop and crop phase can be determined by $d = (Sfc - Si)D$ where Sfc and Si are soil water content in volume percentage at field capacity and just before irrigation and D is rooting depth. To find gross depth of application the irrigation application efficiency should be accounted for.

EXAMPLE:

Cotton, 4th growing month, effective rooting 140 cm
soil is sandy clay loam, Sfc = 14 vol%, Si = 7 vol %, application efficiency is 0.65.
$d = (0.14 - 0.07)\ 140 = 9.8\ \text{cm} = 98\ \text{mm}$
Gross depth of application is $d/EA = 98/0.65 = 150$ mm

If too little water is applied and the rooting depth is not kept permanently moist, the soil volume from which plants can draw water and nutrients will be reduced. When water applications are too light the risk of depressing yields is greatly increased. Under-irrigation will result in the onset of soil water stress sooner particularly when the subsoil layers are dry. The detrimental effect on crop growth and yields cannot be overcome by increasing the depth of water in later applications. Water applied in excess of the amount that can be stored in the root zone will be lost through deep percolation and run-off.

II.4.2 Irrigation interval

Correct timing and regularity of water application are quite as important as the total seasonal amount of water applied to the field. Too frequent irrigation even though the amount applied correctly equals soil water depletion, will reduce water use efficiency mainly by increasing conveyance and application losses. Delayed irrigation, particularly during the periods when the plant is sensitive to soil water stress, can have a considerable negative effect on crop yields, even though the total amount of seasonal water application is about the same.

By excluding the carry-over effect of the soil water reservoir, first estimates on irrigation interval (i) can be obtained for a given crop and growing phase by:

$$i = \frac{(Sfc - Si)D}{ET(crop) - Pe}$$

EXAMPLE:

cotton, 4th growing month, effective rooting depth 140 cm,
Sfc = 14 vol%, Si = 7 vol%, ET(crop) is 280 mm/month,
Pe is 30 mm/month

$$i = \frac{(0.14 - 0.07)\ 1\,400}{(280 - 30)/30} = 12 \text{ days}$$

ET(crop) varies considerably during the growing season even if climatic conditions do not change; also the depth of soil from which water is abstracted by the crop will vary particularly during the early growth stages. Most crops have specific requirements during different stages of growth. Also, the amount of soil water available to maintain ET(crop) at the predicted value will vary with evaporative demand of the air (Chapter I.4.2). Therefore, rather than basing irrigation applications on the calendar or on fixed schedules, considerable flexibility in time and depth of irrigation applications should be maintained to accommodate distinct differences in crop water needs over a period of time. These considerations are often omitted in overall planning. Such data, however, must be available before a detailed field design and preliminary field irrigation schedules for a new scheme are developed.

II.4.3 Irrigation frequency

Irrigation application schedules can be predicted at the planning stage from the monthly field water balance and by selecting from available crop and soil date maximum level of available soil water depletion. An example to develop the necessary data from available information is given below for a barley crop followed by potatoes. The example clearly reflects differences in both frequency and depth of irrigation application and is mostly due to variations in rooting depth and maximum level of available soil water depletion for the two crops.

EXAMPLE:

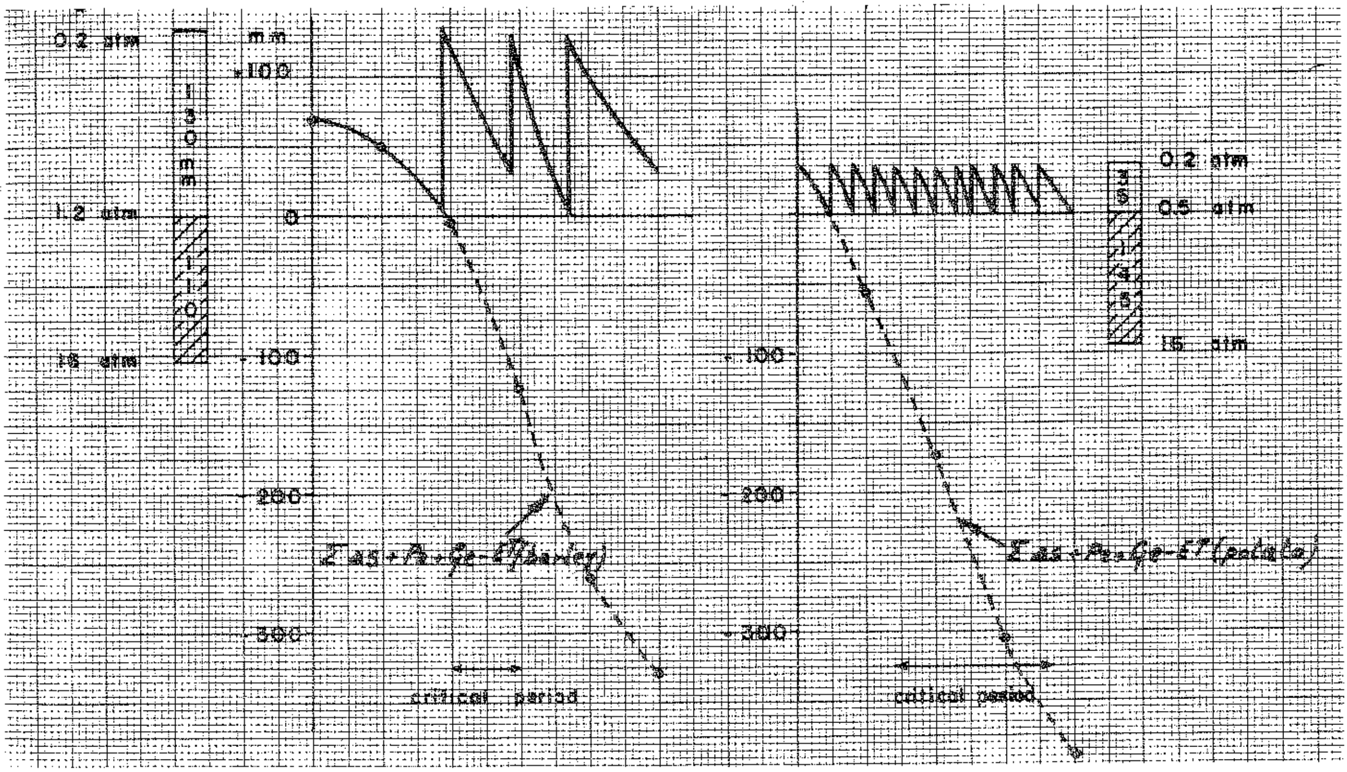
Soil: Soil depth > 130 cm; soil texture is loam; available soil water at soil water tension of 0.2 atm (field capacity) is 20 vol%, at 0.5 atm is 14 vol%, at 1.2 atm is 9 vol%; at 16 atm (wilting point) is 0 vol%.

Crops: barley, sown in February, harvested in June followed by potatoes from July to October.
Barley: effective rooting depth at mature growth 120 cm; irrigation is applied at soil water tension of 1.2 atm; depth of available water between field capacity and 1.2 atm is 1200 x 11 = 130 mm.
Potatoes: effective rooting depth 60 cm; irrigation at 0.5 atm; available soil water 35 mm.

Climate: winter rains with residual soil water available at beginning of season; little rain during crop season; ET(crop) is predicted from available climate records. Effective rainfall is calculated with selected reliability of 3 years out of 4.

Groundwater: groundwater table is at 2 m early in the year; surface and subsurface in and outflow is negligibly small; deep percolation is assumed to be balanced by difference between net and gross irrigation requirements.

	F	M	A	M	J	J	A	S	O
Pre-irrigation Δs initial	+70	+50	- 5	-125	-260	80 35	-55	-175	-310
rainfall Pe	+20	+10	-	-	-	-	-	+ 30	+ 45
groundwater Ge	+ 20	+ 10	-	-	-	-	-	-	-
ET(crop)	-60	-75	-120	-135	- 70	-90	-120	-165	-120
Δs end of month	+50	- 5	-125	-260	-330	-55	-175	-310	-385



	F	M	A	M	J	J	A	S	O
No.of irrigations	0	1	1	1	0	Pre+ 2	3	4	2
net depth of irr.		130	100	130	-	80, 35	35	35	35
irr.fficiency		.60	.60	.60		.60	.60	.60	.60
gross irr.req.		215	165	215		300	210	280	140

PART III CALCULATION OF IRRIGATION SUPPLY, Vs

INTRODUCTION

Calculation of project irrigation supply is needed to quantify project acreage and to determine diversion requirements from river flow, abstraction from groundwater aquifers and to establish reservoir operation. For preliminary planning, irrigation supply from available water resources is determined primarily by project area, cropping pattern and intensity and irrigation requirements over time. Supply is expressed in flow per time unit (m^3/month or or l/sec or a given period).

Calculation of irrigation supply to the individual field is needed to plan field irrigation schedules and operation of conveyance and distribution systems. Main variables determining the irrigation supply to the field are depth and frequency of soil-water replenishment for a given soil and crop, soil intake rate, method of irrigation and size of field. Field supply is expressed in flow per time unit (l/sec).

