Objectives :

The Institute's main Objectives are;

i) To provide in-service training of a multi-disciplinary nature to the staff engaged in Irrigation Water Management and Land Development.

ii) Applied research related to Land and Water Management.

iii) Activities which will promote optimization of use of Water and Land resources, including consultancy services, publication of literature, holding seminars & Workshops, etc.

CROP WATER REQUIREMENTS

WALMI

जल व भूमि व्यवस्थापन संस्था

WATER AND LAND MANAGEMENT INSTITUTE,
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FOREWORD

With the advances in agricultural technology, the precise knowledge of all agricultural inputs has attained paramount importance. Water is one of the major inputs. The knowledge of "Crop water Requirements" is therefore imperative both for economic use of water and optimisation of crop yields.

A vast amount of literature is available on this subject, but most of it, including the books specially devoted to this subject, are aimed at agricultural scientists. They assume a certain background in allied subjects. While teaching this subject a dire need for a book on this subject specially meant for irrigation engineers was felt. It is hoped that this book will cater to this need. In this book special emphasis is laid on explaining the background in allied subjects and the basic concepts of methods used for estimation of crop water requirements. The methods have been explained in details and the use of these methods has been illustrated by solved examples, using the standard tables and charts.

It is hoped that this book will be useful to practising irrigation engineers working in planning of Irrigation projects as well as to those in irrigation management.

The book is originally authored by Shri M. V. Sahasrabudhe, Associate Professor, under the able guidence of Dr. S. B. Varade Jt. Director (Training). It has further been scrutinised by Dr. S. S. Bhalerao, Professor and Head of Agriculture Faculty. Valuable suggestions made by him and his faculty members are gratefully acknowledged. Efforts put in by Sarvashri Sahasrabudhe, Varade and Bhalerao are appreciated.

I would like to thank all of them who have worked for bringing out this publication.

February 1988.

J. T. Jangle
Director.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Good irrigation management is a combination of answers to three crucial questions in irrigation. these questions are :

— How to irrigate ?

— When to irrigate ?

— How much to irrigate ?

Irrigation Engineering and allied sciences are all the while engaged in finding more and more satisfactory solutions to these three questions. The irrigation methods and operation system provide answer to the first question viz; How to irrigate ? The answer to tne second question "When to irrgate ?" is dependent on manv factors such as soils, storage capacity of soils, available moisture, crop water requirement and condition and the irrigation system constraints. The last two questions are interrelated and have to be considered together. The discussions in the following paragraphs are mainly devoted to the third question "How much to irrigate ?" with relevant references to "when to irrigate ?".

The obvious answer to the question, "How much to irrigate ?" is "The irrigation should be just sufficient to provide additional water for the healthy crop growth at that period." This simple statement implies that —

— The water requirement of crop for healthy growth at a particular period has to be estimated.

— This water requirement may not necessarily be the irrigation requirement.

— The water requirement varies according to the grogth stages of the crop.

All these points will have to be considered while estimating either the crop water requirement or the irrigation requirement. For practical purposes in irrigation engineering, we are more interested in irrigation requirement.

METHODS OF ESTIMATION

There are several methods for estimation of Irrigation requirement These can broadly be classified into three categories.

Traditional Methods : These consist of charts, and tables based on experience in the past. The Duty method or the AI/DC method also forms a part of traditional methods. A serious limitation of these methods is that all these are location specific and the data at one place may not be useful in to-to at some other place.

Field Observation Methods : These are the methods based on observing the water used by the crops during a certain period and replenishing the same. The observations of soil moisture content before irrigation are normally necessary. These are useful in estimation of immediate Irrigation needs but are not very useful in predicting long term needs for planning purposes. These methods are accurate only in the specific area where the measurements are taken. They are more useful in experimental work or in varifying the accuracy of other methods.

Climatological Data Methods : These methods predict the crop water requirements on the climatological data and are now commonly used. The only draw back of these methods is they totally depend on the climatological data and any erronaeous data or lack of data renders these methods ineffective.

TRADITIONAL METHODS

Irrigation is practised in India since ancient times. The irrigation water requirement is estimated in traditional methods, from the experience gathered during the past years. The irrigation water requirement of the crop is the water required for the healthy growth of the crops minus the water available from rainfall. It is this irrigation water requirement which is estimated in the traditional methods. In most of the n odern methods based on climatic data, the basic crop water requirements are first estimated and then suitable allowance is made for rainfall contribution ro arrive at the irrigation water requirement. The traditional methods have been successfully used in the past; and they are going to stay for some time to come. Let us therefore be conversant with these methods and specially their terminology.

The irrigation water requirement is estimated for two purposes, viz; for long term planning and for periodical irrigation (which means to satisfy the water requirement of the crop for a short period.). The table No. 1 shows the assumed water requirements of different crops, based on limited experience on adhoc basis.

Table No. 1 : **Water Requirements of Different Crops at Property Head**

Sr. No.	Crop	Water requirement in cms.	Remarks
1.	Sugarcane	255	For the total year.
2.	Plantains	280	— do —
3.	Lucerene, Elephant grass Guinea gram	280	— do —
4.	Vegetables grown in succcession throughout the year	280	— do —
5.	Papayas	220	— do —
6.	Citrus fruit	190	— do —
7.	Guavas, Pomegranates	150	— do —
8.	Rice	75	In Kharif
9.	Rice	25★	In Rabi
10.	Monsoon Seasonals	25	In Kharif
11.	Rabi Seasonals	30 to 40	In Rabi
12.	Hot Weather Seasonals	65	Partly in Rabi & partly in H. W. according to sowing period.
13.	Wheat (Khapla)	90	
14.	Two seasonal vegetables	150	

(10% increase over the above depths will give the corresponding depths at the distributory head.)

★ This requirement is for growth period in Rabi season only and it seems that it does not include percolation losses. The requirements of growth period in H. W. are additional.

(Table adopted From "History and Practice of management of Irrigation waters in Maharashtra" by Shri P. R. Gandhi, Secretary to Irrigation Deptt, Maharashtra State.)

Thus, from table No. 1, one ha. of sugarcane will require 255 cm. or 2.55 m. of water over the entire year. Thus, the annual requirement of one ha of sugarcane will be $100 \times 100 \times 2.55$ cubic meters or 2.55×10^4 M^3. This requirement is at the estate head and the requirement at distribitory head or canal head can be worked out by allowing for losses The annual or seasonal requirements of crops can thus be roughly estimated.

The Duty Method : A more commonly used method in Maharashtra and many Southern states is the duty method. The method is based on the observation that a flow of one cubic foot per second irrigates certain area of cane in 24 hrs. The flow is measured at outlet head. This irrigation is sufficient for 14 days. The terms used in the estimation of water requirements and canal capacity are as under :

i) **Duty** : Duty is defined as the area of land that is irrigated by a flow of one cusec, the water thus provided being shfficient for the healthy growth of crop for the rotation period.

ii) **Base Period** : Base period is the no. of days for which the irrigation flow continues.

Thus the duty per day is the area in acres irrigated by one cusec flow, during one day. Here the base period is one. This duty is known as AI/DC which means AREA Irrigated Per Day Cusec.

iii) **Rotation Period** : Rotation Period is the interval at which water is supplied to the crops. In Maharashtra, the rotation period of 14 days is normally adopted for designs.

iv) **Flow Period** : The actual period of flow of water in a rotation is known as flow period. During rotations, the canal flows for a certain time and remains closed either for maintenance or for some other reason. The rotation period consists of flow period and closure.

v) **Seasonal Duty** : The duty with a base period of the number of days in a season is called seasonal Duty. Thus when we say that the duty for Rabi is 70 acres, we mean that one cusec flowing for the whole Rabi period will be able to irrigate an area of 70 acres. Unless stated otherwise, this area is of cane.

vi) **Irrigation year and seasons** : In Maharashtra State the irrigation year is from 1st July to 30th June. The irrigation year is divided into three seasons viz ;

Late Kharif	:	1st July to 14th October = 106 days.
Rabi	:	15th October to End of February = 137/138 days.
Hot Weather (Also knows as early Kharif).	:	1st March to 30th June = 122 days.

vii) **Conversion factor** : The duty is expressed in Acres per Cusec for a definite base period. It can be for acres of a specific crop, acres of some mixed cropping pattern or acres of equivalent area of sugarcane. For uniformity and comparision, it is many a times convenient, to express duty in terms of equivalent area of sugarcane. This equivalent area is decided on the water requirement of the crop as compared to the water requirement of sugarcane. Thus if the requirement of crop is half that of sugarcone the conversion factor is 0.50. In practice, half the area of this crop is irrigated in one rotation and the remaining half is irrigated in the next rotation. Sugarcane is irrigated in both the rotations. This will be clear from the sketches in Figure No. 1.

Let us assume that a plot of 3 ha is under irrigation out of which 1 ha is of cane and 2 ha of sorghum. The conversion factor for sorghum is 0.50. Therefore, in one rotation 1 ha of sugarcane and 2 × 0.5 or 1 ha of sorghum will be irrigated. In tne next rotation again the cane will be irrigated while as the balance 1 ha of sorghum will be irrigated. Equivalent area for irrigation in each rotation is 2 ha.

Sugarcane	—	1 ha
Sorghum (2 × 0.50)	—	1 ha
Total :		2 ha

This plot measuring 3 ha. is equivalent to 2 ha of sugarcane irrigation.

Table No. 2 gives the conversion factors for different crops which are presently adopted.

Table No. 2
Conversion Factors For Equivalent Cane Area

Sr. No.	Crop	Conversion factor
1.	Sugarcane	1
2.	Other perennials	1
3.	Paddy	1
4.	Hot weather seasonals	1
5.	Vegetables	1
6.	Kharif seasonals	1/2
7.	Rabi seasonals except H. Y. Wheat	1/2
8.	H. Y. Wheat	1
9.	Overlap for Sugarcane	1

(Page 10 of O. F. D. Manual, Govt. of Maharashtra)

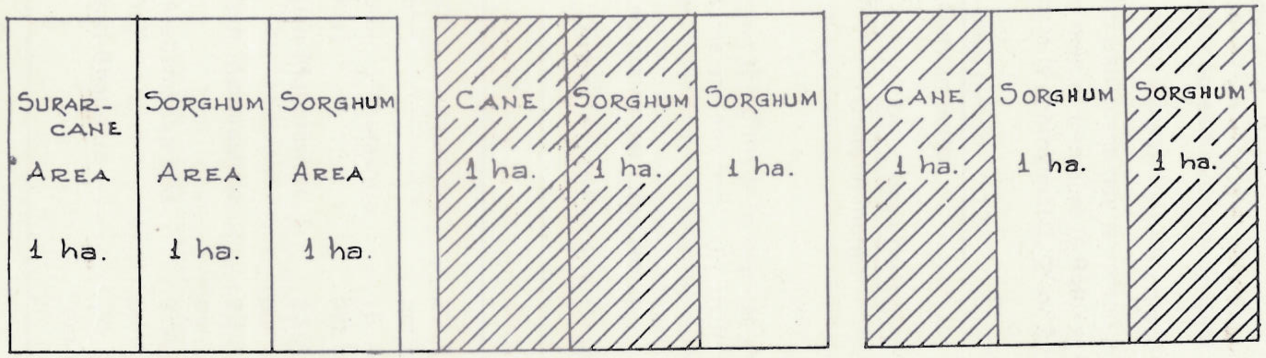

FIG. 1 (A) AREA TO BE IRRIGATED.

FIG. 1 (B) AREA IRRIGATED IN FIRST ROTATION.

FIG. 1 (C) AREA IRRIGATED IN SECOND ROTATION.

Fig1: CONCEPT OF CONVERSION FACTOR

WL/ARU/ DGR No. 20. / Dt. 10-12-87 TRD. BY. LOYA M.M.

It may be noted that the conversion factors are not in exact consonance with water requirements but are modified to suit the actual application of water in rotations.

Relationship Between Duty and Delta :

Delta is the depth of water spread over the irrigation area within the period of irrigation or the base period. Thus when we say that the $\frac{AI}{DC} = 4$ acres we mean that the quantity of water available with one cusec day is spread equally over 4 acres. The quantity of water is 86400 cft. and the area of one acre is 660′ × 66′ = 43560 Sq. ft. Therefore the depth of water over one acre is approximately 2′ or 24″ or over 4 acres it is roughly 6″. The relationship is :

$$\text{Delta in inches} = \frac{2 \times \text{base period} \times 12}{\text{Duty in acres.}}$$

$$\text{or conversely, Duty in Acres} = \frac{24 \times \text{base period}}{\text{Delta in inches}}$$

Duty per Mcft. of Water :

Another way of expressing the duty, is to express the relationship in Acres per Mcft. The basic assumption is the same and the relation 1 mcft = 11.57 day cusecs is used to derive duty per Mcft. of water.

The duties recommended are as per table No. 3.

Table – 3. **Duties of Different Crops**

Sr. No.	Crops	Duty	Remarks
1.	Kharif crops in western Maharashtra region (except paddy)	20 Acres per Mcft.	In good rainfall area
2.	Kharif crops in western Maharashtra region (except paddy)	15 Acres per Mcft.	In low rainfall area
3.	Rabi crops in western Maharashtra	15 Acres per Mcft.	In good rainfall area
4.	Rabi crops in western Maharashtra region	12 Acres per Mcft.	In low rainfall area
5.	Paddy in Western Maharashtra and Marathwada (upland)	7 Acres per Mcft.	
6.	Paddy in Chanda and Bhandara Districts (Kh)	20 Acres per Mcft.	

(Adopted from Page 121 of Manual of Minor Irrigation works in Maharashtra State).

The duties adopted for Bandhara schemes at Distributory head are :

Perennial crops	40	Acres / cusec
Rice (Kh)	40	Acres / cusec
Kharif crops	80	Acres / cusec
Rabi crops	120	Acres / cusec

Calculations of Water Requirements of Crops by Duty Method :

While calculating the irrigation requirement by the traditional "Duty Method", it is important to consider the following :

i) The point at which the duty is considered. The AI / DC value at outlet is different from the AI / DC value at the distributory head or the canal head.

ii) It must be clearly mentioned if the duty is for a particular crop or for a mixed cropping pattern with specific percentage of crops or for cane.

iii) The irrigation water requirement is after due consideration of rainfall contribution i. e. it is the irrigation water requirement.

Specimen calculations by duty method may illustrate the procedure.

Example : A distributory is having the following percentage of irrigated crops. The AI / DC observed on cane basis is 4.5 acres in Kharif 4.0 acres in Rabi and 3.5 acres in Hot Weather. These duties are at distributory head and on equivalent cane areas. The seasonal duties observed at outlet head are 90 acres, 70 acres and 50 acres respectively for Kharif, Rabi and Hot Weather seasons. Calculate water requirements for one rotation in each season and total water requirements in each season.

Sr. No.	Crop	Percentage
1.	Sugarcane	7
2.	Other Perennials	3
3.	Hy. Jowar	10
4.	Paddy	5
5.	Other Kharif seasonals	10
6.	Rebi Jawar & Maize	20
7.	Hy. Wheat	25
8.	L. S. Cotton	15
9.	Ground nut	5
		100

Computations :

Let us first prepare a break up of these crops seasonwise and calculate the equivalent area in each season. The computation can be conveniently done in the proforma of table No. 4.

Table 4. **Computations of equivalent area for 100 acres of Annual Irrigation**

Sr. No.	Crop	Percentage	Kharif		Rabi		Hot Weather		Remarks.
			Conversion Factor	Area in Acres	Conversion Factor	Area in Acres	Conversion Factor	Area in Acres	
1.	Sugarcane	7	1	7.0	1	7.0	1	7.0	
2.	Overlap for Cane Kh. 30% Rabi 40% H. W. 10%		1	2.1	1	2.8	1	0.7	
3.	Other Perennials	3	1	3.0	1	3.0	1	3.0	
4.	Hy. Jwar (Kh)	10	1/2	5.0	—	—	—	—	
5.	Paddy	5	1	5.0	—	—	—	—	
6.	Kh. Seasonals	10	1/2	5.0	—	—	—	—	
7.	Rabi Jwar & Maize	20	—	—	1/2	10.0	—	—	
8.	Wheat (Hy.)	25	—	—	1	25.0	—	—	
9.	L. S. Cotton	15	1/2	7.5	1/2	7.5	—	—	
10.	Ground nut	5	—	—	—	—	1	5.0	
	Total			34.6		55.3		15.7	

Notes ;

i) The above Table is prepared to illustrate the procedure only,

ii) The crops may extend into other seasons accroding to the planting dates. These extensions are however not considered to simplify the computations.

iii) The overlap for cane is considered according to Govt. Tech. Circular No. BIA 1258–T Dated 18-6-1958. The percentage of overlap may change according to local practices.