The calculation of irrigation supply should be preceded by a detailed study on cropping pattern and intensity for the proposed project. Apart from water required and water available at source, pertinent social, financial and economic aspects need evaluation before the final selection of crops to be grown can be made. This should include economic returns per unit of water in terms of production and the economic viability as well as secondary and intangible benefits of the proposed project.

The procedure generally followed in quantifying project and field supplies is first to prepare a preliminary layout of the scheme and next to determine the area distribution of crops to be grown and the cropping intensity. This will also include consideration of the size and shape of commanded areas, water level and flow control and the specific provisions to be made such as location and size of main canals and number, type and size of structures needed. Preliminary estimates of total project supply can be based on monthly irrigation requirement data for the cropping pattern and intensity selected.

The next step is more detailed field layout and for this consideration must be given to such aspects as land ownership and natural boundaries, land slope, need for land preparation including levelling, crops to be grown and method of irrigation. Once the size of fields, cropping pattern and method of irrigation have been selected, the field irrigation supply in quantity over time can be determined. After selecting the method of water delivery - continuous, rotation, demand - the developed data are in turn incorporated in the supply schedules of the project. When determining the necessary supply, the project efficiency in meeting field irrigation requirements must be predicted.

Each phase of project planning will require a specific type and accuracy of data on irrigation supply. This is shown in Table 43. It is obvious that, at the planning stage, no accurate evaluation of future project operation and water scheduling can be given unless pilot projects have been started previously and have been in operation for a number of years. Even then, an allowance should be incorporated in the supply to account for any changes in cropping pattern and intensity but at the same time avoiding any quantity in excess of realistic requirements.

Data for detailed water scheduling will still be required after projects have been constructed and been in operation for some time. Field studies should still be continued after the project has been completed to ensure an acceptable level of water use efficiency at the field level and to arrive at irrigation supply schedules which adequately meet the irrigation requirements of the crops grown. An effective organizational framework is essential to implement irrigation scheduling and to operate schemes.

A large number of approaches have been developed for the planning of optimum water use in crop production. Although discussions here are centered around the development of basic data on crop water requirements and the necessary irrigation supplies only, it is apparent that for planning irrigated agricultural production numerous additional parameters will need consideration.

CALCULATION PROCEDURES

To determine Scheme and field supplies for the planning and operation of irrigation, projects require the following data and to obtain it a procedure is suggested. Determine:

1. The preliminary seasonal project supply for the selected cropping pattern, cropping intensity, level of supply efficiency of the distribution systems and project size;
2. for the month of highest demand, the preliminary peak project supply for the selected cropping pattern and intensity, level of supply and flexibility factor, efficiency of the distribution system and project size;
3. following preparation of the project system layout, preliminary project supply schedules; assess relation between supply and area served; select method of water delivery - continuous, rotation, demand;
4. the field irrigation supply for the given soil and crop, depth and method of irrigation; evaluate field supply schedules in quantity over time; prepare water supply schedules;
5. following project implementation, the detailed supply schedules through field monitoring and applied research; review project organizational framework.

TABLE 43 PHASES OF PROJECT PLANNING AND TYPE OF WATER SUPPLY DATA NEEDED

Phase	Data application	Data required
Reconnaissance	- present hydrologic budget - identification of irrigable areas	Average seasonal water supply
Project identification	- location of project - selection of irrigable area, project size, preliminary determination of main works - predicted water demand - predicted future hydrologic budget	Seasonal supply of main crops
Feasibility study	- determination of project size - alternative proposals for water supply facilities and system - hydraulic criteria - selection of cropping patterns - optimization of scheme water distribution - sizing and costing of main engineering works - phasing of project development	Monthly or 10-day total supply Monthly peak supply
Detailed project design	- final design of distribution system - network and hydraulic structure - detailed cropping pattern - detailed delivery schedules - irrigation methods and practices	5- to 10-day peak supply
Project implementation	- review of scheme water scheduling - check on crop water needs - evaluation of water application methods - water use efficiency studies	5- to 10-day peak supply 5- to 10-day water balance
Project operation	- monitoring of field water balances - detailed operation scheduling - training of farmers in water application and scheduling	Water budget in farmer's field

CHAPTER III.1 PRELIMINARY ESTIMATES OF SEASONAL AND PEAK PROJECT IRRIGATION SUPPLY

In calculating seasonal and peak project irrigation supply, the main variables include the cropping pattern, cropping intensity, project size, irrigation requirements, level of supply in terms of crop production and efficiency of the distribution system.

III.1.1 Cropping pattern and cropping intensity

For the proposed project, the selection of the cropping pattern and intensities is influenced by many factors including suitability of climate and soil for various crops, the return to the farmers, the preference and experience of the farmers, size and type of farms, and such outside factors as market demands and market prices. Detailed studies will be required to determine the cropping pattern and intensities. Pertinent social, financial and economic aspects will also need studying and this should include economic returns per unit of water in terms of production and economic viability and the secondary and intangible benefits of the proposed project.

When establishing a cropping pattern and intensities in terms of an ensured water supply the main aspects include:

a) In terms of water availability - meeting seasonal and short duration peak period irrigation requirements by selecting cropping patterns that follow approximately the same pattern as river flow, aquifer discharge by pumping, operation of reservoir, etc;

b) minimizing total irrigation requirements through optimum use of seasonal rainfall and water stored in the soil from winter rains, by selecting crops with low seasonal irrigation requirements, choosing crop varieties with the possibility of shifting sowing dates and shortening the growing season, applying special field practices, such as transplanting rice, weeding, using optimum field irrigation methods and practices, applying water needed for leaching salts at the end of the growing season, and lining canals to reduce seepage losses, etc;

c) in terms of supply capacities - reducing peak water demands by avoiding peak requirements with periods of rainfall or low evaporative demand, including dormancy periods during times of high evaporative demand (alfalfa during hot summer months in North Africa), avoiding double cropping practices, etc.

Decisions on cropping patterns and intensities must be made at an early stage in project planning. Cropping patterns and intensities for individual fields will differ from those projects as a whole. In general cropping intensities of 100 percent are seldom achieved over an entire project area and are often considerably lower.

Weighted figures on crop acreages can be used when deriving total project supply or irrigation module.

III.1.2 Level of supply

The criteria most commonly applied in determining project supply on irrigation module are based on the principle of maximum supply to prevent the crop from suffering water shortages. An acceptable level of supply to meet crop irrigation requirements is normally established; this level is met in at least x years out of 10, or in other words, the probability that a water deficit will occur during a particular period is never greater than (10 - x) years. Planning is thus based on the risk approach whereby a set water supply or irrigation norm, and the corresponding project size, are linked to an acceptable level of production. In most cases this approach is consistent with the achievement of maximum overall production during years of adequate water supply.

The risk approach has been commonly used until now for a number of reasons. Not only has the concept of risk become more familiar to the irrigation engineer but also, usually few factual data on crop production are available upon which to base the selection of optimum use of the water resources. Furthermore, in methods and programmes developed in connection with designs for operations and system engineering the risk approach can more easily be applied because fewer variables are involved.

The use of the risk approach in many irrigation projects has resulted in on-field delivery being based on criteria in which the increase in production as a result of an additional water supply is zero, i.e. the amount of water supplied per ha will maximize yields per ha irrigated. This standard might be acceptable where the water supply is abundant and land is the limiting resource; but this is seldom the case. When water is limited in supply and land resources are abundant the concept of optimization of production per unit area versus water supplied may need to be pursued, that is the amount of water supplied per ha will have to maximize the yield per volume of water.

An engineer may be reluctant to follow the latter approach because a certain oversupply is a safety valve against the unexpected. Slight changes in growing seasons or the introduction of new varieties of different crops, which are both determined mainly by outside factors such as market demand, may upset carefully selected supply criteria. Moreover, detailed data on the level of supply and crop production are seldom available locally and the transfer of data and supply criteria developed elsewhere will, in most cases, lead to erroneous conclusions.

No irrigation scheme functions fully and perfectly the day it becomes operational. Water supply and scheduling may need altering to match unexpected changes in production patterns. Until any particular significant new facts or data on the optimum utilization of water in the everchanging agricultural pattern become available, the supply of the irrigation project may need to be organized with the possibility of accommodating any future extension of the irrigated area or the cultivation of profitable high water demanding crops should new water resources become available and economic aspects permit.

III.1.3 Distribution efficiency

To quantify the supply needed to meet irrigation requirements at the field, the efficiency of the distribution system must be determined. Distribution efficiency, Ed, is defined as that portion of water released at the headworks and that received at the field inlet. The main factors deciding distribution efficiency are method of water delivery (continuous, rotation, demand), size of project area and effectiveness of management organization. Distribution efficiency can be subdivided into conveyance efficiency, Ec, between headworks and the inlet to a block of fields, and field ditch efficiency, Eb, between main canal and inlet of an individual field. The supply in the main canal is continuous or intermittent; the supply in the field ditches within the block of fields served by the same canal is mostly on a rotational basis. Distribution efficiency is obtained from Ed = Ec x Eb.

A recent study on irrigation efficiency in some 90 projects in progress carried out by ICID[1] provides the data in Table 44:

Table 44 DISTRIBUTION EFFICIENCY IN EXISTING PROJECTS

Conveyance Efficiency, Ec	Function
Continous supply with no substantial change in flow	0.9
Intermittent supply in projects of 3 000 - 7 000 ha and rotation areas of 70 - 300 ha, with effective management	0.8 - 0.85
Large schemes (> 10 000 ha) and small schemes (< 1 000 ha) with respective problematic communication and less effective management	0.5 - 0.7
Field Ditch Efficiency, Eb	
Blocks of 20 ha or more, unlined	0.8
lined or piped	0.9 - 0.95
Blocks of 1 - 20 ha, unlined	0.6 - 0.75
lined or piped	0.7 - 0.9

Source: ICID

The distribution efficiency Ed of a rotational supply system under optimum conditions including adequate project organization and communication was shown to average some 0.65. Corrections to adjust distribution efficieny to quality of management and communication proposed were 1.0 for adequate, 0.85 for sufficient, 0.60 for insufficient and 0.50 for poor management and communications and which need to be incorporated in estimating Ec and Eb.

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[1] M.G. Bos and J. Nugteren. Irrigation efficiency in small farm areas, ICID, 1974, or Publication No. 19, International Institute for Land Reclamation and Improvement, Wageningen, 1974.

The procedure generally followed in determining overall project efficiency, Ep, is to consider the various stages of water conveyance and application or the efficiency of canal conveyance, Ec, the efficiency of field ditch conveyance, Eb, and efficiency of water application at the field, Ea. Overall project efficiency is $Ep = Ec \cdot Eb \cdot Ea$. In planning the relevant efficiency values are usually estimated on the basis of experience. Field application efficiency is discussed in Chapter II.4.

III.1.4 Calculation of seasonal project supply

Once the cropping pattern and intensity have been established, the level of supply and efficiency of the system selected, and irrigation requirements determined as given in Chapter II, the project supply for the project area can be determined by:

$$Vs = \frac{10}{Ea\ Eb\ Ec} \cdot \sum_i In \cdot An$$

where Vs - Seasonal project supply, m^3

Ec - Conveyance efficiency, fraction

Eb - Field ditch efficiency, fraction

Ea - Field application efficiency, fraction

In - Net irrigation requirement for each crop, mm

An - Acreage under each crop, ha

EXAMPLE:

Scheme area is 1 000 ha; of the cropped area in the winter season, October-March, 40% is under wheat and 60% under berseem, the cropping intensity is 65% of the cropped area in the summer season, April-September, 60% is under maize and 40% under cotton, the cropping intensity is 85 percent. Management of the 1 000 ha scheme is assumed to be reasonably effective (Ec = 0.7), the blocks of 25 ha are supplied by unlined canals (Eb = 0.8), while application efficiency Ea is taken at 0.6.

In, mm/month (from Chapter II.2)

	J	F	M	A	M	J	J	A	S	O	N	D
Wheat	-	-	140	-							-	-
Berseem	-	-								-	-	-
Maize					100	200	300	200	?			
Cotton				100	200	300	300	100				

$$Vs = \frac{10}{0.7 \times 0.8 \times 0.6} \left[.65(140)\ 400 + .65(0)600 + .85(800)600 + .85(1\ 000)400 \right]$$

$$= \underline{\underline{23.3}}\ 10^6 m^3/year$$

Using weighted data for crop distribution, weighted irrigation requirement is multiplied by the project area taking into consideration the cropping intensity, or the scheme seasonal water supply (using data from Chapter II.2) is :

$$Vs = \frac{10}{0.7 \times 0.8 \times 0.6} \left[56 \times 0.65 + 880 \times 0.85 \right] 1\ 000$$

$$\underline{\underline{23.3}}\ 10^6 m^3/year$$

III.1.5. Calculation of peak project supply

The project supply should meet irrigation requirements throughout the whole growing season. Preliminary peak project supply can be based on field irrigation requirements of the month of highest demand or

$$Vsmax = C . \frac{10}{Ed\ Eb\ Ea} \Sigma \text{ In peak month An}$$

where Vsmax = Average daily peak supply, m^3

In peak = Net irrigation requirements for each crop during month of highest demands, mm/day 1/

An = Acreage under each crop, ha

C = Flexibility factor

To incorporate flexibility of the delivery capacity, the derived value of Vsmax is normally increased by 10 % when the project area is greater than 2 000 ha. This may be increased progressively with a decrease in acreage served and can be as high as 100 % when the project area is 50 ha or smaller.

EXAMPLE:

Same as before; ET(maize) , July, is 280 mm and ET(cotton), July, is 288 mm or respectively 9.0 and 9.3 mm/day; depth of irrigation is 80 mm per application; peak periods ET(maize) and ET(cotton), using Figure 11 Chapter I.4.1, are respectively 1.08 x 9.0 and 1.08 x 9.3 or 9.7 and 10.0 mm/day; area is 1 000 ha, cropping intensity is 85 %. The correction factor assumed for the area of 1 000 ha is 1.2; conveyance efficiency, Ec, is 0.7, field ditch efficiency, Eb, is 0.8 and application efficiency, Ea = 0.6.

$$Vsmax = 1.2\ .\ \frac{10}{0.7\ .\ 0.8\ .\ 0.6} \left[0.35\ (9.7)\ 600 + 0.85\ (10.0)\ 400 \right] = 300\ 000\ m^3/day$$

1/ Here ET(crop) and effective rainfall should reflect the peak period in the month of highest demand; calculation of peak period ET(crop) and selection of dependable level of rainfall are given in Chapters I.4.1 and II.1.1, and in Chapter II.1.2 respectively.

III.1.6 Project operational field: supply scheduling

An evaluation of supply over a period of time will be needed for preliminary project design. The classic method of deriving the supply for projects greater than 2 000 ha is to consider the layout of the main canal system and acreages it is to serve. Each area served will, for the given cropping pattern and intensity, have its irrigation requirement (mm/month/ha) which will give an ‘‘acreage figure’’ for the necessary supply (m^3/day). The graphical presentation of such a function - supply versus area served for each lateral canal and totalled for the main canal - is called the supply or capacity line. Many capacity lines are empirical.

For large irrigation projects, with irrigation blocks of 200 to 500 ha, a fixed flow is normally delivered to the irrigation blocks, the size of flow being proportional to the acreage irrigated, crops grown and cropping intensity. The water supply is then rotated among the different fields or sections composing the irrigation block.

With any increase in crop diversification the scheduling of the supply to different fields and blocks might become rather irregular; peak supplies for the crops grown might occur at different times for individual areas. An example is rice, where peak supply is most frequently determined by the water required for initial flooding, and flooding of rice fields may need spreading over longer periods to avoid excessively high peak supply [1/]. Actual maximum scheme water supply, Vsmax, can thus diverge considerably from maximum supply figures derived from weighted irrigation requirements of the month of highest demand. A detailed evaluation of supply scheduling will need to be made fairly frequently and should be started at the lowest irrigation unit or for an additional field and subsequently worked out for blocks of fields, for areas served by lateral canals and for total project area served by the main canal.

Variations in irrigation requirements caused by acreage, climate and time are difficult to meet if project scheduling up to the field inlet has been based on continuous supply as is done in some rice schemes. Greater flexibility is obtained by rotating the supply among individual fields and blocks of fields, provided rotation schedules are adjusted from time to time to account for differences in crops and cropping intensity and metereological conditions. However, in periods of low demand the supply may be interrupted, i.e. the canal may be in operation for only part of the time. This may have severe consequences for instance in case of shallow rooted crops grown on part of the project area requiring frequent light irrigation. Large and frequent variations in supply can be attained by programmed delivery. In this case the cost of construction and operation of the supply system may be high while at the same time there should be adequate control at the headworks and throughout the system to regulate the flow.

[1/] See for instance L.T. Chin, Irrigation and Drainage Paper No.12, FAO, Rome, 1972.

Variations in frequency and depth of irrigation are most easily met if supply is based on a demand system. An efficient organizational framework and highly qualified project staff are required to operate these costly systems which consist of many regulating and check structures for the control of fluctuating discharges 1/.

When preparing preliminary operation schedules for the canal system, the irrigation blocks served by the same canal are frequently used as a unit. To determine the necessary supply, the efficiency of the total system, Ep, is then subdivided into conveyance efficiency, Ec, and field efficiency, Ef. For a block of fields Ef is the product of field ditch efficiency, Eb, and field application efficiency, Ea. As discussed in Chapter III.2, Eb is determined mainly by field size and field supply with either a long or short delivery period for the intermittent field supply; and similarly, Ea is determined by the method of irrigation and the soil type (Chapter II.4). Field supply and field application are very much interrelated, i.e. by stream size per unit of area and delivery period or by the method of distribution within the block - continuous, rotational or on demand.

In Table 45 average field and conveyance efficiencies are given for different methods of water delivery, and their product is overall project efficiency, Ep. The data are obtained from a recent ICID study on irrigation efficiencies.