From Table 4, It is seen that for 100 acres of annual irrigation, the seasonal areas are :

	Kharif	Rabi	Hot weather
Area under Irrigation (in acres)	42.1	72.8	15.7
Equivalent area (in acres)	34.6	55.3	15.7

Now, the seasonal requirements of water can be calculated, as the seasonal duties are known.

The seasonal duty for Kharif is 90 acres. It means that one cusec flowing for entire Kharif period of 106 days can irrigate 90 acres, or the requirement of 90 acres is 106 cusec days i. e. 106 × 86400 cft. Therefore, the requirement of one acre of equivalent area for Kharif is :

$$\frac{106 \times 86400}{90}$$

Thus the requirement of water for any season can be generalised as :

$$\text{Water Requirement in Mcft.} = \frac{\text{No. of acres in E. A.} \times \text{No. of days in Season}}{11.57 \times \text{Duty in acres}}$$

This requirement is at outlet head. If requirement **at distributory head** is to be calculated the losses are to be considered. The loss factors for various seasons are :

Season	Loss factor
Kharif	1.30
Rabi	1.35
Hot Weather	1.40

Therefore,

$$\text{Water Requirement at Distributory head in Mcft.} = \frac{\text{Acres in Equivalent area} \times \text{No. of days in season} \times \text{Loss factor}}{11.57 \times \text{Duty in acres.}}$$

Accordingly, the water requirements of 100 acres of annual irrigation in the above example are.

For Kharif,

$$\text{W. R. in Mcft.} = \frac{34.6 \times 106 \times 1.30}{11.57 \times 90}$$

$$= 4.578 \text{ Mcft.}$$

For Rabi,

$$\text{W. R. in Mcft.} = \frac{55.30 \times 137 \times 1.35}{11.57 \times 70}$$

$$= 12.63 \text{ Mcft.}$$

and For Hot weather,

$$\text{W. R. in Mcft.} = \frac{15.70 \times 122 \times 1.40}{11.57 \times 50}$$

$$= 4.635 \text{ Mcft.}$$

The water requirement can be calculated for actually existing crops by taking the actual crop figures.

The irrigation depth to be applied in each rotation can be calculated by the relation.

$$\triangle \text{ in inches} = \frac{24 \times \text{base period}}{\text{Duty in acres.}}$$

For example, the irrigation depth over the entire Kharif season is $\frac{24 \times 106}{90} = 28.26$ inches This depth is for equivalent area. If the depth over the irrigated area is required, it can be computed by multiplying this depth by the ratio of equivalent area to irrigated area.

In our example, it is ;

$$28.26 \times \frac{34.6}{42.2} = 23.22''$$

Many a times the irrigation depth for a single rotation is necessary. This can be calculated from given AI/DC data. In the above example the Kharif value of AI/DC is given as 4.5 acres at distributory head. Thus, the irrigation depth is,

$$\frac{24}{4.5} = 5.33''$$

The AI/DC values are normally used for checking, while as seasonal Duties are usually used for preparation of Irrigation programmes.

FIELD MEASUREMENT METHODS

The basis of the traditional methods is the experience gained over a long period in the past. Each individual experience is gained under a specific set of conditions of soil, climate, location etc. Even for the same location, the other parameters vary from year to year. When some tables are prepared for crop water requirement or Irrigation reqirements, or some values of AI/DC are fixed, they are the result of generalisation of these experiences. The result of experience gained at one location may not be applicable in to to at another location but the general value may be a good pointer to the value of water requitements where similar conditions exist. The value can be modified to suit the changed parameters but the modification has to be intelligently done by an experienced person having a deep knowledge about the parameters and their effects. Thus, the traditional methods are excellent tools in the hands of an experienced irrigation engineer, but cannot be used by one and all, very conveniently. Then the estimation of water requirement of crop becomes more an art than a science.

Moreover, the traditional methods give the average irrigation requirement over the period. The stage of growth of the crop is not considered. The actual water requirement of the crop varies with the crop growth stage. Thus, with the traditional methods of estimating irrigation requitements, the crop in question is either over irrigated or under irrigated during individual rotation period. In modern irrigation practice, precise requirements of crop are taken into consideration.

Concept of Field Measurement methods

The concept of field measurement methods is very simple. The crop draws water from the soil for its growth. If during a interval of time, the crop draws a certain amount of water from the soil, the moisture content of the soil is reduced to that extent. If the quantity of water reduction is determined, or measured, that is the crop water requirement during the specific time interval. The implied requirements are ;

i) There should be sufficient water in the soil for the healthy growth of crop.

ii) The reduction in the soil moisture must be accurately measured.

These limitations and methods are discussed here.

The modern concept of irrigation aims at the optimisation of every input in irrigation including water. It therefore, naturally demands a more precise estimate, as independent from individual skill as possible. A little knowledge about the soil-water–plant relationship and the parameters influencing the water requirement of crops is therefore necessary. The board concepts necessary as the background for the various methods discussed later, are explained here. These are by no means very exhaustive. Standard text books can be referred to if any additronal details are required.

Physical Model of Soil

A soil volume can be considered to comprise of three phases or components viz, soil solids, soil water and air voids. These three phases are deplicted in figure No. 2.

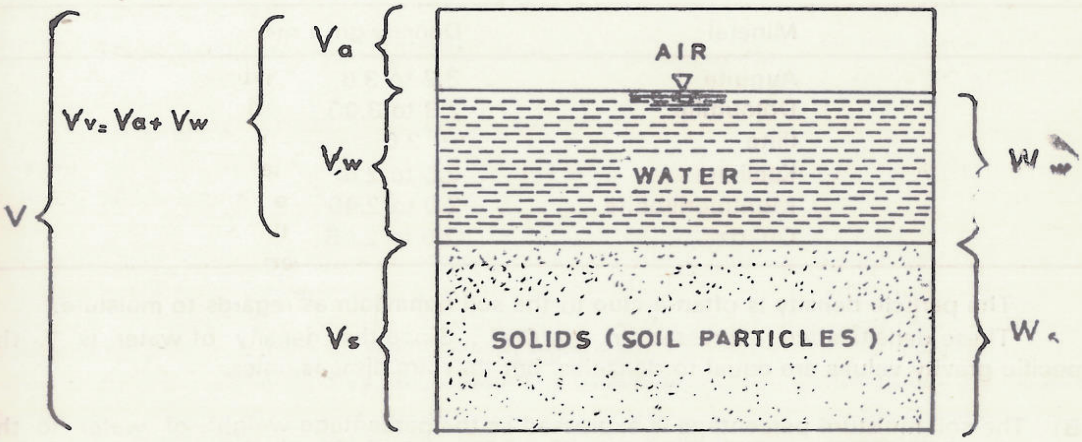

Figure 2 : Simplified Schematic of a Unit Volume of Soil.

In the above figure :

V = Total volume of soil

V_a = Volume of a air

V_w = Volume of water

V_s = Volume of soil solids.

V_v = Volume of voids = $V_a + V_w$

W = Total weight

W_s = Weight of oven dried soil solids

W_w = Weight of water

Some useful relationships can be established.

(A) i) The wet density of soil $= \dfrac{W}{V} = \dfrac{W_w + W_s}{V}$

ii) The dry bulk density of soil $= \dfrac{W_s}{V}$

iii) Particle density :

The density of soil solids is the ratio of mass of soil solids to the volume of soil solids and is often referred to as the particle density or real density of soil. It gives an indication of the prominent minerals present in the soil.

Particle density $= \dfrac{W_s}{V_s}$

The real densities of some of the minerals are given in Table No. 5.

Table No. 5 Real densities of minerals

Mineral	Density gm/Cm3
Auguite	3.2 to 3.6
Doloumite	2.8 to 3.00
Illite	2.6
Kaclinite	2.5 to 2.6
Montmorillonite	2.0 to 2.40
Quartz	2.6 to 2.65

The particle density is often a clue to the soil behaviour as regards to moisture.

These densities are expressed in gm/Cm3 . Since the density of water is 1, the specific gravity values are equal to densities, but they are dimensionless,

(B) The soil moisture percentage is expressed as the percentage weight of water to the dry weight of soil solids or

$$\text{Soil moisture } \% = \frac{W_w}{W_s} \times 100$$

It is more convenient to express this relationship as depth of water in unit depth of soil. Consider a cubic meter of soil with one square meter of base area and one meter height. (Figure 3).

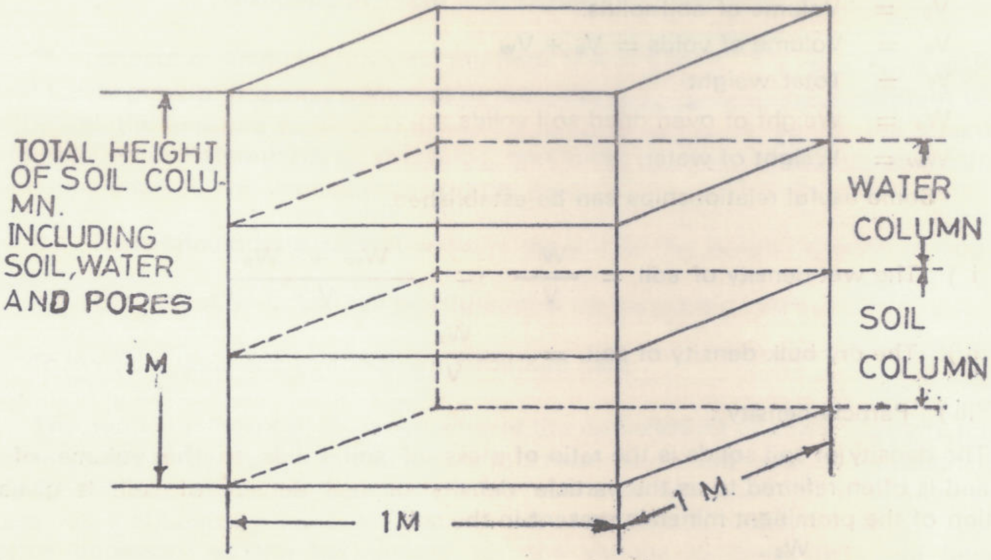

FIGURE 3 : Equivalent Depth of Water Per Meter of Soil.

Let the soil moisture percentage in this soil be p. Then

$$\frac{W_w}{W_s} \times 100 = P \text{ or } W_w = \frac{P.\ W_s}{100}$$

Since density of water is 1, $W_w = V_w$ (in metric units)

$$\text{Therefore } \frac{P.\ W_s}{100} = W_w = V_w$$

Dividing both sides by V,

$$\frac{P.\ W_s}{100\ V} = \frac{V_w}{V}$$

$$\frac{V_w}{V} = \frac{\text{ht. of water col. X base area}}{\text{ht. of total soil. column X base area}}$$

= depth of water per m. (As the soil of one meter height is considered).

$$\therefore \text{ Depth of water per m.} = \frac{P}{100} \frac{W_s}{V}$$

$$= \frac{P}{100} \text{ Dry bulk density of soil.}$$

$\therefore$ Depth of water per m. (in cms.) = Px Dry bulk density of soil (in gm/cm^3)

The dry bulk density depends on the texture and structure of the soils. There can be considerable variation in the dry bulk density of soil, under various conditions of tillage compaction, swelling, shrinkage etc. Since the volume changes with these factors, the dry bulk density has therefore to be actually determined under the field conditions.

C) **Porosity** : Porosity (n) is defined as the ratio of the volume of pores to the total soil volume. It is an index to the relative volume of pores or,

$$\text{Porosity n} = \frac{V_w + V_a}{V}$$

The porosity varies from 30 to 60 percent. The coarse soils have less porosity than fine textured soils. The porosity of organic soils or well graded clay is sometimes even more than 60%.

SOIL WATER

As seen earlier, the soil volume consists of soil solids arranged in a particular fashion known as structure of soil. The interstices in between the soil solids form the voids or pores. The voids are partly or fully occupied by water. When voids are partly occupied by water, the remaining voids are occupied by air. The water occupying the voids in the soil volume is known as soil moisture or soil water. The water requirements of plants is drawn from this soil water. The total requirement of the plant is drawn from the soil water but the total soil water is not available to the plant. Let us look into this phenomenon in some details.

Let us consider that water is slowly added to a perfectly dry soil volume. The water first gets distributed to the solid surfaces in the form of a very thin film and held there by the forces of adhesion.The adhesion force is very large ranging between 31 bars to 10,000 bars. As more water is added,the thickness of the film increases, and the water is held in the film thickness by cohesion. When further water is added, the film thickness also increases & the water on the film boundary is held by surface tension or capillary forces. The water added further occupies the voids but remains free and is subjected only to gravitational forces.

The water in the thin film held by adhesive force is not available to the plants, because the adhesion force is far greater than the force that the plant can produce. This water is called the hygroscopic water. The water in the region of progressive thickening of the film is in tension in the range of 1/3rd bar to 31 bars. The capillary adjustments between the range 15 bars to 31 bars are very sluggish and water movements in this part of the water film is not easy. In the zone where tension is between 1/3 rd bar to 15 bars easy water movements are possible and it is from this zone that the roots are able to draw the major share of their water requirement. With the thickening of water film, the tension also reduces to less than 1/3 rd bar and then the water is only under gravitational force. This water is called free water or gravitational water and is easily drained out of the soil under gravity. This water is also, therefore, not availadle to the plants. This distribution of water is schematically represented in **figure No 4**. The values of tension are only indicative and vary according to the minerals of which the soil solids are formed; the soil texture and soil structure. This is because the adhesive force will depend upon the soil mineral, its crystal shape and surface area and the capillary force depends upon pore sizes as the result of texture and structure.

FIELD CAPACITY

We have considerd the effect of addition of water to a perfectly dry soil. Let us consider that the soil volume is saturated either due to rains or irrigation. If the soil is saturated at the time the irrigation or as heavy rains stop, the gravitational water in the soil volume will be draining under gravitational force creating voids to be occupied by air. This

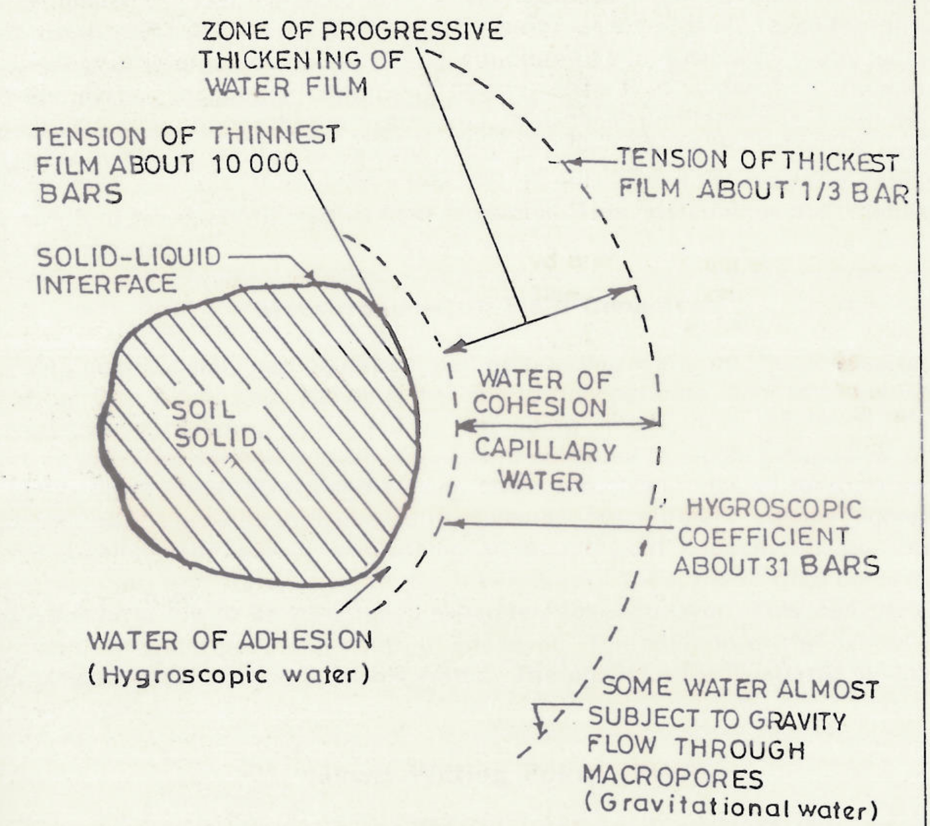

FIG.4. DIAGRAMATIC REPRESENTATION OF THE PROGRESSIVE THICKENING OF WATER FILM IN A MACROPORE AND THE CORRESPONDING DECLINE IN TENSION AT WHICH THE SURFACE MOLECULES ARE HELD

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process will continue till the gravity force is not sufficient to overcome the force of capillary action or surface tension, or so to say, an equilibrium is reached between the forces trying to retain the water in the soil volume and the force of gravity which is trying to draw water out of the soil volume. This stage of moisture content is called the field capacity of the soil.

The field capacity is defined as the moisture content at which the drainage of gravitational water has become very slow (practically stopped). This situation is attained usually one to three days after full saturation and start of drainage. The terms field capacity, field carrying capacity, normal moisture capacity and capillary capacity have been used synonymously by different authors.The tension at field capacity for different soils is different but varies betwden 1/10 th to 1/3 rd bar.

Formerly, the field capacity was considered to be a soil constant. However, recent research has established that the field capacity is not aconstant value even for the same soil. It may vary with the organic content of soil, structure of soil, system of water removal such as drainage, evapotranspiration conditions, dew, etc. The field capacity is therefore today considered as a range rather than a fixed value. With these limitations in mind, the concept of field capacity still continues to be very useful in determining the irrigation requirements with fairly good accuracy. Where more precision is not desired the moisture retention with tension at 1/3 rd bar is considered as field capacity. This determines the highest level of available soil moisture.

Measurement of Field Capacity

The field capacity can be determined by ponding water on the soil surface in an area of about 2 to 5 m^2 and allowing the soil to fully saturate and then permitting it to drain. Surface evaporation is prevented by spreading a polythene sheet or thick straw mulch. One day after saturation, soil samples are collected by auger at uniform intervals of 12 hrs. at depths of about 30 cm and 60 cm. These samples are tested for moisture content by usual method. When the moisture content values for different depths achieve a fair degree of stability, the soil is considered to be at field capacity. If the soil is not homogeneous upto root zone, or some depth below root zone, then, field capacity in each homogeneous layer has to be determined saparately for each layer. This can be converted into mm depth of water per meter depth of soil layer. The addition of the water depth of the layer is used in calculating available water. The procedure is illustrated in Table No. 8 in later paragraph.

Permanent Wilting Point (PWP)

Permanent wilting point is another very useful soil constant that determines the lowest level of available soil moisture (though it is not supposed to be constant any more). When plant starts drawing water from the soil, and there is no external addition of water, the soil water reservoir starts depleting. Upto a particular depletion level the plant can draw water enough for its growth requirements. As the moisture in the soil is further reduced the plant has to draw water from the capillary water storage from the smaller pores. It has to overcome more and more forces of surface tension or capillary action which is evident from the equation of flow in unsaturated soils.

$$q = -K(\theta) \frac{h_2 - h_1}{L}$$

Where θ is the moisture content of the soil, $h_2 - h_1$ is the pressure head and L is the length of water path, 'K' is unsaturated hydraulic conductivity and 'q' is the flow rate.

Thus with the decrease in the moisture content the rate of water uptake of plant also gets reduced. In the initial stage this rate may be slightly less than the actual growth needs, then the uptake rate gets further reduced, and the growth may stop and plant strives just for survival. The leaves start yellowing and then wilting. The wilting occures in day-time, but disappears in the cooler and humid night. When the uptake rate is further reduced, the plant is not able to survive and the wilting of leaves occures. Even if the plant is placed in humid weather, the wilting leaves do not recover. The turgidity of the leaves cells is reduced and the decaying of the cells starts which is an irreversible process. The moisture content at this stage is called the permanent wilting point of the soil. By definition the permanent wilting point is the moisture content in the soil at which the irreversible process of wilting starts. Formerly this was also considered a soil constant but now it is considered a range than a constant value, as in case of field capacity. In case where more precision is not required, the PWP is taken as moisture at 15 bars tension.

Determination of Permanent Wilting Point :

The permanent wilting point of the soil is determined by actually growing an experimental plant in the soil under controlled conditions and allowing it to wilt under stress of water when the plant is at about 8 leaves stage. Since sunflower is a very sensitive plant, it is used for this experiment. The procedure is as under :

a) Take approximately 1.25 Kg of the soil for which PWP is to be determined, sieve it through 2 mm mesh, and store in an earthen pot. Two or three such pots may be prepared.

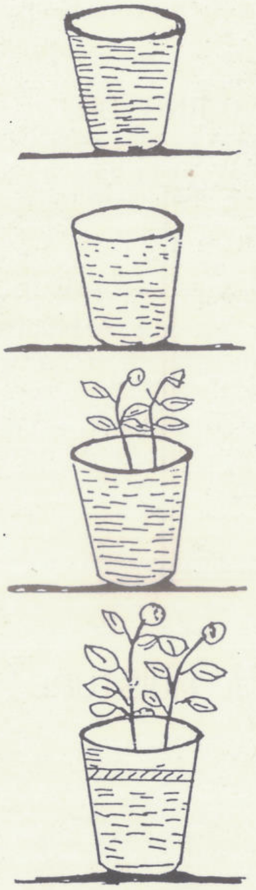
(b) If the soil is deficient in nutrients, supplement it with necessary doses of NPK and mix thoroughly before placing it in the earthen pot.

(c) Add water to the soil till it is near field capacity. When the soil is moist and friable, sow 4 seeds of sunflower with adequate spacing. Cover the seeds with soil.

(d) After germination, retain only two healthy seedlings per pot. Allow them to grow up to 8 leaf stage duly irrigating them when necessary. Cover the soil surface with thick mulch to check evaporation losses.

(e) Stop irrigation now. Allow the seedlings to extract water for their growth from the soil only. Provide adequate light and temperature conditions. After a certain period it will

SCHEMATIC REPRESENTATION OF MAJOR STEPS INVOLVED IN PWP ESTIMATION:



1. FILLING UP APPROXIMATELY 1 Kg. SIEVED SOIL IN EARTHEN OR PLASTIC WITH DRAINAGE HOLE ; IRRIGATING IT UP TO F.C.

2. SOWING 4 SEEDS OF SUNFLOWER AT OPTIMUM MOISTURE IN SOIL.

3. RETAINING TWO HEALTHY SEEDLINGS AND PROVIDING OPTIMUM AIR, TEMP, LIGHT AND IRRIGATION CONDITIONS.

4. COVERING SURFACE OF POT WITH STRAW AT 8 BROAD LEAF STAGE

Fig. No. 5 A

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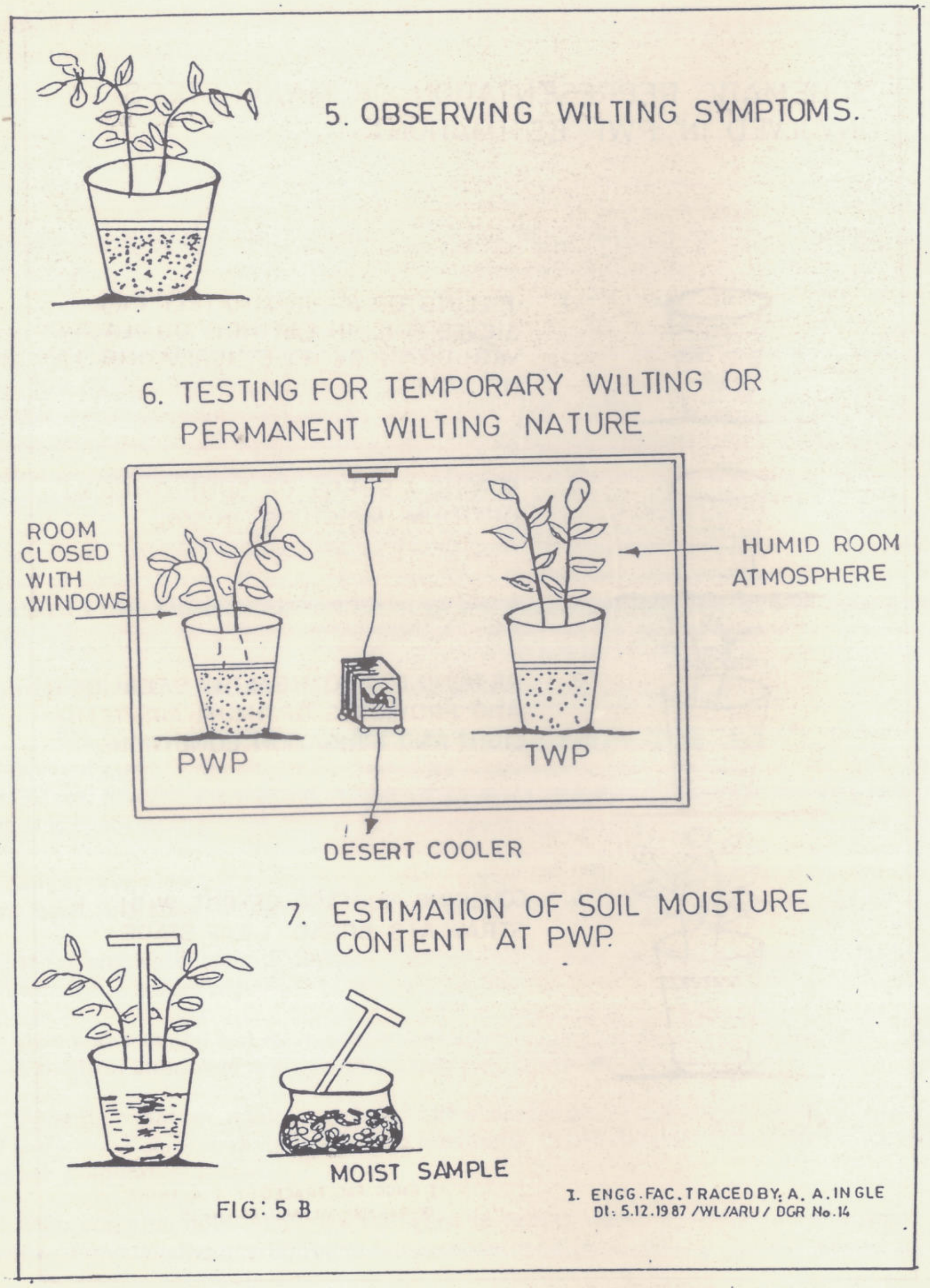

5. OBSERVING WILTING SYMPTOMS.
6. TESTING FOR TEMPORARY WILTING OR PERMANENT WILTING NATURE
ROOM CLOSED WITH WINDOWS
HUMID ROOM ATMOSPHERE
PWP
TWP
DESERT COOLER
7. ESTIMATION OF SOIL MOISTURE CONTENT AT PWP.
MOIST SAMPLE
I. ENGG.FAC.TRACED BY: A. A. INGLE
Dt: 5.12.1987 /WL/ARU/ DGR No.14

FIG: 5 B

be observed that the leaves start yellowing and wilting. They loose freshness and droop. Place the plants in 95% humidity atmosphere. The leaves will recover. The soil is now near Permanent Wilting Point.

(f) Continue the observations till the wilted leaves do not recover even after being placed in humid temperature for 12 hrs. The soil is now at the permanent wilting point.

(g) Take the soil samples and test them for water content by weight. This is the Permanent wilting point,

A schematic representation of the above procedure is presented in figure 5A & 5B

Available Moisture Content

It has been seen that the plants can not extract water enough for survival, below the permanent wilting point. Thus, the water content in the soil below permanent wilting point is not useful for the plants, and forms the lower limit of water available from soil to the plants. Similarly, the water above the field capacity is easily drained out of the soil under gravity within a short period, and is not available to the plants. The field capacity, therefore forms the upper, limit of the available water from the soil. The available water is therefore the difference between the field capacity and the permanent wilting point and can be expressed as :

Available water = Field capacity — Permanent wilting point.

A. W. = F. C. — P. W. P.

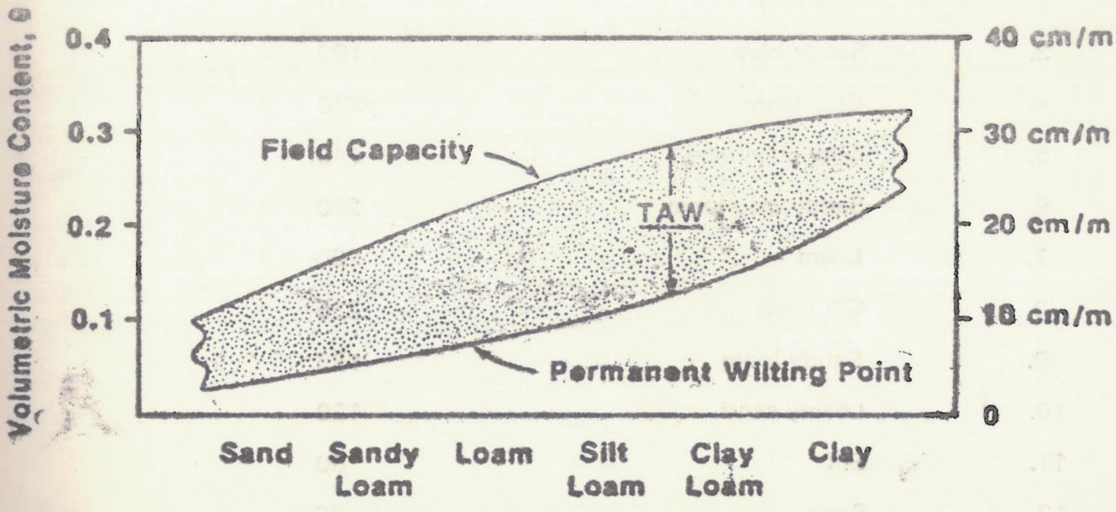


Figure 6 : Representative Values of Total Available Water (TAW), for different Soil types.

Figure No. 6 illustrate the above relationships. Since field capacity and permanent wilting points are expressed in percentage water content, the available water can also be expressed in percentage water content. Thus if the field capacity and P. W. P. of a soil are 45% and 20% respectively, the available water in the soil is (45 — 20) = 25%. Another useful way of expressing these three levels of moisture contents is depth of water in the soil per meter depth of soil.

The depth in cm/m = percentage Moisture × Dry density.

Thus if the field capacity of the soil is at 40% and the dty density is 1.25 g/cm^3 , it can be said that at field capacity, the water depth in soil is 40 x 1.25 = 50 cm. per meter. Similarly at PWP, if the moisture content is 20% for the same soil, the water depth per meter at PWP is 20 x 1.25 = 25 cm. and naturally the available watar in the soil is (50 — 25) cm. per meter or 25 cm. per mtr.

Table No. 6, shows the values of available water in defferent soils. These values are general values and are only indicative. Actual values can be obtained only by determining F. C., PWP and dry bulk density of the soil.

Table - 6 General values of available water for different soils

Sr. No.	Soil	Available water in mm/m. soil depth
1.	Clay	190
2.	Silty clay	210
3.	Sandy clay	180
4.	Clay loam	220
5.	Silty clay loam	240
6.	Sandy clay loam	200
7.	Loam	200
8.	Silt loam	235
9.	Sandy loam	185
10.	Loamy sand	120
11.	Silt	80
12.	Sand	60

The increase in tension releases more and more water. The water retention characteristics for different soils studied by Ali et al (1966) show that most of the water is released within 1 to 2 bar tensions. The table showing the result of these studies is given as Table No. 7.