Table 45 AVERAGE FIELD AND CONVEYANCE EFFICIENCY IN EXISTING IRRIGATION PROJECTS SUBDIVIDED INTO METHOD OF FIELD DELIVERY

Method	Ef	Ec	Ep
Continuous block supply with small changes in stream size; paddy fields	0.27	0.90	0.25
Rotational supply based on predetermined schedule	0.41	0.70	0.29
Rotational supply based on advance request by farmers	0.53	0.53	0.28
Supply on demand, supply by pipeline system under pressure, sprinkler irrigation	0.70	0.73	0.51

Source: ICID

1/ For a detailed description of methods of water delivery including design criteria, reference is made to I. Nugteren, Irrigation and Drainage Paper No.13, FAO, Rome, 1972.

Depending on the accuracy of data required, the supply to the irrigation block for different periods during the season can be obtained either from weighted data on frequency and depth of irrigation of the most important crops grown in that block, or from detailed water scheduling programmes for the different crops, including the soil intake rate and method of irrigation. The latter is discussed in Chapter III.2.

In the case of the former, the supply or irrigation module to the irrigation block can be obtained from

$$qf = \frac{A.d}{8.41I} \cdot \frac{1}{Ef}$$

where: qf = Supply to irrigation block, l/sec

A = Area, ha

d = Mean value of net depth of application, mm

I = Number of days allowed for completion of one irrigation, or so-called rotation interval

Ef = Field efficiency, fraction

To increase the flexibility and to account for higher water requirements, a flexibility factor C, greater than unity is sometimes applied, similar to the peak project supply.

In the case of a fixed supply qf, the value of I will depend on whether the irrigation block is supplied continuously or intermittently. In the latter case, the supply from the lateral serving the irrigation block is rotated among the various irrigation blocks. This is mainly determined by the layout of the canal system.

Values of A, d, and I will vary throughout the season. For each period qf can be determined provided the variables A, d and I are predetermined for the different periods within the growing season.

EXAMPLE:

Irrigation block is 70 ha; main crops are maize (60%) and cotton (40%); for a given period the net depth of irrigation (mean) is 100 mm and irrigation interval (mean) is 12 days; Ef = 0.50.

Supply to irrigation block is continuous; I = 12 days

$$qf = \frac{70 \times 100}{8.41 \times 12} \times \frac{1}{0.50} = \underline{140 \text{ l/sec}}$$

Supply is rotated between 3 irrigation blocks; I = 4

$$qf = \frac{70 \times 100}{8.41 \times 4} \times \frac{1}{0.50} = \underline{420 \text{ l/sec}}$$

After calculating qf for different perods within the growing season, the necessary supply over a period of time to the irrigatig block can be determined. The supply over a time to the individual blocks is totalled for each lateral serving a number of blocks; subsequently the supply over a time from each lateral is totalled to obtain the project supply over a time. This is often done graphically The preliminary operating rules for the canal distribution system can then be drawn up.

CHAPTER III.2

FIELD IRRIGATION SUPPLY

Field supply in flow and time units (l/sec) for a given field size is primarily determined by the depth of water needed to replenish the soil water in the root zone, the rate at which water can be applied or soil intake rate, method of irrigation, and method of delivery.

III.2.1 Relation between depth of soil water replenishment and supply

Water supply at the time of irrigation for a given soil and crop, expressed in stream size qa (l/sec) and delivery time ta (sec), is:

$$qata = \frac{10}{Ea} \ (Sfc - Si) \ . \ D \ . \ A$$

where Ea = Field application efficiency, fraction

Sfc = Soil water content at field capacity, volume fraction

Si = Soil water content at time of irrigation, volume fraction

D = Rooting depth, mm

A = Area, ha

EXAMPLE:

Cotton, 4th month, Sfc is 14%, Si is 7%, D = 140 cm, A = 5 ha,

Ea = 0.65%

$$qata = \frac{10}{0.65} \ (0.14 - 0.07) \ 1\,400 \ . \ 5 = 7\,540 \ m^3$$

The rooting depth, D, and the soil water content at the time of irrigation vary for different crops and for each crop during the growing season. Details about the selection of D and Si values are given in Chapter I.4.2 and I.4.5.

III.2.2 Relation between soil intake rate and supply

To quantity stream size, qa, and delivery time, ta, the rate at which the applied water will enter the soil must be determined. Intake rates will vary with soil texture and structure and soil water content. These rates for some soil textures and corresponding supply qa in l/sec for an area of 1 ha are given in Table 46 [1].

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[1] The soil intake rate is not constant over a period of time but decreases as the soil profile becomes wet. The figures quoted refer to average intake rates as opposed to initial and basic intake rates, i.e. respectively at the start of irrigation and when the intake rate has become more or less constant.

Table 46 APPROXIMATE RELATION BETWEEN SOIL TEXTURE, INTAKE RATE AND STREAM SIZE

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

EXAMPLE:

Cotton, 5 ha field, soil texture is loam, net depth of application is 100 mm, irrigation application efficiency is 0.65.

$$qata = 7\,540 \ m^3; \ ta = \frac{7\,540}{50\,000 \times 0.0125} = 12 \text{ hr and } qa = \frac{7\,540}{12}$$

$$= 625 \ m^3/hr \text{ or } 175 \ 1/sec$$

The stream size and delivery time given in the example may be impractical.

Usually irrigation is spread over one or more days; other conditional aspects prevail such as the quantity of water that can be handled by the irrigator, the number of plots irrigated simultaneously, the method of irrigation and the capacity of the supply channel. Basing the irrigation supply only on the intake rate of soils may lead to erronous supply schedules.

III.2.3 Relation between method of irrigation and stream size

a) Surface irrigation

The stream size, qa in l/sec, for a given field or block of fields will, apart from the intake rate of the soil, depend on the method of irrigation, the stream size that can be handled by the irrigator or irrigation crew and the number and size of furrows, borders or basins irrigated simultaneously. For spinkler irrigation the stream size is furthermore determined by the available irrigation equipment.

To attain uniform water distribution over the field the rate of application will vary with the method of irrigation. In the case of the basin (or level border) method, the stream size to each border should be at least twice that required for the average soil intake rate; or 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 on sloping lands, the soil takes the water when the soil surface is covered with flowing water. The stream size per furrow and border should be large enough to reach the end of the run in the desired time and small enough to be non-erosive, and should not cause extensive flooding or tail losses. The size of the stream must be adjusted to the length of the run, land slope, erosion hazards, shape of the flow channel, soil infiltration rate and the water depth to be applied.

Field trials on layout and irrigation practices are required to determine optimum values of stream size qa and delivery time ta. Such physical data must be available at the design stage of the project.

For easy reference, the stream size in l/sec for a suggested size or length of field under basin, border and furrow irrigation is given in Tables 47, 48 and 49. The size and length of the field is primarily determined by the soil type and land slope. Stream size is based on the intake rate of the soil and erosion control. Since, during irrigation application, the intake rate of the soil changes with time, the stream size into the border or furrow is often reduced after an initial period of wetting. The stream size in the supply canal is normally constant; sufficient flexibility can be maintained by regulating the depth of application through controlling the inflow to each border or furrow, varying the number of borders and basins served simultaneously and by lengthening or shortening the delivery time, ta. In the case of sprinkler irrigation, the stream size is based on the minimum intake rate of the soil over the total time of application and on the type of sprinkler equipment used 1/ .

EXAMPLE:

Furrow irrigation; soil is medium texture, infiltration rate is 13 mm/hr; land slope is 0.5%. Crop is cotton, depth of water application is 100 mm; irrigation application efficiency Ea is 0.65; number of furrows served simultaneously as determined by slope of supply lateral is 50; furrows are spaced at 0.8 m. Field distribution efficiency Eb = 0.8.

From table or field data: furrow length = 370 m.
From table or field data: maximum flow per furrow is 1.2 l/sec.

$$\text{Depth of application per hour is } \frac{3\,600 \times 1.2}{0.8 \times 370} = 14.6 \text{ mm/hr.}$$

$$\text{Stream size per furrow adjusted } \frac{13}{14.6} \times 1.2 \simeq 1.05 \text{ l/ sec}$$

Depth of application is $d/Ea = 100/.65 \simeq 150$ mm.

$ta = d/i = 150/13 = 11.5$ hrs.

$$qa = \frac{50 \times 1.05}{Eb} = \underline{65 \text{ l/sec}}$$

1/ For the evaluation of irrigation methods, reference is made to Merriam (1968), Slabbers (1971), Booher (1973); for sprinkler irrigation Pillsbury (1968).

Table 47 - SUGGESTED SIZE OF BASINS AND STREAM SIZE FOR DIFFERENT SOILS 1/

Size of Basin (ha)				Flow Rate (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 48 - SUGGESTED LENGTH OF FURROWS AND STREAM SIZE FOR DIFFERENT SOILS, LAND SLOPE AND DEPTH OF WATER APPLICATION 1/

Slope (%)	Length of Furrow (m)												Max. 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	1.2*
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 49 - SUGGESTED SIZE OF BORDERS AND STREAM SIZE FOR DIFFERENT SOILS AND LAND SLOPE 1/ (DEEP ROOTED CROPS)

Soil type	Slope, %	Width, m	Length, m	Flow/meter width, 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

1/ Under conditions of perfect land levelling.