Table 7 — Moisture at various tensions in differant soil types in %

Soil		Tension In Bars 0	1/10	1/3	15	Available moisture %
1		2	3	4	5	6 (4-5)
ALLUVIAL						
Delhi	A	34.0	27.2	10.7	4.4	6.3
	B	37.4	29.9	17.7	7.7	10.0
Lucknow	A	47.0	42.1	29.2	8.1	21.1
	B	41.2	34.6	25.8	6.0	19.8
Chinsurah	A	54.1	48.2	36.7	19.0	17.7
	B	46.5	42.9	33.6	17.3	16.3
Burdwan	A	47.6	47.0	35.3	16.1	19.2
	B	55.6	41.8	32.2	17.0	15.3
Ludhiana	A	24.8	20.5	12.1	3.6	8.5
	B	25.7	21.9	11.3	3.7	7.6
Pusa	A	32.1	31.6	15.5	1.9	13.6
	B	36.6	34.9	23.8	2.8	21.0
BLACK						
Rajendranagar	A	58.1	36.4	23.7	12.7	11.0
	B	54.5	34.4	23.2	12.0	11.2
Achalpur	A	60.0	48 1	38.0	15.8	22.2
	B	61.5	55.5	41.1	20.0	20.1
Bhatsa	A	58.1	45.8	30.0	16.1	13.9
	B	54.5	40.5	28,3	16.2	12.1

Table 7 Continued

1		2	3	4	5	6
Padegaon	A	83.8	68.3	43.5	25.7	16.8
	B	76.3	68.8	43.3	27.2	16.1
Nagpur	A	58.1	54.4	38.9	21.1	17.8
	B	54.5	51.3	34.8	20.5	14.3
RED						
Cheruvukomimupalem	A	33.8	30.2	17.5	8.5	9.0
	B	41.4	34.9	23.0	12.3	10.7
Yemmiganur	A	34.5	31.4	19.8	8.2	11.6
	B	44.3	38.7	24.9	13.6	11.3
Hebbal	A	26.1	24.9	11.6	5.6	6.0
	B	29.3	62.2	12.8	7.8	5.0
Tolukhal	A	35.0	27.4	13.4	8.8	4.6
	B	35.6	25.8	16.8	11.6	5.2
Raichur	A	31.4	26.2	13.7	7.4	6.3
	B	32.2	24.3	14.0	7.5	6.5
LATERITE & LATERITIC						
Midnapore	A	27.6	21.8	13.7	5.2	8.5
	B	37.2	27.9	18.2	9.1	9.1
Khuttapanna	A	30.0	36.8	15.1	9.7	5.4
	B	43.0	33.8	25.6	19.9	5.7
Narkodu	A	51.6	43.2	22.2	16.9	5.3
	B	55.0	43.4	29.4	21.1	8.3
Bhata	A	43.0	35.2	26.5	13.1	13.4
	B	48.5	36.9	27.5	15.5	12.0
Suri	A	24.0	22.5	14.2	4.3	9.9
	B	23.0	20.5	13.3	4.4	8.9
MOUNTAIN & FOREST						
Bhowali	A	56.2	44.9	32.0	9.1	22.9
	B	50.3	36.4	27.2	10.4	16.8

Table 7 Continued

1		2	3	4	5	6
Ootacamand	A	49.7	42.0	30.5	18.7	11.8
	B	45.2	34.9	26.7	17.3	9.4
Dehra Dun	A	41.3	37.0	29.1	8.4	20.7
	B	43.7	35.0	26.7	9.8	16.9
DESERT						
Pali	A	40.1	29.8	19.3	8.0	11.3
	B	48.2	36.5	29.5	10.7	9.8
Beriganga	A	29.4	24.5	8.5	3.7	4.8
	B	24.5	20.8	6.0	2.7	3.3
SALINE						
Sonapur	A	52.5	45.4	38.1	11.9	26.2
	B	57.9	42.1	36.3	13.2	23.1
Mankhanda	A	50.7	42.3	33.6	10.5	23.1
	B	44.2	38.8	32.0	10.5	21.5
Canning	A	55.6	54.2	41.9	15.5	26.4
	B	48.8	47.5	35.1	15.4	19.7

A and B represent surface (0-15 cm) and subsurface (15—30 cm) samples respectively. (Pages 23 to 25 IARI Monogram 4).

LAYERED SOILS :

If the soil has different textural layers or horizons, the values of field capacity, permanent wilting point and dry bulk density have to be decided layerwise for each layer. The available water depth can be decided for each layer and the total depth. An example in Table No. 8 will illustrate the procedure.

Table No. 8 Available Water Depth in Layered Soils

Soil depth (Cms.)	Soil Class	% Gravimetric water content			Bulk density	Depth of available
		F.C.	P.W.P.	A.W.	gm/Cm^3	water (Cms.)
0–20	Silt clay	35	15	20	1.25	5.00
20–40	Silt loam	28	10	18	1.30	4.68
40–60	Sandy loam	20	8	12	1.35	3.24
Total	(12.92 cms in 60 cms soil depth)					12.92

Management Allowed Deficit :

Within the range of available water, the plant draws water at different rates. The rate is maximum when the soil is in the field capacity range and goes on decreasing till the permanent wilting point is reached. Just before the wilting point, the plant is able to draw water which is just sufficient to survive, but is not enough for its growth. This is mainly because the soil water suction decreases with the decrease in water content. For unsaturated soil condition, the flow is governed by the equation :

$$q = -(\theta)\frac{h_2 - h_1}{L}$$

Where, θ is the moisture content of the soil $h_2 - h_1$ is the pressure had L is the length. K, the unsaturated hydraulic conductivity and q is the flow rate.

For healthy plant growth, it is therefore not advisable to let the water content fall below a certain limit. Water has to be added before this point, when the water drawn by the plant is insufficient for its healthy growth. Generally, this point is taken at 50% of the available water though strictly speaking, this point also depends on the crops grown. The deficit that is allowed before the management has to start irrigation is called the Management Allowed Deficit, and it means that upto this deficit, the plant can draw water sufficient not only for its survival but also for its normal growth, Figure No. 7 shows these relationships. For more precision, the MAD for different crops are given in Table No. 9 (Refer stress irrigation for more details)

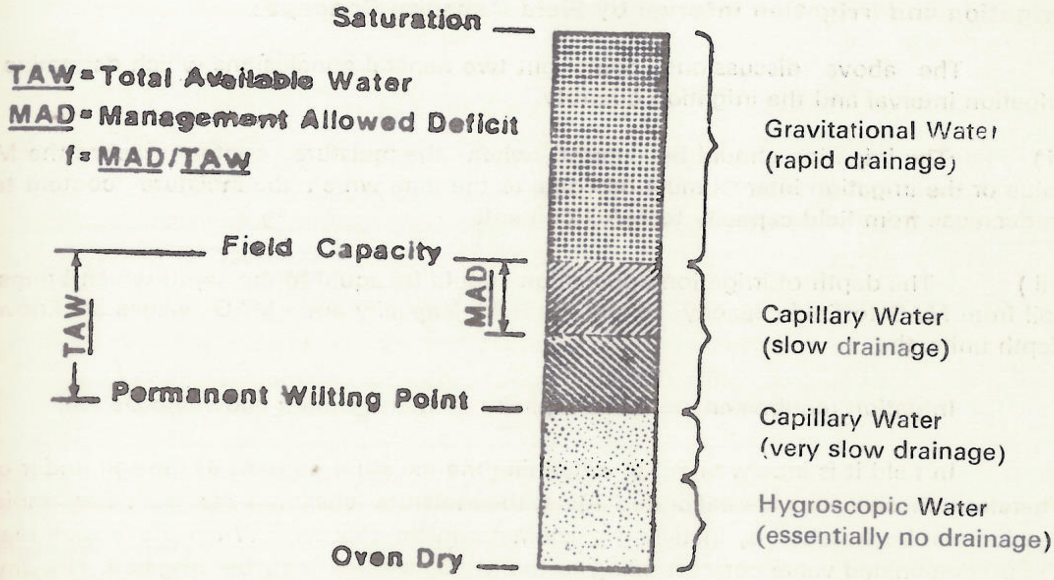


Figure 7 : Schematic representation of field capacity and permanant wilting point soil moisture content.

Table No. 9 :- Table Showing Management Allowed Deficit for Different Crops

Sr. No.	crops	MAD
1.	Leafy vegetables, strawberry	0.20
2.	Potato, onion	0.25
3.	Lettuce	0.30
4.	Bannana, carrots, grapes, Melons, peas, Tobacco	0.35
5.	Groundnut, Tomato	0.40
6.	Beans, Cabbage, Sunflower	0.45
7.	Beet, Citrus, Maize, Soyabean	0.50
8.	Wheat, Lucerne Barley	0.55
9.	Safflower	0.60
10.	Cotton, Sugarcane, Sweet, Potato, Jowar	0.65

Note : Increase the MAD values by 30% when ET_c is less than 3 mm/day. Decrease MAD values by 30% when ET_c is more than 8 mm/day.

Irrigation and Irrigation interval by Field Capacity Concept :

The above discussions point out two general conclusions which determine the irrigation interval and the irrigation quantity.

(i) The irrigation should be started when the moisture content reaches the MAD value or the irrigation interval must be equal to the time which the moisture content takes to decrease from field capacity to MAD content.

(ii) The depth of irrigation application snould be equal to the depth which brings the soil from MAD to field capacity. Since the field capacity and MAD values are known in depth units, the

Irrigation requirement = Field capacity — Management allowable Deficit.

In field it is inconvenient to determine the moisture content of the soil under crop. Therefore, these values are calibrated aginst the moisture tension in the soil. The moisture tension can be watched by installing tensiometer in the rootzone. When the tension reaches the predetermined value corresponding to the MAD, the soil is to be irrigated. The amount of irrigation can be determined by the depth difference at this reading. A solved example will illustrate the procedure. The factors that are necessary to determine the irriaation requirment are :

— Field capacity
— Permanent wilting point
— Management Allowable Deficit
— The bulk density of soil
— Root zone depth.

The last is also necessary, since this depth governs the availability of soil water to the plants. Even if water is available in lower depth, the roots are not able to reach and extract it.

Example :

Wheat is grown in a field with silty clay soils. The F. C. of the soil is 35% and P. W. P. is 15%. At the time of irrigation, the wheat is 6 weeks old. Determine the requlred depth of ırrigation assuming that the soil has reached the MAD at the timo of Irrigation. The bulk density of the soil is 1.25 g/cm^3

i) The available water = F. C. – P. W. P.

$$= 35 - 15 = 20\%$$

ii) The wheat is six weeks old. The root zone depth can be assumed to be 45 cm. Therefore, the available water in terms of depth is :

$$\frac{20 \times 1.25 \times 45}{100} = 11.25 \text{ cm.}$$

iii) The Management allowable deficit factor for wheat is 0.55 (from Table No. 9) Hence the depth of irrigation necessary at root zone is :

$$11.25 \times 0.55 = 6.12 \text{ cm}$$

Irrigation Interval :

If the evapotranspiration of the crop is known, (the methods for determining evapotranspiration are discussed separately, the irrigation interval can be determined by

$$\text{Irrigation Interval in days} = \frac{(P \times TAW \times D)}{ETc}$$

where,

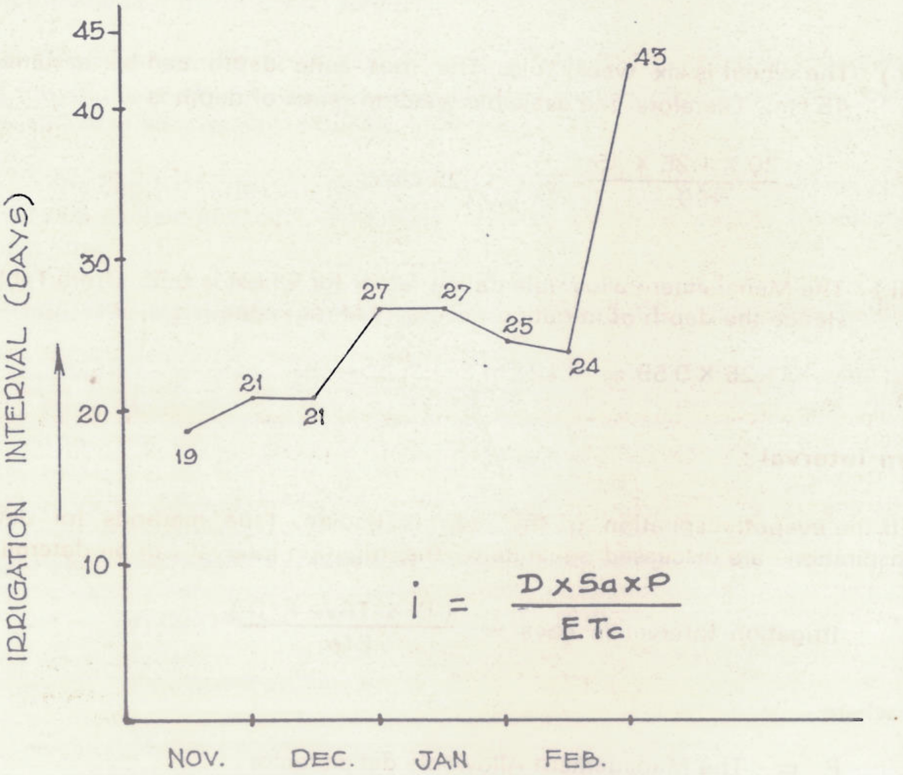
P = The Management Allowable deficit factor

TAW = Total Available Water in mm/m of soil

D = Depth of root zone in mtrs

ETc = Evapotranspiration in mm/day

In fact, this concept provides a logical method approach to determine the rotation periods of irrigation systems. The method considers the soil properties in shape of TAW, the crop requirements in shape of root zone depth and the climatic conditions in ETc. It is true that rotation period can not change with every crop and every soil type in a sizable irrigation system. However, for soil types, and different crops grown, seasonwise rotations can be computed and the best compromise for each season can be adopted. Figure No. 8 shows the graph for a type study of irrigation interval required for wheat in different periods. Such graphs can be plotted for all crops and the best compromise can be selected.



PARAMETER	MONTHS AND FORTNIGHTS							
	NOV.		DEC.		JAN.		FEB.	
	I	II	I	II	I	II	I	II
ROOT ZONE (D) IN METRES	0.20	0.40	0.60	0.90	0.90	0.90	0.90	0.90
M.A.D. OR p IN FRACTION	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
AVAILABLE WATER CAPACITY (SA) IN mm/m.	240	240	240	240	240	240	240	240
E.T.c. mm/DAY	1.38	2.48	3.70	4.42	4.46	4.76	4.87	2.70
FREQUENCY (i) IN DAYS	19	21	21	27	27	25	24	43

FIG. 8: SAMPLE CALCULATION OF IRRIGATION INTERVAL FOR WHEAT (DHOM PROJECT)

WATER BALANCE CONCEPT

Water balance concept is used to estimate the irrigation requirement for a certain period. The concept can be used for long periods such as irrigation season or even an irrigation year with certain modifications. However, the discussions here are limited only for a short duration irrigation or a rotation period.

At the end of some irrigation, whether it is by artificial means or by rains, the soil has a storage of water in the root zone. At the end of the rotation period or just before the start of the next rotation, this water storage gets changed. During the interval of two irrigations or water applications, the storage gets decreased by certain factors and gets increased by other factors. The difference between the total effects of these two sets of factors is the change of storage of water in the soil. This change in storage in either incremental or decremental. If it is decremental, and if this decrement is made good by water application, i. e. if the soil water storage is again restored to its original state, the crops can continue to get water from the soil storage. This is the basic water balance concept. The basic limitation of course, is that the water balance should not drop down to a level where the crops can not usefully absorb water from soil storage.

The factors contributing to the decrease in water Balance are :

— Evaporation from soil surface (D_e)

— Transpiration of crop (D_t)

— Deep percolation (D_{dp})

On the other hand, the factors contributing to the increase in the water balance are -

— Precipitation (D_p)

— Applied water i. e. irrigation (D_a)

— Water entering the root zone from ground water reservoir because of capillary rise (D_{gw})

Thus, normally the change in water balance $D\triangle_s$ would be.

$$D\triangle_s = \text{Outflow} - \text{Inflow}$$

or $$D\triangle_s = (D_e + D_t + D_{dp}) - (D_p + D_a + D_{gw})$$

Further modificatiom to this equation are required because all the rains or all the applied water does not reach the root zone storage.

A part of the applied water may overflow the boundary and only the balance will infiltrate the soil. Thus the contribution to the soil watar (D_z) is (Applied water–overflow) i. e. Tail water.

or, D_a can be replaced by D_z

where $D_z = (D_a - D_{tw})$

Similarly, the rainwater or precipation does not totally contribute to the soil water. The surface run off (D_{pr}) is totally lost. Some precipitation is intercepted by plant in the atmosphere and cannot reach soil water. This part is termed as (D_{pl}) Thus, the part of precipition reaching the root zone is (D_{pz}) where,

$$D_{pz} = D_p - D_{pl} - D_{pr}$$

Substituting D_a by D_z , and D_p by D_{pz} the original equation reduces to

$$D\triangle s = (D_e + D_t + D_{dp}) - (D_{pz} + D_z + D_{gw})$$

Now. ($D_e + D_t$) is the evapotranspiration of the crop and together, is called Det

Therfore,

$$D\triangle s = (D_{et} + D_{dp}) - (D_{pz} + D_z + D_{gw})$$

The general form of the equation is

$$D\triangle s = (D_{et}\ D_{dp}) - (D_p - D_{pl} - D_{pr} + D_a - D_{tw} + D_{gw})$$

Or

$$D\triangle s = (D_{et} + D_{dp} + D_{pl} + D_{pr} + D_{tw}) - (D_p + D_a + D_{gw})$$

This relation is schematically represented in Fig. 9. The depth of root zone only is considered for water balance.

This equation can be used for estimation of Irrigation requirement for a certain period, between two irrigations. The change in storage is the difference between outflow and inflow. If the difference is positive, the soil water balance is reduced during this period

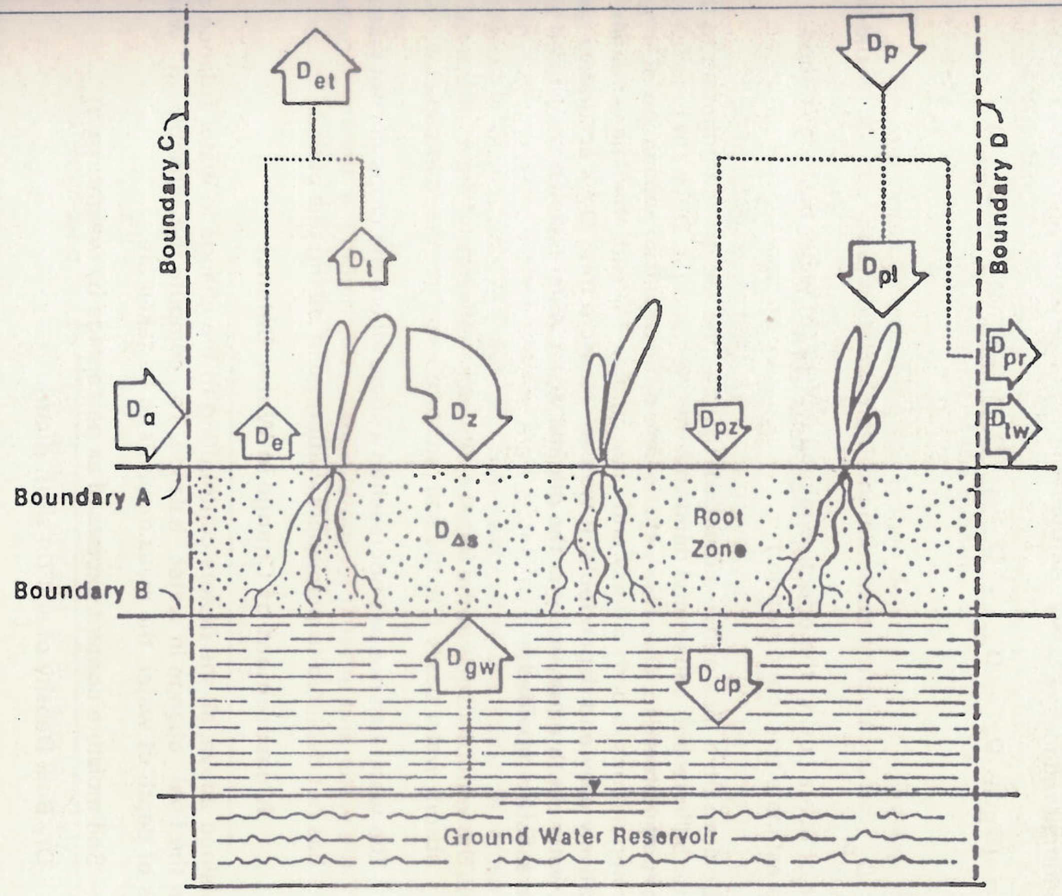


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Figure 9. The water balance parameters for a surface irrigated field.

and water will have to be added to the soil to bring it to the initial position. If the difference is negative, i. e. inflow is more than outflow, there is no necessity to add any water to the soil water reservoir.

Now, if this eqution is being used for irrigation requirement between two irrigations, the Depth of applied water (Da) is zero. Naturally, D_z and D_{tw} also have zero values.

The equation therefore reduces to –

$$D\triangle_s = (D_e + D_t + D_{dp} + D_{pr} + D_{pl}) - (D_p + D_{gw})$$

where,

$(D_p - D_{pr} - D_{pl})$ is the contribution of precipitation and can be estimated from the records of rainfall using the effective rainfall tables. (In water balance method it is not necessary to estimate this contribution.)

It will be seen from the above euquation, that all the factors contributing to the depletion of water balance are considered and the net depletion is D$\triangle$s. In practice the measurements of parameters like, D_p, D_{gw}, etc. is very difficult. The estimation of these parameters by computations is both clumsy and inaccurate. Instead, the measurement of D$\triangle$s is comparatively easy and dependable. If we can measure this D$\triangle$s accurately and apply irrigation water depth equal to D$\triangle$s the original water water balance is restored and irrigation need is satisfied provided,

— The water balance in the initial stage was sufficient to allow the crops to absorb water easily i. e. the soil moisture was near the field capacity.

and

— The water balance has not reached a stage where the crops can not take up the water and utilise it for growth during this period i. e. the soil moisture has not depleted to permanent wilting point during this period.

Measurement of Change in Water Balance

As explained above, all the factors contributing to the change in water balance are accounted for in the final change in water balance. To compute the change in water balance in terms of depth of water, the measurements to be taken are,

— Soil moisture content expressed as percentage by weight. (g/g)

— Dry Bulk Density of soil (in situ). g/cm^3

The in situ bulk density of the soil can be determined by the standard 'cylinder driving test" or the "pit test" depending upon the nature of the soil. The detailed procedures of these tests can be found in any standard book on soil mechanics. The outline of the tests is given here for quick recollection/recapitulation.

Cylinder method :

This method is used for soils having sufficient clay content, so that the cylinder once driven in to the soil can be extracted with the soil column within. A mild steel hollow cylinder with cutting edge (weight w_1) is driven gradually in to the soil; after removing the top loose soil, the cylinder is extracted by excavating around it and weighed again. if this weight is w_2 , the weight of soil column in the cylinder is ($w_2 — w_1$). The volume of the soil column is equal to the internal volume of the cylinder. The wet Bulk density is therefore.

$$\frac{W_2 - W_1}{\text{Int. Volume of the cylinder}}$$

The moisture content of the soil is then determined by weighing the soil sample before and after oven drying. Finally the dry bulk density is computed.

Pit and Sand Method

This method is normally used for gravelly soil where penetration of sampling tube and its extraction (with soil sample) is difficult. The loose soil surface is removed and a small pit is excavated. All the excavated material is cerefully collected and weighed. This weight is the weight of the soil from the pit. The moisture content of the soil is determined by the usual methods.

To determine the volume of the pit, a very simple procedure is used. A vessel containing uniformly graded fine dry sand with known specific gravity is weighed. The sand is poured in the pit just to fill the pit completely. The container is again weighed. The difference in these two weights gives the weight of sand poured into the pit.

Now,

$$\text{Sp. gravity of sand} = \frac{\text{Density of sand}}{\text{Density of water}}$$

$$= \frac{\text{Wt. of sand}}{\text{Vol. of sand} \times \text{Density of water}}$$

Or,

$$\text{Volume of sand} = \frac{\text{Wt. of sand}}{\text{Sp. gravity of sand} \times \text{Density of water}}$$

Since, Density of water in C. G. S. units is 1,

$$\text{Volume of sand} = \frac{\text{Wt. of sand}}{\text{Sp. gravity of sand}} \quad \text{(if C. G. S. units are used)}$$

Knowing the volume, the density (wet) can be calculated. From the moisture content, the dry density is computed.

Soil Moisture Content :

The soil moisture content is determined and expressed as percentage of dry weight of the soil.

Water Balance in Soil :

It is more convenient to express the moisture content in terms of depth of water per meter. The relation is,

Depth of water in mm = Soil moisture percentage × Dry bulk density × 10

Change in Water Balance :

The depth of water at the end of the first irrigation is determined as above. The depth of water before the start of the irrigation is similarly determined. The difference is the application depth required. It is better to determine the first depth about 24 hrs after the first irrigation so that the rapid drainage is completed by that time. It must be remembered that this depth is depth per meter of the root zone. The root zones at start and end of the period may vary and necessary cerrection has to be considered.

Measurements of change In water Balance under controlled conditions :

If a soil mass is enclosed in a container, and arrangements are made to measure all the water entering or leaving the soil mass, the change in water balance can be computed from the above equation. The soil mass container can be weighed at the beiginning and end of time interval. The weight difference gives the direct measurement of change in water balance. Having Known D $\triangle$s, the equation can be used to measure Det i.e.the evapotranspiration, more commonly known as ETc. This principle is used in determining Daily ETc or ETo by lysimeters.

LYSIMETERS

The most accurate method, available today to determine the ET_c (of a crop) is to measure the same directly by Lysrmeter. The measurements are accurate up to 0.05 mm of ET_c and Lysimeters are developed to record almost continuous measurments (Tal Amara) Lysimeter in Lebenon). These lysimeters, though very simple in principle are somewhat complex in construction and costly also. Because of the high cost their use is limited to research work and to corelate the results by other methods.

Definition :

Lysimeters are defined (Hillel et al 1969) as " Large containers filled with soil, generally located in the field to represent the field environment, and in which soil water plant conditions can be regulated and monitored more conveniently and accurately than in natural soil profile."

Concept :

In simple terms, thc lysimeter can very accurately measure the water content change either by weight or by volume in an enclosed soil mass which represents the field conditions as nearly as possible. The water balance in the lysimeter can be expressed as.

$$\text{Precipitation} + \text{Irrigation} \pm \text{Runoof} = ET_c + \text{Drainage} \pm \triangle w$$

Where $\triangle w$ is the change in weight of soil mass.

Normally, the lysimeter is so designed, that the protruding rims prevent any surface run off either into or out of the system. The equation then reduces to :

$$ET_c = P + I - D \pm \triangle w$$

Precipitation 'P' and irrigation 'I' can be directly measured very accurately. Drainage from a lysimeter can also be collected and measured. If the measurments are taken after drainage occurrance 'D' can be totally neglected. W is then related to the change in weight of the enclosed soil mass, I. e. the change of weight of the moisture in the soil.

Types of Lysimeters : The lysimeters are classified as "Weighing type" and "non weighing type" according to the method used for measuring the chage in the water content of the soil container. Basically, non-weighing type lysimeters enable us to determine Evapotranspiration for a given period by deducting drainage from the total water input. In weighing type lysimeters, the Evapotranspiration and drainage components can be separately determined or if the measurement is taken after the drainage is completed, the drainage is totally eliminated and Evapotranspiration can be directly measured.

The non-weighing type is further classified as -

— Drainage lysimeters without water table.

— Compensation lysimeters with constant water table.

— Compensation lysimeters with surface water table.

— Special types of drainage lysimeters.

The weighing type is further subclassified according to the weighing system used as under :

— Mechanical weighing lysimeters.

— Electronic weighing lysimeters.

— Hydraulic weighing lysimeters.

— Floating lysimeters.

— Combinations of weighing devices.

These types follow the same principle discussed above. Selection of the type depends on the accuracy desired, the resources (mainy financial) available and the physical constraints if any.

Performance And Limitations of Drainage Type Lysimeters

Due to its simplicity in construction and measurement, the drainage type lysimeter has found very wide application all over the world. A minimum size between 2 and 4 m^2 in area is recommended for most grasses and field crops. Smaller units have often been used, but scale and border effects greatly restrict results. other limitations of the drainage type lysimeters are related to :

— the inaccuracy resulting from changes in soil moisture storage. The water moisture content (field capacity) in the lysimeter is not necessarily equal after successive, drainage occurrences, while very frequent wetting to minimize these changes leads to the water regime in the lysimeter not being the same as that of the surroundings ;

— the time delay in the percolation of water through the soil profile. Especially for heavy soils it takes several days for all superflous water to be drained out and equilibrium established.

These limitations imply that determination of evapotranspiration can be carried out only over longer periods (weekly to monthly ET values).

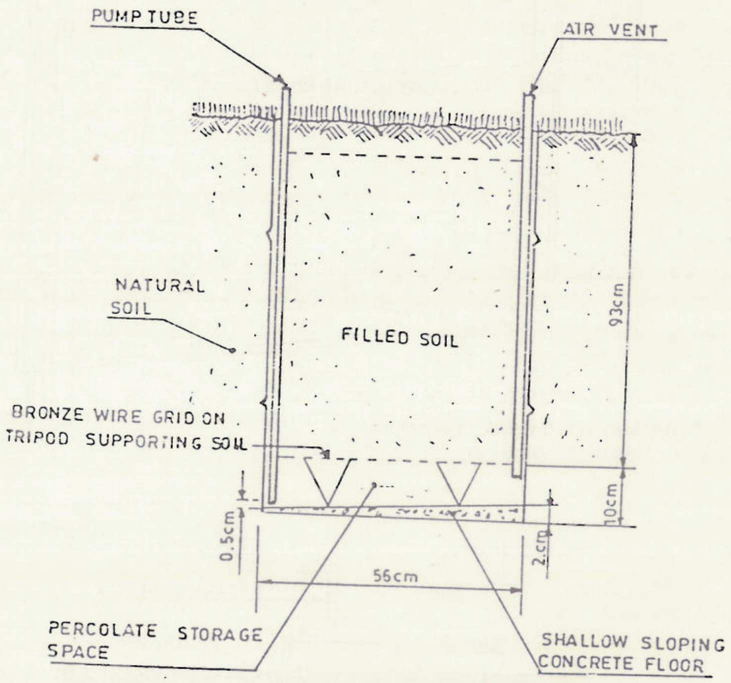


FIG.10. SIMPLE DRAINAGE LYSIMETER (OIL DRUM)

E.I.F./ TRO- INGLE A. A.
WL/ARU/DGR No. 21

Dt 11-12-87

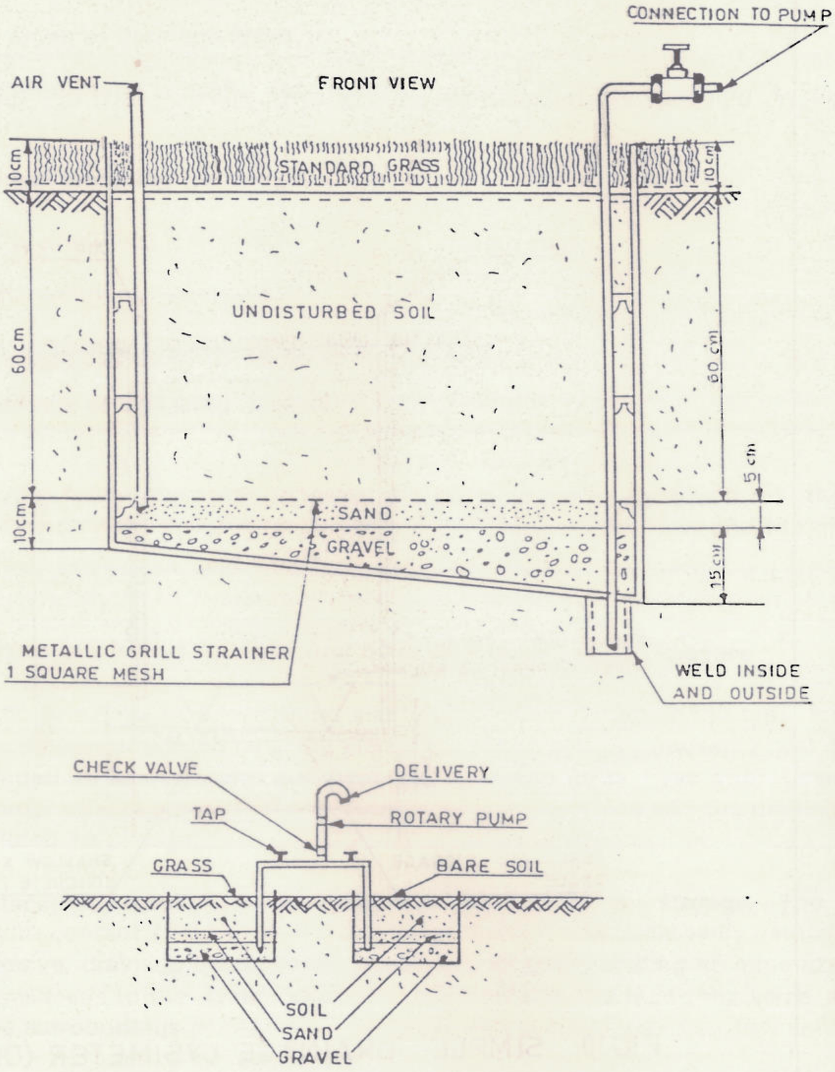


DIAGRAM OF FIELD INSTALLATION OF TWO TANKS WITH PUMP CONNECTION

FIG. 11 THORNTHWAITE TYPE EVAPOTRANSPIROMETER (UNDP/WMO 1974)

E.I.E./TRD-INGLE A. A.
Dt. 7.12. 1987
WL/ARU/DGR No. 17

Drainage type Lysimeters :

Two very simple drainage type lysimeters are described below to illustrate the principle. They are by no means, standard types The lysimeters are to be designed and developed according to the needs

(i) Simple drainage lysimeter :

Simple steel oil drum of 0.27 m^2 and 1.0 m deep is filled with soil in layers as they occur in the field. A bronze wire grid is placed at 93 cm depth to support the soil. The grid is supported by tripods. A shallow sloping concrete floor Is provided, on which the drum rests. The drainage water collected at the bottom, below the bronze is periodically pumped out by a hand pump and measured carefully. The arrangement is schematically shown in figure No. 10. This type was developed by Slayter and MacIlroy in 1961. Despite the simplicity the errors in measurements are large because of small size. Besides these containers are likely to corrode very easily.