If night irrigation is acceptable, the area irrigated per day when supply is slightly more than 65 l/sec is $2 \times \frac{(50 \times 0.8 \times 370)}{10000} = \underline{3 \text{ ha}}$

If night storage is provided equal to $\frac{12 \times 60 \times 60 \times 65}{1\,000}$ or some $2\,800 \text{ m}^3$, the area irrigated over a two-day period is 3.2 ha when supply received is 65 l/sec for 24 hours.

b) Sprinkler irrigation

The supply for sprinkler irrigation, is determined similarly to surface irrigation; the main difference being in the detail of information required to operate the system at lowest cost c.q. to minimize the equipment required.

The stream size is determined by the application rate as governed by the basic intake of the soil and the number of sprinklers operating simultaneously. This latter is conditioned by the system layout and number of laterals which in turn is largely dictated by size and shape of the field, frequency of irrigation application and the farmer's preference on the number of hours per day and number of days per week that the system will operate. These factors have a distinct effect on water supply in terms of total stream size, qa, and delivery time, ta.

For a given system, the depth and frequency of irrigation can be changed by varying the application time and number of days between irrigation. Any alteration in the number of laterals and sprinklers operating at any time, other than 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, therefore, should - as far as possible - conform to the discharge rate used in the design.

EXAMPLE:

Crop is cotton; net depth of application at peak period ET(crop) is 84 mm. Basic soil intake rate (i) is 11 mm/hr. Gross depth of application is equal to net depth plus allowance for losses. Assuming irrigation efficiency equal to 75 % gross depth of application is $84 \div 0.75 = 112$ mm per application. Application time $ta = 112 \div 11 = 10$ hrs. With an application rate of 11 mm/hr and selected spacing along a lateral (S_1) 12 m and spacing between laterals (S_2) of 18 m, the required stream size per sprinkling is $q = \frac{i}{1\,000} \times S_1 \times S_2 = \frac{11}{1\,000} \times 12 \times 18 = 2.38 \text{ m}^3/\text{hr}$.

From tables supplied by manufacturers of sprinkler equipment: for spacing = 12 x 18 m and $q = 2.38 \text{ m}^3/\text{hr}$ commercially available sprinklers can be selected with nozzle size 4.5/4.8 mm, pressure 2 atm, spray length 14 m, capacity $2.3 \text{ m}^3/\text{hr}$. (Table 50).

For a given field (shape and size), number of hours of application per day and per week and irrigation frequency, the system field layout, the number of sprinklers per lateral (usually a maximum of 15) and number of laterals operating simultaneously can be found; stream size for the system is equal to the number of sprinklers operating at one time multiplied by the sprinkler discharge.

The total pressure required can be determined from height of pump lift, the friction losses in the pump, the pipe friction losses, sprinkler height, and the pressure at the sprinkler nozzle. Consequently, for a given stream size and total pressure required the type and size of pump can be selected.

Table 50 OPERATING FIGURES FOR SOME SPRINKLERS (SQUARE PATTERN)

Nozzle mm	Pressure kg/cm^2	Spray m	Delivery m^3	Spacing m	Area m^2	Precipitation mm/ hr.
4.5	2.0	13.5	1.1	12 x 18	215	5.0
	2.5	14	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	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

c) Drip irrigation

With drip irrigation individual trees, groups of plants or plant rows are supplied by emitters placed on laterals delivering a flow (qe) of 2 to 10 l/hr. Only a portion of the soil surface is wetted. The required stream size is determined mainly by the number and type of emitters, soil type, crop and allowable soil water depletion. In a well operated system a nearly constant low tension soil water condition can be maintained; for selected level of soil water depletion, the frequency and duration of application can be varied depending on ET(crop) and soil infiltration rate.

EXAMPLE:

Given: Area is 40 ha; crop is tomatoes; soil is silty clay loam with Sfc = 16 vol% and selected Si = 11 Vol % ; soil infiltration rate is 5 mm/hr; effective rooting depth (D) is 100 cm; ET(tomato) is 7 mm/day.

Crop rows are spaced (Sl) at 1.2 m; an emitter with flow rate (qe)of 2 l/hr is selected with spacing on lateral (Se) of 0.6 m; uniformity of application (Eu) is 95%; it is assumed that unavoidable losses (Tl) including evaporation of the wet soil surface are 10% of the total amount of water applied.

Calculation: Fraction of surface area wetted (P), from Table 53, is
W/ (Se x Sl) = 0.4/(0.6 x 1.2) = 0.55.
Maximum net depth of application d = (Sfc - Si) . D . P . =
(0.16 - 0.11) . 1 000 . 0.55 = 27.5 mm.
Irrigation interval I = d/ET(crop) = 27.5/7 = 3.9 days.
Maximum gross depth of application dg = d/(Tl x Eu)
= (27.5)/(0.95 x 0.9) = 32 mm.
Duration of application It = (dg x Se x Sl)/qe
= (32 x 0.6 x 1.2)/2 = 11.5 hr.

Maximum number of operating units into which the field can be divided is N $\leqslant$ (I x 24/It) or $\leqslant$ (3.9 x 24)/11.5 or $\leqslant$ 8.1 or 8.
Required discharge of system is 2.8 A/N x qe/(Sl x Se)
= 2.8 x 40/8 x 2/(0.6 x 1.2) = 39 l/sec.
NB: Above calculation assumes continuous operation of the system.

Table 51 FLOW RATE PER DRIP EMITTER IN l/hr, CONTINUOUS FLOW, FOR DIFFERENT ET(CROP) AND NUMBER OF EMITTERS PER ha

ET(crop) 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
2.5	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
5.0	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
7.5	12.50	6.25	4.17	3.13	2.08	1.56	1.25	0.63

Example: With 1500 emitters/ha and ET(crop) = 5 mm/day; application for 12 hrs every 3 days; emitter flow: $\frac{24}{12}$ x 3 x 1.39 = 8.34 l/hr; qa =3.5 l/sec/ha (losses to be added). This presumes all 1500 emitters in operation simultaneously. Actually of total acreage only 1/6 would be needed for any 12-hour period or qa = 0.6 l/sec/ha.

Table 52 - FLOW RATE PER TREE, CONTINUOUS FLOW, FOR DIFFERENT ET(CROP) AND TREE SPACING, 1/hr.

Tree spacing m	ET(orchard), 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 53 - SURFACE AREA WETTED IN m^2 FOR DIFFERENT EMITTER FLOW AND SOIL INFILTRATION INFILTRATION RATE 1/

Emitter flow 1/hr cont.	Soil infiltration rate, mm/hr		
	2.5	5	7.5
2	0.8	0.4*	0.25
4	1.6	0.8	0.5
6	2.4	1.2	0.75
8	3.2	1.6	1.0

1/ Source: Personal communication Duffin, UC, Davis.

III.2.4 Relation between field size, field layout and supply

Individual fields within an irrigation block are normally supplied in rotation. When a shallow rooted cash crop is also grown, requiring frequent and light irrigation applications, a double rotation is often practised within the interval, I.

For surface irrigation schemes in most cases, a fixed supply for large irrigation blocks (50 ha or more) is preferable; this system is the easiest to operate and can be controlled from headworks. Any variation in the supply required by the block during the growing season results either in interrupted deliveries or in reduced flow in the supply channel. The latter requires a higher degree of sophistication, both technical, structural and organizational. In the case of interrupted delivery, the canal serving the irrigation block is in operation for only a portion of the interval, I, in periods when crop water requirements are low. The interruption can be either random or according to a pre-arranged schedule and if the latter, then it can be completely rigid - fixed supply and fixed period of supply - or, preferably, have a certain flexibility and be adjusted from time to time to allow for changes in crop water requirements due to variations in cropping pattern and climatic conditions (ET(crop), rainfall) during the season. A more sophisticated type of project operation is required for this compared to the rigid schedule. The degree of flexibility necessary in supply and subsequent operation of the field canals can normally only be determined after the project has been in operation for some time.

If detailed water scheduling programmes are required for final design purposes, the prediction of stream size and delivery time including their variations during the growing season should start at the lowest field unit. As shown in the previous sub-chapter, the criteria for field supply of the lowest unit are based on acreage and type of crops grown, irrigation water needs, irrigation interval, soil and method of irrigation. Timetables for irrigation supply are prepared for the irrigation season and plotted on a weekly or 10-day basis. The water supply schedules derived for individual fields can be totalled for the irrigation blocks served by the same canal.

A similar approach can be used to determine supply schedules for the irrigation blocks and these schedules for blocks of fields are then totalled to find the total project supply schedules. The following example applies to a surface irrigation scheme.

EXAMPLE:

Irrigation block is 70 ha. Crops are cotton (60%) and potatoes (40%); the cropping intensity is 85%; acreage of cotton is thus 36 ha, potatoes is 24 ha.

For a given period the irrigation interval for cotton is 12 days and for potatoes 6 days. The net depth of application is 100 mm for cotton and 40 mm for potatoes. Field efficiency for both crops is 0.5. From Chapter III.2.3, field supply for cotton is 65 l/sec to irrigate 1.5 ha or 36 ha in 12 days. Similarly, the field supply for potatoes can be determined as 35 l/sec to irrigate 4.0 ha/day or 24 ha in some 6 days. Within the rotation of the supply to the cotton fields a sub-rotation among potato fields is deemed necessary.