(ii) Drainage lysimeter (Thornthwaite) :

Another type of Drainage lysimeter (Thornthwaite type) used for evapotranspiration measurements is illustrated in figure 11. It consists of a steel tank of 1 m x 1 m, the depth at one end being 90 cm and at the other end 80 cm. This sloping gradient in the bottom enables drainage water to be collected in a sink. The water is pumped out at regular intervals and measured. The figure shows two tanks with pump connection. One tank is used to estimate evapotranspiration, from standard grass while the other is used for evaporation from bare soil. A 60 cm layer of soil lies over sand and gravel layer which acts as a drainage conduit.

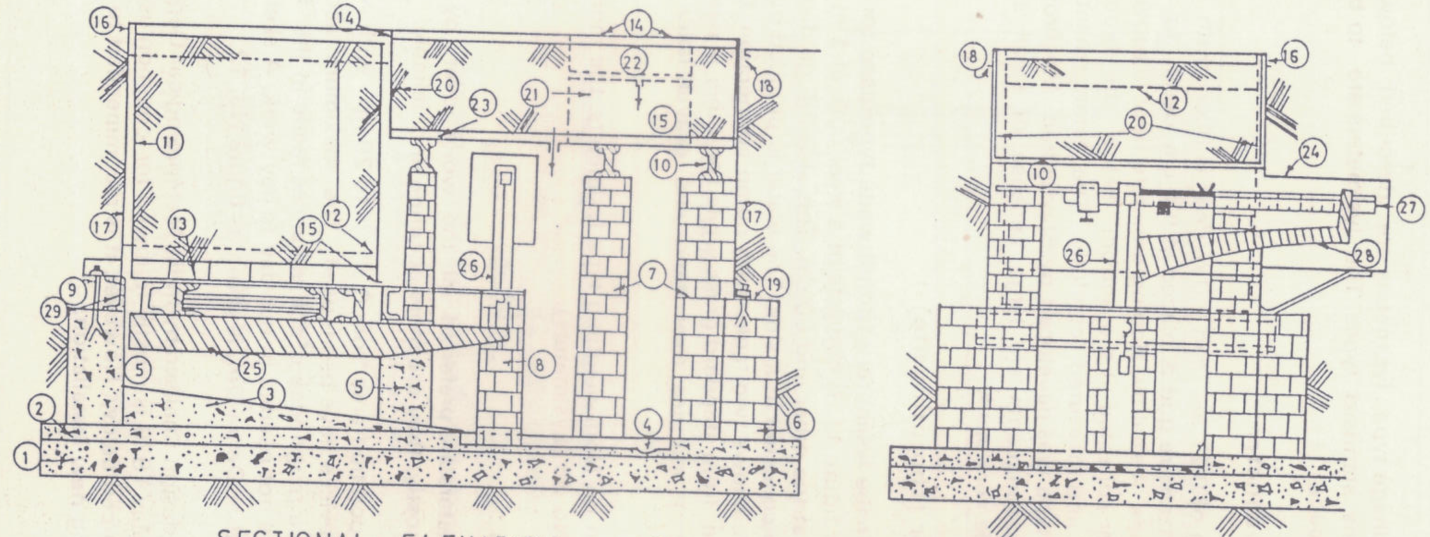
For more information on Non-weighing type lysimeters, the more interested reader is referred to F. A. O. Paper No 38 (Lysimeters).

Weighlng type Lysimetars :

Weighing type lysimeters are preferred all the world over, by research workers because, though somewhat costly, they are more accurate and reliable.

Lysimeters with evaporation area from 0.3 m^2 to 29 m^2 with various degrees of sophistication in weighing devices have been used. The maximum accuracy obtained is 0.03 mm. This is just to give a rough idea of the advances made in the field of Lysimetry, though this much accuracy is not needed in our day to day work. A sketch of typical weighing type lysimeter installed at Dehra Dun is given as figure No. 12.

In our country, the design finalised by India Meteorological Department under their circular No. 53 dated 26th May 1979 is mostly followed for common use. Relevant extracts from this circular are reproduced below. However, it is recommended to study the circular in original before undertaking new installation.



SECTIONAL ELEVATION   Scale 1: 20   SECTIONAL SIDE VIEW

Fig No.12. Weighing-type lysimeter, designed and Installed at Dehra Dun,

Trd. by. B.S. Dulguch/ARU No.1 /1-1-1988

Fabrication Details of Lysimeter (Figure 12)

Three weighing type lysimeters have been installed at Soil Conservation Research Farm, Selakui, Dehra Dun. Lysimeter tank has 120 cm^3 undisturbed soil monolith and provision for measuring runoff and deep percolation. The sensitivity of mechanical dormant platform weighter is 200 g (0.14 mm water). The details of sectional elevation and side view of fabrication are given below :

A. R. C. C. Structure

1. Lean concrete 1 : 3 : 6 (4 cm) — 370 x 220 x 15 cm.
2. Concrete 1 : 2 : 4 (2 cm) — 370 x 220 x 8 cm.
3. Floor with 10% slope
4. Pit/Depression
5. R. C. wall 177 x 177 x 73 cm.
6. Brick wall – 168 x 177 x 88 cm.
7. Pillars for supporting soil tray, 25 x 25 x 143 cm
8. Supporting structure for weigher's pillar
9. Grouting bolt 1.27 x 28 and 13 cm.
10. I–Beams — 12.7 x 7.6 x 125 cm

B. Lysimeter Tank

11. Lysimeter tank - 120 cm^3
12. Welded angle iron - 3.81 x 3.81 x 0.635 cm
13. Perforated bricks - 20 x 10 x 5 cm
14. Runoff outlet
15. Seepage outlet
16. Soil/Ground level

C. Retaining Tank

17. Retaining tank – 296 x 127 x 120 cm
18. Top angle iron for reinforcement 3.81 x 3.81 x 0.635 cm
19. Bottom angle iron for reinforcement 7.5 x 7.5 x 0.63 cm
20. Soil tray 164.5 x 125 x 50 cm
21. Manhole - 60 x 50 cm
22. Dummy soil tank - 59 x 20 cm
23. Sand layer - 3 cm
24. Pocket for steel yard – 60 L x 35 W x 45 H cm

D. Weighing Bridge

25. Platform 125 x 125 x 15 cm
26. Pillar – 60 cm high
27. Steel yard
28. Steel yard arrester
29. Frame of weigher.

2. Principle :

Out of the known methods for measurement of evapotranspiration, use of lysimeters is the best and the most convenient for obtaining ET data on a day–to-day basis. In lysimetry relating to aerobic crops the amount of moisture gained or lost by a suitably enclosed volume of natural soil is found through determination of the weight of the soil mass at the beginning and at the end of a time interval.

The lysimeter can measure either evaporation from soil surface or evapotranspiration from crops depending on whether the soil block and its surroundings are kept bare or are cultivated.

Measurements made with growing plants in isolated containers will be highly erroneous due to the well known 'Oasis' or 'Island' effects. For realistic results, the lysimeters have to be placed in the midst of a large cropped field. The plants in the lysimeters should have growth features and a population density similar to the field plants and they must form continuous rows with those in the field The soil block in the lysimeter must be sufficiently large to support a fair number of plants and must be deep enough to permit normal development of absorbing roots. In other words the dimensions of the soil block would decide/restrict the types ofcrops that can be taken up for ET determinations. The lysimetric soil block may either be of the back-filled or of the monolith type. In the monolith typo an undisturbed core of soil is cut from the same field and is enclosed suitably in a container, which then forms the experimental tank. In the back-filled type, the soil is dug out from the field carefully, layer by layer, and filled into the experimental tank, so as to maintain the same soil profile and packing as in the field.

Lysimeters are classed as mechanical, hydraulic, manometric and buoyed types on the besis of the principle used in determining the weight of enclosed mass of soil A gravimetric lysimeter system, described below, has been developed by the India Meteorological Department (IMD) keeping in view the sturdiness, accuracy, ease of operation, absence of risk of failure of the measuring system and suitability for network operation.

3. Description :

The gravimetric lysimeter consists of a sensitive dormant type weighing machine of two tonne capacity (as per specification No. Agri. No. M. 1/7) It is erected in the middle of a field on a reinforced concrete foundation, constructed inside a pit of size about 3 5 x 3 x 2 m When in position, the platform of the weighing machine will be at a depth of about 1 meter from the soil surface.

A steel tank of size 1.3 x 1.3 x 0.9 m. (as per specification No. Agri. M. 2/71) in which the plants are grown, is mounted on the platform of the machine such that its rim is in level with the surrounding soil surface. The steel tank carries a perforated plate at a depth of 75 cm so as to form a hollow chamber at the bottom. A tube inserted through the perforated sheet into the bottom of the hollow chamber facilitates the removal of percolated water from the hollow chamber. A tap is also fitted to drain out the percolatade water from the hollow chamber. The soil is backfilled in the steel tank to simulate the natural soil profile.

A steel frame work (as per specification No. Agri. M. 3/71) is erected around the weighing machine such that the gap between the steel frame wall and the steel tank is less than 3 cm. except near the headwork position of the balance.

A smaller tank of the size of 30 × 30 × 90 cm (as per specification No. Agri M. 4/71) is placed in the gap near the headwork so as to prevent overheating of the sides of the field tank near the weighing machine pillar.

4. Selection of site for lysimeters :

A field of about 60 × 60 m planted with a bulk crop and located in the midst of a cropped area is required. Ideally, this field should be surrounded by other fields having similar crop varieties which receive similar cultural treatments as given to the crop in the ET field. Water channels if any, running through the field should be arranged to run at least 15 m away from the central area of the selected field where the lysimeter is proposed to be installed.

5. Installation :

An area of 3.5 × 3.0 m should be marked in the centre of the selected field installation. The orientation of pit should be such that the lysimeter plants would have the maximum possible fetch of crop up wind of the most predominant direction of wind.The pit dug for lysimeter should be 175 cm deep in case of deep soil and 160 cm deep in case of the other soils. The measurements of the pit at the top and at the bottom should be 3.2 x 3.0 m and 3.0 x 2.5 m respectively to avoid caving in of earth into the pit. A trial pit should be dug before starting the actual excavation to ensure a minimum soil depth of 75 cm.

The soil should be excavated from the pit in layers of 15 cm up to a depth ot 90 cm and stacked in separare heaps, with indentification tags, at least 3 meters away from the edges of the pit. If the soil is homogeneous, stacking of layers in 15 cm intervals is not necessary and 30 cm intervals can be adopted.

Removal of soil may be done in layers corresponding to the typical soil horizons below the depth of 90 cm. Soft and hard material must be removed and stacked separately outside the field.

In the case of deep soils the bottom of the pit may be watered and rammed well. If necessary, an additional 15 cm deep layer of the soil may be dug out and replaced by small boulders and hard stones before watering and ramming. A lean concrete foundation (1 cement, 5 sand and 10 metal) of 15 cm thickness should be laid over the rammed bed.

Such a foundation is not necessary if hard rock is struck during the excavation. In such a case excavation up to the depth of 160 cm only would suffice and the bed may be levelled by plastering.

6. **Erection of lisimeters : (Figure 13 A)**

The weighing machine will be positioned by the staff of the firm supplying the weighing machine. When positioned, the gap between the platform and the 'box' of the machine should move freely.

After erecting the machine, lower the outher frame wark using a chain pulley block. Fix thick wooden planks inside the outer frame work, especially in the extended portion to avoip any possible deformation of the frame work.

If chain pulley block is not available, fill in the soil up to the height of foundation wall and take two pipes or rails which will just protrude above the pit when kept in inclined position. It should be ensured that the pipes or rails exert no pressure either on the foundation wall or on the weighing machine.

Slide the outher frame work over the pipes/rails until it touches the opposite side wall of the pit.

Slightly lift one side of the outher frame work manually and remove the rail/pipe. Remove the other rail/pipe similarly. Care should be exercised to see that outher frame work does not drop suddenly on to the foundation.

Slightly raise the outer frame work above the foundation and apply cement mortar on the foundation. Now lower the outer frame work to rest on the wet cement mortar and see that the gap between the outer frame work and the balance frame is the same all around. This gap should be filled with cement mortar.

Fill in the gap below the outer frame in the extended portion.

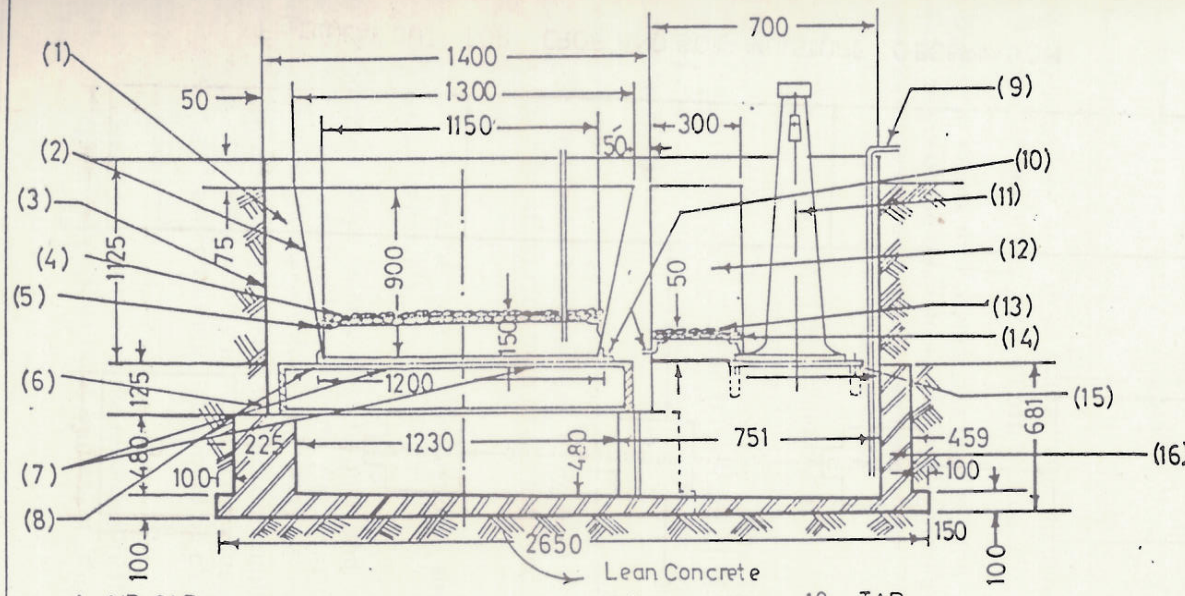
Apply cement mortar on the flange of the outer frame work all around to a height of 15 cm to avoid seepage of water. Allow it to cure.

Apply white pait on both sides of the outer frame work up to the depth of 30 cm from the top. Apply coal tar below this depth.

Lower the steel tank, painted white at the top and outside and tarred at the bottom and inside, either manually or by chain pulley block.

Lower the separator plate in the steel tank.

Place a nylon net over the separator plate. Put in a 2 cm thick layer of small pebbles or other material that would aid drainage.



1. AIR GAP
2. STEEL TANK
3. STEEL FRAME WORK
4. PERFORATED PLATE
5. 37 X 37 X 6 ANGLE FRAME
6. 75 X 75 X 6 ANGALE STEEL FRAME WORK
7. 6mm. STRIPS ON MACHINE PLATFORM
8. 75X75X6 ANGLE FRAME
9. WATER EXTRACTION TUNE CONNECTED TO SUCTION
10. TAP
11. BALANCE PILLAR
12. DUMMY TANK
13. PEBBLES
14. PERFORATED PLATE
15. 25 THICK M.S. ADAPTOR PLATE
16. C.C. FOUNDATION

Note:- Drawing not to scale. All Dimension in mm.

Fig. 13(A) GENERAL ARRANGEMENT

Trd: by B.S.Dulguch /WL/ARI/DGR No.2/Dt:15.1.88

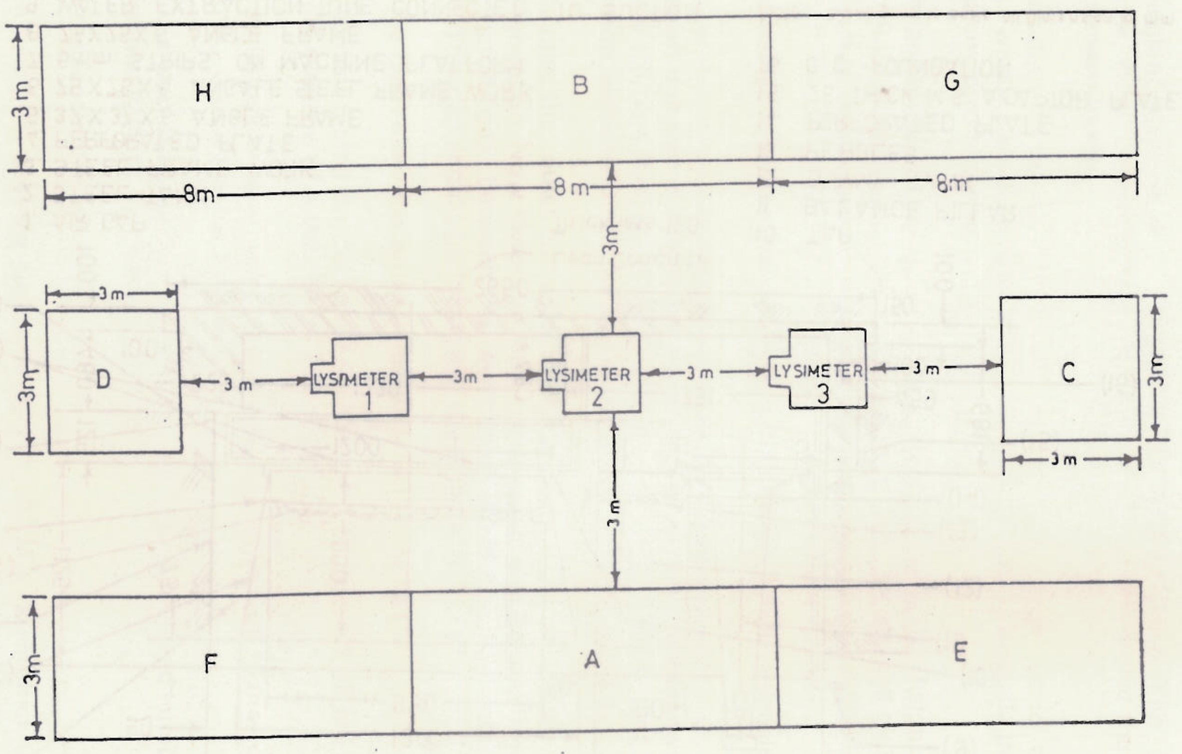


Fig.13(b) LAY OUT FOR CROP AND SOIL MOISTURE OBSERVATION

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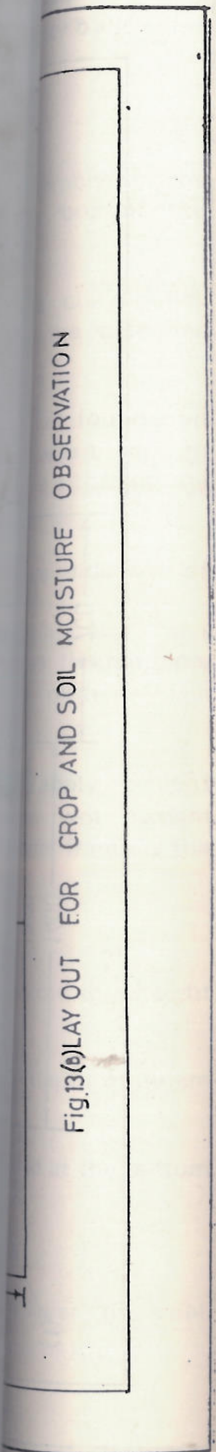

Fig.13(c)LAY OUT FOR CROP AND SOIL MOISTURE OBSERVATION

Lower the dummy tank and keep the nylon net.

Get the weighing machine adjusted to read zero weight.

Backfill thc soil in the soil tank and the dummy tank after putting the pipes for pumping out water.

Backfill the soil around the outer frame work.

The lysimeter is now ready for operation.

Crop observations :

Crop observations have to be started after thinning out the plants or after gap filling if necessary and the plants get well established.

Selection of plants for observations may be done avoiding an area of about 3 meters from the edges ot the lysimeters. The idea is that even with very good precautions, the plants around the lysimeters might have been disturbed slightly and hence, may not be be suitable for representative crop observations.

The crop observations may be carried out in the areas marked out as A, B, C and D in Figure 13 B The distance of the plots from the lysimeters and the area of the plots will remain the same irrespective of the number of lysimeters. The date when the first seedling is noticed in the field and tanks and when 50 percent of the field tank appears covered may be noted. At this point, the emergece in tanks may be critically checked for any corrective action that may be necessary.

Dates of other crop phases like complete germination, initial tillering, 50% tillering, 100% tillering, first boot leaf, 50% boot leaf, 100% boot leaf, first flowering, 50 % flowering, 100% flowering, milk stage etc., both in the field and tanks, should be noted in the crop observation sheet.

In case of sugarcane, 'Brix' observations should be started at fortinghtly intervals 3 months prior to harvest.

In case of grain crops, observations of grain and straw yield from the lysimeter tanks and from two representative blocks in the field, one each from the blocks A or B, C and D should be made. From these values the yield of grain and straw in quintals per hectare should be calculated. For making these observations, the dry weight of the grain and the straw/fodder, i. e. the compete plant minus the roots, should be taken into account. In the case of sugarcane and cotton the yield would be cane and lint weights respectively.

Soil Moisture Observations :

Soil moisture observations are to be recorded in the field only in the areas E.F.G.H as indicated in the sketch. These plots must be free of irrigation channels and sufficiently away from them. (Figure 13 B).

In the case of irrigated crops, soil moisture sampling may be done, 24 hrs. after irrigation, in the early morning or late evening as the case may be. The post-irrigation samples may be taken only from the centre of each of area E, F, G, H, to know the extent of moisture penetration.

while recording the above observations, great care may be exercised not to damage or disturb the plants in the field.

In the case of rainfed crops, soil moisture observations may be recorded on fixed days of the week. Following heavy rains of 25 mm or more in 24 hours, observations may be recorded in the centre of areas E, F, G and H to know the depth of penetration of rain water. However, if the field has become water logged, soil moisture observations need not be recorded as long as there is water logging.

Profiles of field capacity, wilting point, and bulk density for the ET field may be got recorded by the soils Department before comencement of sowing. This data may also be sent to Agrimet, Poona.

Times of observations :

Lysimetric observations have to be recorded around 0700 hrs. when the wind is calm. One more observation is to be recorded at 1730 hrs. I. S. T. or 30 minute before sunset whichever is earlier.

Meteorological elements like saturation deficit of air, wind run, rainfall, radiation or sunshine, have the most vital bearing on evapotranspiration. Pan evaporation integrates the effects of the weather factors on water loss. These have, therefore, to be recorded along with evapotranspiration observations to enable scrutiny of data.These elements will also help in estimating ET from cropped surfaces, especially under conditions of incomplete crop cover and soil drying.

The ET observations are recorded at about 0700 hrs. (LMT) and the rainfall is recored at 0830 hrs. Whenever ET is corrected for rainfall, any rainfall that occurs between 0700 LMT and 0830 IST will decrease ET loss. So, if there is any rain between the time of recording lysimter and rainfall observations, the amount of rainfall may be noted with the help of self Recording Raingauge records, if available. Otherwise the fact that there was rainfall during that period may be entered in the remarks column.

During heavy showers, there may be scattering of rain drops by leaves reducing the catch of rainfall by the field tanks. This will increase the ET loss. Sometimes, rain may be collected by the foliage overhanging the lysimeter and this may fall into the tank. This will decrease the ET loss. If the foliage in all three tanks is not the same, the contribution of rainfall to evapotranspiration will be different in each tank, and hence each tank may produce different results. When such a thing occurs, the reasons, for the the differential behaviour should be noted and entered in the ET return.

The daily values of ET should be checked for consistency and any local reason for abnormal variation in the values from one day to the succeeding day, which cannot be made out from the meteorological parameters such as sunshine, windspeed etc., should be entered in the remarks column.

Tabulation of observations :

The change in weights (in kgs) of tanks during the period between 2 observations should be multiplied by a conversion of 0.6 and corrected for rainfall during the same period as per sample calculations given in table 10.

Table 10

Example to calculate Evapotranspiration

S. No.	Date	Soil Tank weight (kg.)	Change in weight (kg)**	Rainfall (mm)	ET = (Col.4 X 0.6 + Col. 5) (mm.)
1	2	3	4	5	6
Day with no rain					
	15-6-76	1853.5	—	—	—
	16-6-76	1851.3	2 2	0.0	1.3
Day when weight decreased inspite of rain					
	20-6-76	1851.3	—	—	—
	21-6-76	1850.1	1.2	1.5	2.2
Day when weight increased due to rain					
	15-5-76	1851.3	—	—	—
	16-5-76	1865.3	(—) 14.0	12.0	3.6

** A loss in weight is taken as +ve
A gain in weight is taken as −ve

Plant Water Relationship

Uptill. now, the methods discussed aimed at recouping the loss of moisture fror the soil during the irrigation interval. This loss was actually measured by direct or indirec means and the irrigation requirement was the recoupment of this loss. Another approac would be to estimate this loss and recoup it. This approach is known as estimation o evapotranspiration of crop. Various methods are developed for estimation of the Evapotrans piration losses. Before discussing these methods, let us understand the nature of these losse and the process by which these losses occure.

As the name itself implies, the losses can be divided in two components viz: evapo ration losses and transpiration losses. The soil surface is in direct contact with atmospher and soil moisture in the surface layer is evaporated into the atmosphere.The rate of evapora tion is dependent on the wind velocity, radiation, temperature and Humidity conditions.Thi loss is known as Evaporation. Soil moisture is absorbed by plants roots in the rootzone, it i translocated through the plants upto the leaves and the leaves in turn release part o the absorbed water to the atmosphere. This process of absorption of water, its translocatio and release into atmosphere is called transpiration and the loss is named as transpiratio loss. The process of release of plant water into atmosphere is very similar to the process o evaporation. This transpiration also depends on the wind velocity, radiation. temperature an humidity, and sunshine hours etc. It is logical that part of the absorbed water is utilised b the plant for its growth and other biological needs such as maintaining the temperatur within a certain range. However, this part is very small ranging from 2% to 5 % of the tot absorbed water. The major quantity of absorbed water is again transpired into the atmosphe Though the water consumed by the plant is in a small quantity it is necessary that th intake of water by the plant is at a optimum level. Hence the whole quantity of th absorbed water has to be recouped Thus most of the water absorbed by a plant is agai released into the atmosphere and this forms a cycle.

The water applied to the soil surface, either by rains or by irrigation, infiltrates int the soil and is stored there in the soil pores. (The surface run off and deep percolation i not now considered as it is not available to the plants). The water is subjected to variou forces such as -

— gravity

— capillary action

— osmosis

— pressure (or hydraulic head)

--- electric potential (very small)

Without going into the details of these forces, it can be said that as a result of these forces, water is held in the pores with a certain force and if water is to be removed, an equal force will have to be applied. This force which must be exerted per unit area to remove water from the soil is called soil moisture tension and is a measure of the tenacity with which water is held in the soil, It is usually expressed in atmospheres which is the average air pressure at sea level (1 atmosphere is equal to 1036 cm of water or 76.39 cm of mercury). With different soil moisture Tensions even in the soil itself, a pressure gradient can be established. The gradient, i, is.

$$i = \frac{h_1 - h^2}{L} \quad \text{where}$$

($h_1 - h_2$) is the differential potential and L is the length between the two points.

The velocity of the flow is given by

$$V = - K_{\theta}\, i$$

Where $K =$ is the unsaturated hydraulic conductivity of the soil

and $\theta =$ is the moisture content.

This is as far as the water movement in the soil is concerned. However, the same analogy can be extended and it can be said in very general terms that water will move in to the root system of the plants if a suitable gradient from soil to root to stem to leaves of the plants is established. The general values of the moisture tension are indicated in **fiqure No. 14** These are only indicative to show how water moves from soil to root system and up to the leaves. The process of transport of water from the roots up to the leaves is called translocation. The rate of absorption however, depends on the rate of transpiration which is a process by which the leaves release the moisture in to the atmosphere. When water reaches the leaf, it is stored in intercelluar spaces. The leaf surface has micro openings called stomata. The stomata closes and opens intermittently by a complex process. The water is lost to the atmosphere when the stomata cpen. **Fig No. 15** explains the path of water through leaves and to the atmosphere. When water is released to the atmosphere a pressure drop occures and water is sucked in the leaves cavities. Thus a sort of pumping arrangement is established from root to leaves. This process is very complex and above discussion provides only a general concept of the process. For more details the reader is referred to "Water ement and Irrigation Management of Crops in India."

Thus the water absorption rate depends on-

— The adequacy of soil moisture content in the soil and then on transpiration rare which depends on the plant and clamatological factors which govern the rate of transpiration and evaporation.

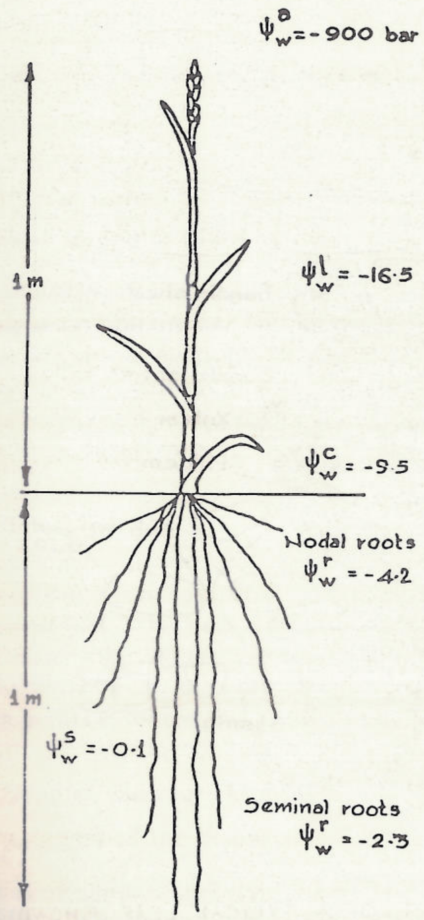

FIG. 14 WATER POTENTIALS EXPECTED AT DIFFERENT LOCATIONS THROUGHOUT THE PATHWAY FOR WATER TRANSPORT FOR A WHEAT PLANT GROWING IN SOIL AT A POTENTIAL OF 0.1 BAR AND IN AN ATMOSPHERE WITH A POTENTIAL OF -900 BAR ψ_w^s = SOIL WATER POTENTIAL, ψ_w^r = ROOT WATER POTENTIAL, ψ_w^c = CROWN WATER POTENTIAL, ψ_w^l = LEAF WATER POTENTIAL, AND ψ_w^a = ATMOSPHERIE POTENTIAL.

LOYA N.M.

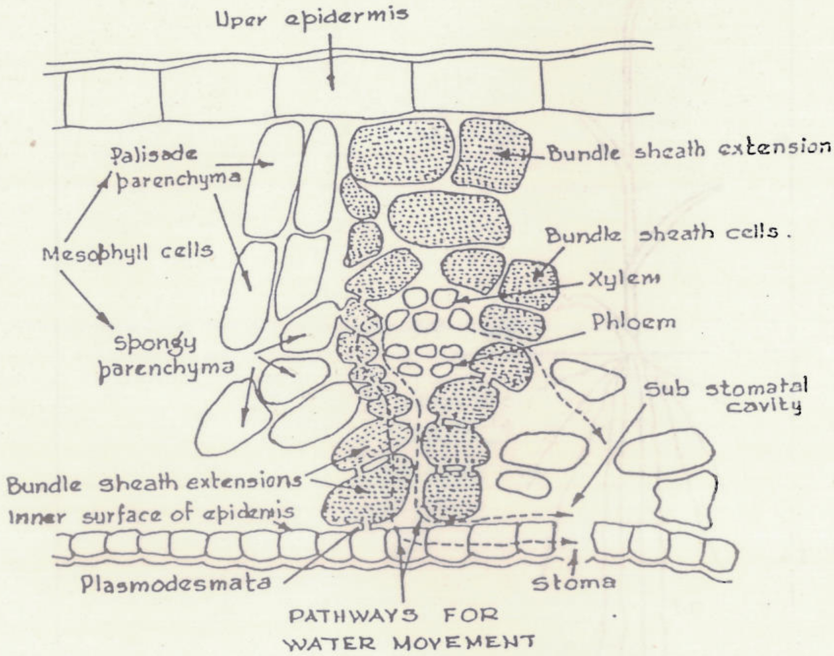

FIG. 15 ANATOMICAL STRUCTURE OF A TYPICAL LEAF SHOWING THE VASCULAR BUNDLE AND ASSOCIATED CELLS. THE PATHWAYS OF WATER MOVEMENT FROM THE XYLEM TO THE SUBSTOMATAL CAVITY ARE INDICATED.