For a given period and selected project and field layout, the following summary can be prepared assuming a 12-day supply to the irrigation block; for simplicity the cropping pattern and cropping intensity is assumed to be the same for the total project.

Section	Acreage (ha)	Delivery Time (days)	Supply (l/sec)
Field (cotton)	1.5	0.5	65
Field (potato)	1	0.25	35
Block	70	12	100
Sub-lateral	560	12	800 1/
Lateral	2 240	12	3 200 1/
Main	11 500	12	16 000 1/

1/ If required an additional supply should be added for inefficiency of the conveyance system and for flexibility.

Similar calculations can be made for different periods of the growing season and for supply over a certain time or the supply schedules thus determined.

CHAPTER III.3 REFINEMENT OF FIELD IRRIGATION SCHEDULING DEVELOPMENT AND USE OF DATA ON SOIL, WATER, CROP AND CLIMATE

In most projects, field delivery is based on fixed quantities and periods of delivery. This type of operation, where timing and quantity are based on the calendar regardless of variation in irrigation needs due to changes in crops and climate, still prevails in many irrigated areas in the world. Efficient water utilization can only be achieved by concentrating operation of the system on the primary purpose, that is to provide optimum soil water conditions for plant growth. Crops have shown that over a period of time they require different amounts of water; in the operation of the irrigation system, sufficient flexibility must therefore be maintained to meet adequately these changing demands, but at the same time excess quantities must not be given. At the planning stage, only approximate rules of operation for projects can be given. Any refinements to water scheduling that may be required can be done after projects have been constructed and in operation for some time.

Apart from their improvement of managerial and technical aspects of operating the distribution network, refined data at the field level are required on crop irrigation needs (ET(crop), effective rainfall), soil physical qualities and depth and frequency of irrigation for a given crop, soil and climate. This data is necessary to improve irrigation scheduling already in progress and project operations. The collection and application of such refined data is briefly discussed below.

III.3.1 Refinement of field irrigation data

Irrigation requirements for planning purposes can be predicted by using concepts and methodologies developed elsewhere but prevailing local conditions must be taken into account. Such an approach is followed in this publication.

Input data and methodologies used should be correlated to local conditions through field studies. Lines of action may include the following:

a) Agro-meteorological stations

Meteorological stations for the collection of essential climatic variables should be established early.

Where possible, new agro-meteorological stations should conform to agricultural requirements. The location of stations with respect to environment is of the utmost importance; meteorological information used on many projects is based upon data obtained from stations located in non-agricultural areas, such as airports, bare ground or roof tops. The real value of agro-meteorological stations can only be realized when they are located in similar conditions to those found in agricultural areas. Where possible the 10 x 10 m station should be placed within an irrigated area and short grass should be provided as station cover. This will have a substantial effect on the accuracy of the data obtained;

for instance, a Class A evaporation pan surrounded by an irrigated area will give results more than 20% lower than when surrounded by dryland crops. The buffer area with planted crops should be as large as possible, but a minimum of 100 x 100 m.

A simple, standardized agro-meteorological station should include minimum observations on (a) temperature (maximum and minimum); (b) relative humidity (wet and drybulb thermometer); (c) preciptation (raingauge) (d) wind (totalizer); (e) sunshine hours (Campbell Stokes); (f) evaporation (Class A or sunken pan).

Reference stations, which are usually established in collaboration with meteorological or agricultural research institutes, should be provided with the following equipment in addition to the minimum instrumentation listed above: (a) thermograph (weekly charts); (b) hygrograph (weekly charts); (c) anemograph (hourly, wind directions and velocity); (d) pluviograph (weekly charts); (e) solar radiation with recorder and/or integrator; (f) barograph (weekly charts); (g) net radiometer with integrators; (h) Class A pan; (i) soil thermometers, minimum and maximum, at 10 cm; (j) standard shelters for the foregoing where necessary.

It should be ensured that properly trained meteorological observers are employed. Particularly with respect to radiation measurements, the services of an experienced consultant should be secured to select the equipment and sites, to train personnel, to advise on observation programmes to be carried out and on the analyses of the data obtained.

b) Soil survey

Preferably a detailed soil survey (scale 1:5 000 to 10,000) should have been completed before planning, design and implementation of the project. Additional investigations will be required, in particular on physical and chemical properties of the soil and their changes under prolonged irrigation 1/.

c) Water requirement studies

To ascertain crop water requirements, the following field studies should be implemented depending on facilities, quality of staff and the budget available 2/.

i) Experiments to determine seasonal crop water requirements:
   - predictive approach, based on preselected frequency and amount of irrigation, crop factors and climatic indices;
   - predictive-direct approach, monitoring soil water levels to verify predicted soil water regimes and to post-evaluate net irrigation requirements.

1/ For details see Soil Survey in Irrigation Investigations, Soils Bulletin (draft), Land and Water Development Division, FAO, Rome, 1974.

2/ See for instance A.W. Marsh, Applied Irrigation Research, FAO, Rome, 1967.

ii) Experiments to determine irrigation requirements; direct approach; monitoring and evaluation of all water components under selected soil water regimes for various stages of crop growth and evaporative demand.

iii) Experiments on irrigation practices (frequency and amount studies) based on
  - soil water tension or soil water depletion;
  - crop appearance;
  - standard references - lysimeter, reference field, ET(crop) estimates from formulae, evaporation pans.

iv) Experiments on water/yield relationships, as part of the above-mentioned field trials to determine effect of seasonal, periodic and diurnal water deficits on yield.

v) Experiments on field irrigation methods which should include field trials on layout, length of run, permissible stream size for method selected - furrow, border, basin, sprinkler, drip and sprinkler irrigation 1/.

vi) Experiments on fertilizers, irrigation/fertilizer interactions.

vii) Additional experiments on cultural aspects and land preparation

d) <u>Monitoring water supply scheduling for projects in progress</u>

The following points should be considered under this heading:

- Evaluation of method of delivery and supply scheduling practiced including determination of project, conveyance, field distribution and field application efficiency by direct measurement of separate components, or of water balance and budget or of a combined method.
- Evaluation of scheme management including institutional aspects, personnel, communication facilities.
- Water use studies in the farmer's field by testing or monitoring water use aspects including irrigation methods and practices for traditional or new crops and cropping patterns.

Applied irrigation research should be carried out in fields typical of the project area. Field trial plots laid out on representative soil types should be as large as possible and placed within an existing agricultural area to avoid the effect known as ''clothes line'' which occurs in a patchwork of small experimental plots.

Applied research on a continuous basis is necessary to evaluate the scheduling of a project and the control of water application for both traditional and new crops. Specific problems will need studying such as the use of brackish irrigation water, leaching of salts, application of fertilizers, etc. The type and detail of applied research programmes will depend greatly on the purpose of the research and available financial resources, existing

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1/ See for instance references quoted in Chapter I.4.3.

governmental organizations and institutes, and the experience of the staff. The time needed for collection of necessary data should form an integral and essential part of the total duration of project planning, design and execution. Ideally, applied research should start as early as possible and, if possible, well before the stages of detailed project design and project execution. Different approaches can be used:

Experimental stations. Many permanent experimental stations engaged in basic and applied research have been established on a national basis (see for instance, for the Near East, Raffiq, 1971). Optimum use should be made of knowledge and experience gained within any one country and applied research programmes should be carried out in close collaboration with established institutes. Studies should be selected carefully and reflect the most critical problems met in project design and operation. The cost of running such stations is high and, depending on the size of the project, they can normally be maintained only if they form part of government-sponsored research institutes or universities.

Field sub-stations and field plots. Instead of conducting extensive and detailed applied programmes, normally sub-stations are equipped to apply the results from research stations to local conditions on a practical scale. They are mostly found in connexion with planned or established large scale projects. Apart from agronomic and fertilizer trials, their type of activity should include simple studies on water requirements, crop/water response and irrigation methods and practices. The operation of a second-degree weather station should be included if possible and the value of such stations for demonstration purposes should not be overlooked. Not many personnel may be required, but supervisory assistance should be available.

Field experiments in the farmer's field. Practical studies can be carried out in the farmer's field as part of project operations because they provide results whose value is often greatly under-estimated. The value of such experiments for demonstration and training is inestimable if full cooperation with the farmers is achieved, although the survival rate of such experiments may be lower than 50 percent because of uncontrollable factors and the difficulty of maintaining the farmer's interest and getting him to keep appropriate records. Close collaboration should be maintained with the local extension service especially as they may be of help in convincing partners of the benefits of their field experiments.

Pilot projects. The need to set up pilot projects before embarking on large-scale project development cannot be over-emphasized. The area should cover between 100 and 500 ha to allow for a detailed analysis of future project operations. Apart from water requirement and application experiments, problems concerning the distribution of water, use of surface and/or groundwater, water and salt balance, and water losses can be considered and many other studies carried out at project level. The scheme should be located with an eye to its inclusion in the anticipated large project.

III.3.2 Application of field irrigation data

Once basic data on depth and frequency of irrigation for a given crop, soil and climate are available, various ways can be used to put these data into practice.

In irrigation projects where water is supplied on demand, the supply to individual fields can be scheduled on the basis of direct measurement of the soil water by soil water indicators, by plant indicators and by evaporation measuring devices such as pans. All these methods require substantial insight into the effect and importance of the factors involved and can only be successfully applied when, for the given condition, the essential data on crop-soil-water-atmosphere relations are available. 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 1/. However, results from the use of these devices by farmers is often disappointing simply because they have not the required technical knowledge or understanding to extract full benefit from the indications obtained. Therefore it is often preferable for advice and assistance to be given by central irrigation authorities or extension services rather than to leave all the work of collecting necessary data to the farmers. The data needed 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 and will give a sufficiently high degree of accuracy (Israel, Hawaii). An example is cited of the use of the evaporation pan in scheduling of irrigation. A simple method is sometimes followed in India; within an irrigated field of medium or heavy-textured soil, a soil block of 1 m^3 is mixed with about 10% sand; early wilting of plants grown in the soil-sand mixture is noticed indicating that irrigation of the cropped field should follow soon.

Other methods are based on meteorological data combined with known soil and crop data and supplemented by sufficient field checks. For development and testing of such prediction methods adequate experimental data on these and related subjects must be available for the given conditions. These methods can be applied more readily if water delivery is based on controlled or free demand. 1/

Efficient extension services can be of much assistance not only in collecting information from field experimental work but also in applying its resultant data for the improvement of irrigation efficiency.

1/ Hagan, Haise and Edminster, Irrigation of Agricultural Lands, (1967). FAO/Unesco, International Sourcebook on Irrigation and Drainage of Arid Lands, Unesco, Paris (1973). Stanhill, Practical soil moisture problems in agriculture, WMO (1968).

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

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

Required:
- standard rain gauge 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 19). For given stage of crop growth kc is selected (Tables 21-30). ET(crop) = kpan x kc x Epan. From soil water balance, subtract ET(crop) and add daily rainfall and irrigation application. Irrigation is applied when soil water depletion has reached soil water tension of 0.5 for most vegetable crops, onions and potatoes, and 1.0 to 1.5 for most field crops. Depth of application equals /soil water content at field capacity minus soil water content at time of irrigation in volume percentage/ times rooting depth.

SOIL WATER BALANCE SHEET

Scheme: Ralinkua Soil type Siloam.......... Total available soil water 25 v% 0- 30 cm
Field: ...14.................. 25 v% 30- 60 cm
Farmer: ..Lokotce......... 25 v% 60- 90 cm
Months: ..April - Sept..... ... v% 90-120 cm
Pan location: 100 m 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-irrig
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 flowers
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	Irrigate
										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	

The following is an example of the sequence of soil, water, crop and climatic data which should be available on which to base recommendations for irrigation scheduling:

Action	Requirements
1. Estimate ET for reference crop (grass, alfalfa)	Field plot or adequately tested radiation/energy 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 (crop and field surveys)
3. Determine effective contribution of rain since last irrigation	Rainfall observations, determination of effectiveness, field checks
4. 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
5. Predict future rainfall contribution	Rainfall frequency distribution analysis of long-term daily data
6. Predict with computed ET(crop) when day of maximum allowable soil water will be reached	Detailed soil and crop data, water use/production function
7. Calculate total amount of water to be delivered to the field at predicted time	Irrigation efficiency, groundwater contributed to root zone
	Information centre

Optimum timing of irrigation is even more essential when there is a short supply of water at the source. Decisions must be made early regarding the times at which water can be saved and when its allocation is most essential. The amount of irrigation water needed during the growing season may be reduced appreciably by the 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. Minimizing the total depth of water and the number of irrigations on the basis of a better understanding and use of the soil water reservoir should receive particular attention in water scheduling programmes where water is scarce and expensive.

When water is in short supply decisions must be made early in project operations for the allocation of water when most needed in terms of attaining acceptable yields. Water distribution to the fields should be planned to avoid the water supply to the crop being restricted during its critical period for water stress; for most crops this is from flowering and early fruit development onward. Thus during periods of water shortage, irrigation delivery should be programmed on preselected ET(crop) deficits, with the least deficit allowed during the most sensitive growth stage. It is obvious that to avoid the plant drying out during the vegetative growth periods, some water must still to be applied.

Refinements in knowledge of crop water requirements and field applications can only be of value if the design and operation of irrigation systems are geared to meeting actual field requirements and by delivering the proper quantities 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 farmer in planned irrigation developments. New techniques cannot be applied wholesale but must be assimilated according to capacity; the transfer of knowledge on the most effective use of water at the level of the farmers fields will not be achieved overnight, but must gradually seep in and be accepted as benefits are demonstrated. A whole range of long-term activities will be required such as the setting up of extension services, the establishment of demonstration plots and the provision of training facilities. It is only when this framework has been established and is functioning, that carefully developed techniques can be tested and applied once their validity has been proved.

APPENDIX I

GLOSSARY

ACTUAL CROP EVAPOTRANSPIRATION, ETa(crop): rate of evapotranspiration equal to or smaller than predicted ET(crop) depending on the level of available soil water, wilting phenomena, salinity, field size, or other causes; mm per day.

ACTUAL VAPOUR PRESSURE, ed: pressure exerted by water vapour contained in the air; millibar.

ADVECTION: transport by air movement of sensible heat from large dry fallow surrounds into irrigated areas.

AVAILABLE SOIL WATER STORAGE, ΔSi: amount of water storable in the root zone at time of irrigation; weight or volume percentage or mm over rooting depth.

AVERAGE INTAKE RATE: rate of infiltration of water into the soil by dividing the total depth of water infiltrated by the total time from start of irrigation to the moment when infiltration rate is equal to the basic infiltration rate; mm/hour.

BASIC INTAKE RATE: rate at which water will enter the soil after a period when the change in rate becomes very slow; mm/hour.

CANOPY INTERCEPTION: depth of precipitation caught and held by plant foliage and lost by evaporation without reaching the ground surface; percentage or mm.

CARRY-OVER SOIL WATER: amount of water stored in the soil from earlier rains, snow or irrigation applications which meets water deficiencies in following periods; volume or weight percentage.

CLOTHESLINE EFFECT: horizontal heat transfer from warm upwind area to a relatively cooler crop field resulting in increased ET(crop) particularly at the field border or patchwork of small interspersed fields.

CLOUDINESS: degree of cloud cover as mean of several observations per day; expressed in oktas - in eights of sky covered; or tenths - in tenths of sky covered.

CONTINUOUS SUPPLY: continuous and constant discharge to inlet of the individual farms or fields; 1/sec.

CONVEYANCE EFFICIENCY Ec: ratio between quantity supplied to a block of fields or rotation unit and total quantity supplied to the irrigated project area; fraction.

CRITICAL PERIOD: period during crop growth when the crop is most sensitive to soil water stress which will have a lasting effect on crop growth and will reduce yields.

CROP COEFFICIENT, kc: ratio between crop evapotranspiration ET(crop) and reference crop evapotranspiration ETo when both are in large fields, under optimum growing conditions.

CROP DEVELOPMENT STAGE: for given crop time between end of initial stage and when crop reaches 70 to 80% full ground cover; days.

CROP EVAPOTRANSPIRATION, ET(crop): 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 fertility and achieving full production potential of that crop under the given growing environment; mm/day.

CROPPING INTENSITY: at a given time the percentage of the total scheme area which can be supplied by the irrigation system and is fully equipped for water distribution that is under an irrigated crop; at a given time, the percentage of the cultivated area that is under a crop; percentage.

CROPPING PATTERN: sequence of different crops grown in regular order on any particular field or fields.

CROP WATER REQUIREMENTS, ET(crop): depth of water, regardless of its source, required by a crop or a diversified pattern of crops for evapotranspiration; mm and period; mm/day.

DAYLENGTH, p: number of hours between sunrise and sunset; hours or in percentage of total annual daylight hours for each day.

DEEP PERCOLATION, F: rate of downward movement of soil water from the root zone prior to and following attainment of field capacity after ample irrigation or heavy rains; mm/day.

DELIVERY TIME, ta: length of time during which a given streamsize is delivered to the field or block of fields; hour or day.

DEWPOINT TEMPERATURE: temperature to which the air needs to be cooled down in order to become saturated and at which water vapour starts to condense; degree Celsius.

DEPTH OF IRRIGATION, d: depth of irrigation applied to the soil in one irrigation, or volume of water delivered to a given area in one irrigation divided by the acreage and which is needed to bring the water content of root zone to field capacity; mm.

DRAINAGE: removal of excess surface and groundwater from the soil; mm/day.

EFFECTIVE FULL GROUNDCOVER: percentage of groundcover by the crop when ET(crop) is approaching maximum - generally 70 to 80%.

EFFECTIVE PRECIPITATION: that fraction of total precipitation useful for meeting crop water requirements; it excludes deep drainage, run-off, and evaporation from the soil surface; fraction.

EFFECTIVE ROOTING DEPTH, D: soil depth from which the crop extracts most of the water needed for evapotranspiration (also called design rooting depth); cm.

ELECTRICAL CONDUCTIVITY, DRAINAGE WATER, ECdr: measure of salt content of excess soil water that is removed by downward flow through the soil; mmhos/cm.

ELECTRICAL CONDUCTIVITY, IRRIGATION WATER, ECirr: measure of salt content of irrigation water; in mmhos/cm; salts in part per million $\approx 0.64 \times EC \times 10^3$ for irrigation water up to 5 mmhos/cm; mmhos/cm.

ELECTRICAL CONDUCTIVITY, SATURATION EXTRACTS, ECe: measure of salt content of soil water extracted from the soil, when saturated with water; mmhos/cm.

EVAPORATION, E: rate of transformation of water from liquid to vapour phase through purely physical processes, mm/day.

EVAPOTRANSPIRATION, ET(crop): rate of transpiration from a vegetal cover, evaporation from the soil and from the wet surface of the vegetation; mm/day.

EXTRA-TERRESTRIAL RADIATION, Ra: amount of radiation received at the top of the atmosphere; equivalent evaporation mm/day.

FIELD APPLICATION EFFICIENCY, Ea: ratio between water placed in the root zone and directly available to the crop versus total quantity applied to the field; percentage or fraction.

FIELD CAPACITY, Sfc: amount 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; also called effective water holding capacity or soil water content at soil water tension of 0.2 to 0.3 atmoshpere; volume or weight percentage.

FIELD DITCH EFFICIENCY, Eb: ratio between the quantity supplied to the individual fields and the total quantity supplied to a group of fields or rotation unit; percentage or fraction.

FIELD EFFICIENCY, Ef: ratio between quantity of water placed in the root zone and quantity supplied to a group of fields or rotation unit;Ef = Ea x Eb; percentage or fraction.

FIELD SCHEDULE: quantity and timing of water delivered to the individual field or block of fields; volume and interval.

FIELD SUPPLY, Vs: quantity of water delivered during a certain length of time to an individual field or block of fields; volume.

FIELD WATER BALANCE: sum of all gains and losses of water over a given period in the root zone.

FLEXIBILITY FACTOR, C: coefficient greater than unity to account for fluctuations in water supply in excess of those determined for an assumed cropping pattern and cropping intensity; fraction.

FULL GROUND COVER: amount of soil covered by crops approaching 100 percent when looking downwards.

GROSS IRRIGATION REQUIREMENT, If: depth of water, excluding contribution by precipitation, groundwater, stored soilwater, or surface or subsurface inflow, required for normal crop production plus water losses and operational wastes; mm and period.

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.

GROUNDCOVER: percentage of soil surface shaded by the crop when sun is directly overhead; percentage.

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 groundcover is less than 10 percent; days.

INITIAL INTAKE RATE: rate at which water will enter the soil when water is first applied; mm/hour.

IRRIGATION INTERVAL OR FREQUENCY OF IRRIGATION, I: time between the starting of one irrigation and the starting of the next on the same field; days.

IRRIGATION MODULE: flow of water designed for or used in irrigating a unit of land.

LATE-SEASON STAGE: for a given crop the time between the end of the midseason stage and harvest; days.

LEACHING: removal of soluble salts by passage of water through soil.

LEVEL OF SUPPLY: quantity of water selected 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.

MAXIMUM RELATIVE HUMIDITY, RHmax: maximum or mean of maximum of each day over the period considered of 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; percentage.

MAXIMUM TEMPERATURE, tmax: maximum temperature during the day or mean of maximum temperature for each day for the period considered; degree Celsius.

METHOD OF WATER DELIVERY: way of making an irrigation system function to convey water from the source of supply to each field served by the system.

MIDSEASON STAGE: for a given crop the time between effective full ground cover and the onset of maturity (i.e. leaves start to discolour or fall off); days.

MINIMUM RELATIVE HUMIDITY, RHmin: minimum or mean of each day over the period considered 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; percentage.

MINIMUM TEMPERATURE, tmin: lowest temperature during the day or mean of lowest temperatures of each day for the period considered; degree Celsius.

NET IRRIGATION REQUIREMENT, In: depth of water, excluding contribution by precipitation, groundwater, stored soilwater, surface or subsurface inflow, required for normal crop production; mm and period.

NET LONGWAWE RADIATION, Rnl: balance between all outgoing and incoming longwave radiation; equivalent evaporation mm/day.

NET RADIATION, Rn: balance between all incoming and outgoing short and longwawe radiation; Rn = Rns + Rnl; equivalent evaporation mm/day.

NET SOLAR RADIATION, Rns: difference between shortwave radiation received on the earth surface and that reflected by the soil, crop and water surface; equivalent evaporation mm/day.

OASIS EFFECT: vertical energy transfer from air to the crop; effect of dry fallow surrounds on the microclimate of a relatively small acreage of land where an air mass moving into an irrigated area will give up much sensible heat. For small fields this may result in a higher ET(crop) as compared to predicted ET(crop) using climatic data collected inside the irrigated area; conversely ET(crop) 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 crop evapotranspiration ET(crop) and water loss by evaporation from an open water surface of a pan.

PAN EVAPORATION, Epan: rate of water loss by evaporation from an open water surface of pan; mm/day.

PEAK PERIOD CROP WATER REQUIREMENTS, ET(crop) peak: for a given crop the peak crop water requirements during the month of highest water requirements; mm/day.

PLANT POPULATION: number of plants per unit of 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 run-off, infiltration or evapotranspiration; mm/day.

PROJECT EFFICIENCY, OR OVERALL EFFICIENCY, Ep : ratio between water placed in the root zone and total quantity supplied to the irrigated project area; Ep = Ec x Ef = Ec x Eb x Ea; percentage or fraction.

PSYCHROMETER: device to measure air humidity; generally consisting of a normal thermometer and a thermometer whose bulb is surrounded by a wet muslin bag; the latter, called wet-bulb thermometer, should normally be force ventilated (Assmann type).

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 per day.

REFLECTION COEFFICIENT, α: ratio between the amount of shortwave radiation received at the earth surface and that reflected back by the soil, crop or water surface; fraction.

ROTATION INTERVAL, I: time between the start of supply to a given field or block of fields belonging to the rotation unit and the start of the next supply; days.

ROTATIONAL SUPPLY: supply of water on a rotational basis within a distribution system amont laterals, sub-laterals or field inlets at a regular or varied interval; larger streamsize and shortened time of delivery for a number of days to each section, with no supply during those days to the other sections belonging to the rotation unit; 1/sec and delivery time.

SATURATION VAPOUR PRESSURE, ea: upper limit of vapour pressure at a given temperature or vapour pressure which the air would have if saturated at that air temperature; millibar.

SEASONAL IRRIGATION REQUIREMENTS: depth of water, exlcluding contribution by precipitation groundwater, stored soil-water surface or subsurface inflow, 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: rate at which water will enter the soil under given conditions including soil water content; mm/hr.

SOIL SPECIFIC GRAVITY, As: ratio of the weight of water-free soil to its volume; grammes per cubic centimeter; g/cm^3.

SOIL STRUCTURE: arrangement of soil particles into aggregates which occur in a variety of recognized shapes, sizes and strength.

SOIL TEXTURE: characteristization of soil in respect to its particle sizes and distribution.

SOIL WATER STRESS: sum of soil water tension and osmotic pressure to which water must be subjected to be in equilibrium with soil water; atmoshperes.

SOIL WATER CONTENT, Si: at a given time the amount of water held in the soil; weight or volume percentage.

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; atmosphere or bar.

SOLAR RADIATION, Rs: amount of shortwave radiation received at the earth surface; equivalent evaporation mm/day.

STREAMSIZE, qa: flow selected for delivery to field inlet or irrigation block; 1/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; not to be confused with sun brightness; hours.

SUPPLY ON DEMAND: supply in size and duration of flow to satisfy request for water at any time during the growing season without advanced notice; 1/sec and time of delivery;

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.

TOTAL AVAILABLE SOIL WATER STORAGE, ΔS: amount of soil water available in the root zone to the crop; difference between water content at field capacity and at wilting point; weight or volume percentage or mm over rooting depth.

TOTAL SOIL WATER STORAGE, ΔW: total amount of water that can be stored in the root zone between a completely dry state and water content at field capacity; volume or weight percentage or mm over soil depth.

TRANSPIRATION: rate of waterloss from the plant through the formation of water vapour in living cells which is regulated by physical and physiological processes; mm/day.

WET BULB TEMPERATURE, t wetbulb: temperature recorded on a thermometer with the bulb surrounded by a wet muslin bag, thus lowering the temperature by loss of latent heat through evaporation; degrees Celsius.

WET BULB DEPRESSION: difference between readings of wet and dry bulb thermometers at given temperature; degree Celsius.

WILTING POINT, Sw: water content of the soil below which the plant cannot effectively obtain water from the soil; water content at 16 atmosphere soil water tension; available soil water is nil; volume or weight percentage.

WINDSPEED, U2: 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 II

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.

Joint FAO/IAEA Div. of Atomic Energy in Food and Agriculture, Vienna: Y. Barrada.

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

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APPENDIX IV

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
Demagnez 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)	Tananarive, 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°

Source	Location or Range of locations	Constants a	b	a+b	Latitude°
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 ø[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

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[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] ø is the latitude in degrees