LOYA M.M.

Climatological Methods for Estimation of Evapotranspiration

It is not always possible to measure the actual evapotranspiration on field either by lysimeter or by actual moisture content measurements. It is also many a times necessary to estimate the crop water requirements in advance either for project designing or annual water budgeting. It has already been estiblished that the evapotranspiration depends on the climatological factors such as :-

- Radiation or Solar energy received
- Temperature
- Wind velocity
- Relative Humidity.
- Sunshine hours (duration)

Several formulae are developed by research workers, considering some of these factors in various combinations. The formulae have been developed by co-relating the data collected with the actual evapotronspiration measured by lysimeters. The formulae therefore give weightage to different factors depending on the data available. No formula is universally applicable. While selecting the formula for use the data available and the climatological conditions must be taken into account. The general understanding of the above factors may be useful.

Radiation :

The main source of radiation for our purpose is Sun. The Sun radiates energy in the form of light and heat. The height of atmosphere is about 32 kms. The amount of Radiation reaching this outer atmosphere is known as Extra Terrestrial Radiation and is denoted by Ra This Ra depends upon the distance of the earth from the sun and the location of the point on the earth's surface, where the radiation is being measured. The radiation is therefore dependent only on two factors viz.

- Time of the year (Month)
- Latitude of the place.

This extra terrestrial radiation can be directly measured. Tables showing the values of Ra for different latitudes in each month are available.

All this radiation does not reach the surface of the earth. While travelling through the atmosphere, part of it is absorbed by the atmosphere, and part is scattered. The remaining part reaches the earth and is known as Solar Radiation and is denoted by Rs. This solar radiation is dependent on Ra and cloud cover or the sun shine hours in a day. If the clouds are more, the sun-shine will be for less hours and consequently the portion of Ra reaching the earth will be less, or Rs will be small.

Thus Rs depends upon n/N where

n = Actual sunshine hours in a day

N = Maximum possible sunshine hours in a day.

ahd the relationship is :

$$Rs = Ra\ (0.25 + \frac{n}{N} \times 0.50)$$

Tables showing maximum possible sunshine hours in a day for different lattitudes and months are available.

Again a part of Rs is reflected into the atmosphere by the earth surface. The quantity of reflected radiation depends on the nature of the reflecting surface. The reflection factor varies from 5% to 7% for water surface and about 15 to 25% for cropped soil. For crop water requirement the reflection factor ($\propto$) is assumed to be 0.25 This means that 25% of Rs is reflected back into the atmosphere and only 75% is absorbed by earth. This absorbed quantity of Radiation is known as Net Shortwave Solar Radiation and deneted by Rns, or

$$Rns = (I - \propto)\ Rs.$$

Earth receives short wave as well as long wave raditions and emits long wave radiation. The energy received by earth as long were radiation is small but it emits large amount of long wave radiations. The energy absorbed by earth is the difference between Rns and the long wave radiation by earth Rnl. i. e. The Net Energy absorbed by earth.

$$Rn = Rns - Rnl.$$

The above relationships between these radiations components is schematically represented in figure 16.

The Rnl varies with temperature, sunshine hours and vapour pressure. The Tables showing these variations are prepared and annexed:

$$Rnl = f\ (T) \times f_i\left(\frac{n}{N}\right) \times f\ (ed)$$

A figure showing the various Radiations discussed above is given in figure No. 17.

Various formulae use different radiations levels. Due to the complicated calculations tables are prepared to give the values of radiations at different levels as Table Nos. 14 to 26. The use of these tables is discussed along with each method and solved examples. All the energy of radiation is converted into heat units and then to equivalent evapotranspiration in mm based on the relation that –

1 gram of water at 20° C. requires 590 calories of heat for its evaporation. Since one gram of water has a volume of 1 cubic centimeter, this means that 590 calories evaporate

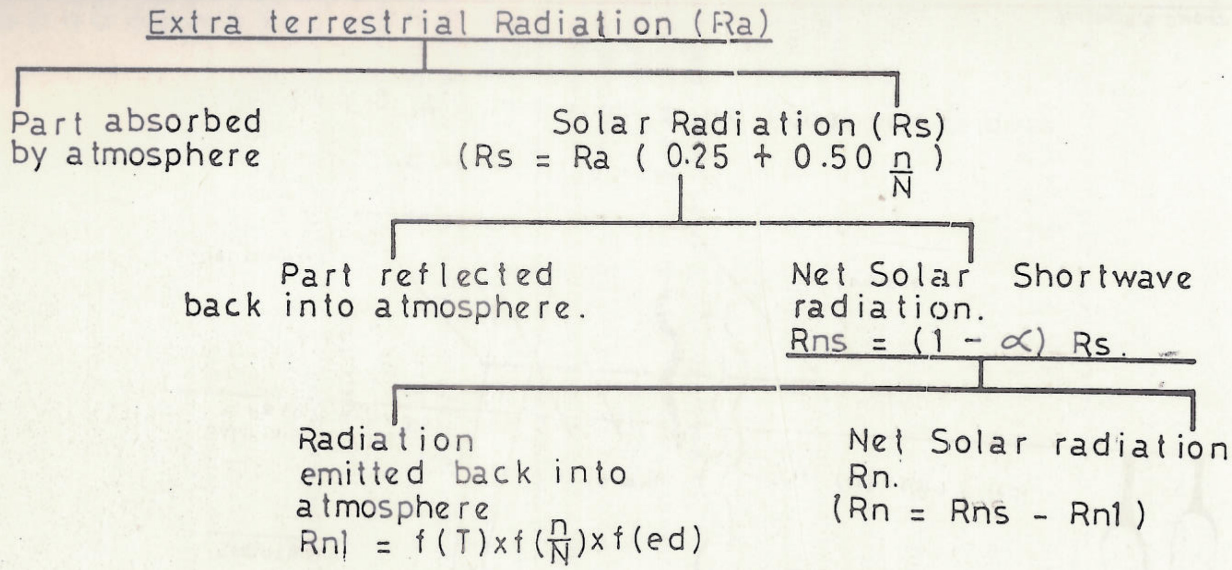

Figure No: 16 Radiations

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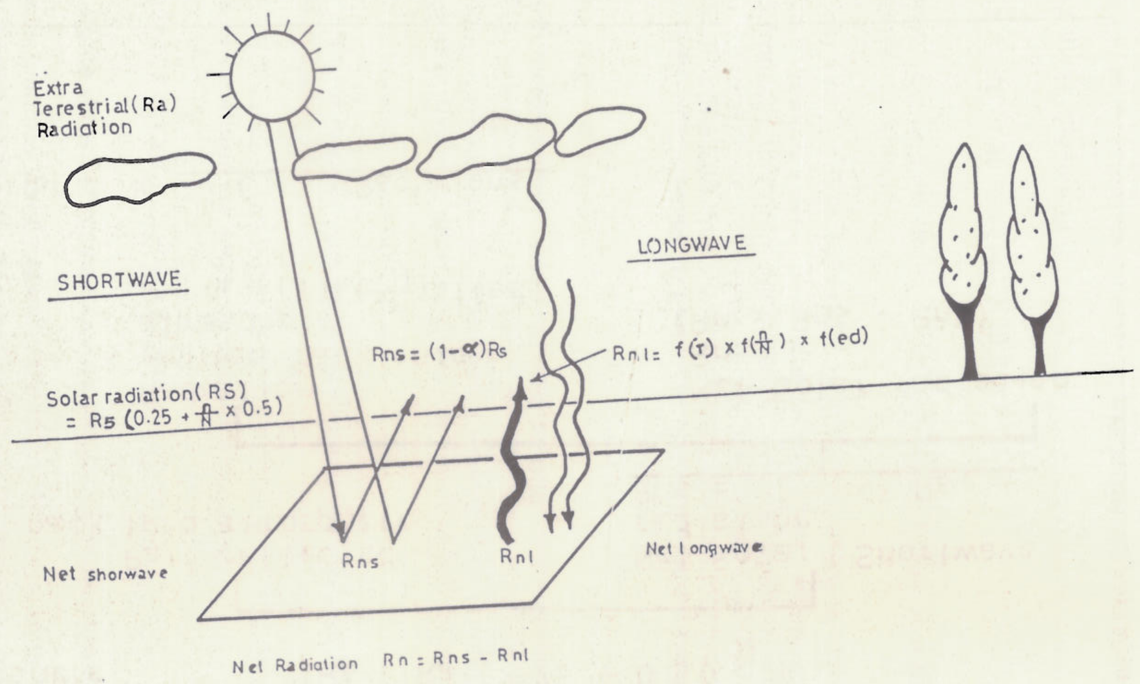


Fig: 17 Illustration of the radiation balance

Trd: by. B.S. Dulguch.

10 mm depth of water from 1 cm^2 area. All tables give the depth of evaporation in mm per day. Since heat is measured in calories per cm^2 the evaporation is 10mm over stretch of land where such climatic conditions occur.

Temperature :

Temperature has a direct effect on the evapotranspiration. As the temperature increases the rate of evapotranspiration increases for the same amount of radiation. Similarly, the long wave radiation which is emitted by the earth also increases with temperature. Besides these direct effects, the temperature variations has indirect effects also. The heat storage capacity of soil is assumed to be 0.5 cal/cm^3 / $^\circ$c. The soil upto 2M depth changes temperature with the air temperature. The soil heat flux in cal/cm^2 /day can be calculated by :

$$G = \frac{T_{i-1} - T_{i+1}}{t} X 100$$

Where T is the mean Air temperature in $^\circ$c for the period i. and t is the time in days between the midpoints of the two periods.

This heat flux indirectly affects the evapotranspiration. Record of maximum and minimum temperature can be easily maintained and is almost invariably available.

Wind Velocity

The effect of wind velocity on evaporation is experienced by us in our daily life also. When washed clothes are hung for drying, the clothes dry faster if wind is blowing. This is a type of evaporation only. The water molecules are held in the clothes by adhesion and cohesion. The outer molecules are wiped away by the blowing wind and this action increases with the increases in wind velocity. Wind acts in a similar way during evapotranspiration also. The wind effect is governed by the wind function f (u)

$$f(u) = 0.27 \left(1 + \frac{u_2}{100}\right)$$

Where u_2 is the wind velocity in kms/day at a height of 2 mtrs.

If wind velocity is measured at heights different than 2 m. the following correction factors are applied.

Table No. 11

Correction factors for wind measurements at different heights :

Measurement height (M)	Correction Factor
0.5	1.35
1.0	1.15
1.5	1.06
2.0	1.00
3.0	0.93
4.0	0.88
5.0	0.85
6.0	0.83

Relative Humidity :

If we take the anology of the drying clothes, it is experienced that the clothes take a longer time to dry in humid atmosphere on a rainy day while they dry in a less time on a dry day. Thus, when the relative humidity is high, the rate of evapotranspiration is low. The evapotraspirantion rate partly varies as the difference between the mean stauration water vapour pressure (e_a) and the actual mean water vapour pressure (e_d).

Air humidity data is reported as relative humidity (RH_{max} and RH_{min} in percentage) and psychometric readings (i. e., $T^{\circ}c$ of dry and wet bulb) or as dewpoint temperature ($T^{\circ}c$ dew point). The tables are given for (e_a) and (e_d) from this data. The vapour pressures in these tables are in m bars. If the data is in mm Hg, it can be converted into m bar by multiplying by 1.33.

The relationship between the evaporation and the difference in vapour pressures and wind velocity has long been established by Dalton (1882) as :

$$E = (e_a - e_d)\ f(u).$$

Where :

E = Evaporation from free water surface.

e_a = Saturation vapour pressures at the temp. of evaporating surface.

e_d = Salturation vapour pressure at dew point temperature.

$f(u)$ = Wind velocity function.

Crop Water Requirement : ET_c :

The crop water requirement for the purpose of the ensuing discussions, is defined as

"The depth of water needed to meet the water loss through evapotranspiration of a disease free crop, growing in large fields under nonrestricting soil conditions, including soil water and fertility and achieving full production potential under the given growing environment."

The crop water requirement will naturally vary from crop to crop and period to period. This crop water requirement is inclusive of all sources of water i. e , precipitation, irrigation, water available from underground water table etc. If net irrigation, requirement is to be computed the water available from other sources, i. e., from rainfall and underground water table has to be deducted from crop water requirement.

The crop water requirement is denoted by ET_c and is usually expressed in mm/day.

Reference crop evapotranspiration (ET_o) :

The effect of climatological factors on crop water requirements are given by reference crop evapotranspiration. It is defined as :

"The rate of evapotranspiration from an extensive surface of 8 to 15 cm tall green grass cover of uniform height, actually growing. completely shading the ground and not short of water."

All the formulae give this ET_o under the defined set of conditions for the reference crop.

Crop co-efficient (Kc) :

The crop water requirement of any crop, in additon to the climatological factors. depends on :

— Crop characteristics
— Stage of growth
— Growing season
— Crop density

The Eto considers all the climate conditions. The factor Kc for each crop for a particular period takes care of the above three factors. The crop water requiremnt ETc is computed by the relationship.

ETc = ETo x Kc

The crop coefficient has to be decided for each crop for every fortnight of its growth period. The procedure to compute Kc is seperately discussed.

Short term and Long term requirements :

When crop water requirement (ETc) is computed for immediate irrigation. the climate data for the previous rotation period can be used for computation. This gives the Evapotranspiration losses in the preceding rotation and these losses can be recouped by way of irrigation. If however, the crop water requirements are required for project planning for a long range, all the available data, preferably for 15 years or more has to be analysed, Usually values for 75% or 80% probability are adopted. This may involve a large volume of computations and the use of computer becomes almost obligatory. Computer programmes are available for this use. (Appendix III of F.A.O. Paper No. 24, 1977).ETo for each fortnight of the data period is separately worked out and the probability for each fortnight of a year is then workedout. Thus if 20 years data is available we can get 20 values of ETo for a particular fortnight say 1st April to 15th April. From this set of 20 values, the probable value of ETo for this fortnight is computed.

Interpretation of Data

Many a times climatological data is not completely available or some parameters are available only in general terms. For example, the relative humidity measurements are not available but the relative humidity is described as high, medium or low. The interpretation of such data is necessary. On the other hand some methods such as rediation method or Blaney criddle method provide graphs which can be used only in these general terms even if precise values of parameters are available. It is therefore necessary to know the ranges within which these general terms are used. Table No. 12 gives the ranges and meanings of the general terms used in climatic data.

Table No. 12

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° C
cool	Tmean < 15° C

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

data collected from max/min thermometer or thermograph records.

HUMIDITY

RHmin, : minimum relative humidity

RHmin is lowest humidity during daytime and is reached usually at 14.00 to 16.00 hrs. It can be read 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.

Blaney-Criddle

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

Crop coeff.

dry	<20%
humid	>70%

RHmean, mean relative humidity

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.

Radiation method

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

Pan method

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

medium-high	55-70%
high	>70%

medium	40-70%
high	>70%

15°c lower than Tmax.

WIND

General

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

For rough estimation purposes sum of several windspeed observations divided by rumber of readings in m/sec or multiplied by 86 4 to give wind run in km/day

With 2 m/sec : wind is felt on face and leaves start to rustle

With 5 m/sec : twigs move, paper blows away, flags fly.

With 8 m/sec : dust rises, small branches move.

With > 8 m/sec : small trees start to move, waves form on inland water etc.

RADIATION

Blancy–Criddle

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

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

n/N > 0.8 : near bright sunshine all day

n/N 0.6 – 0.8 : some 40% of daytime hours full cloudiness or partially clouded for 70% of daytime hours.

or

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

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

4 oktas : 50% of the sky covered all daytime hours by clouds or half of daytime hours the sky is fully clouded

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

Climatological Methods :

A number of climatological methods are available for estimation of crop wate requirements. These methods are mostly empirically derived relationships between ET_o an the climatolocal factors based on data collected from certain weather stations and actu observations of Evapotranspiration under controlled conditions. The weightage given t various factors in different methods vary according to the locations where the methods ar developed and the data available or used. No method can therefore be said to be a perfe method. Each method has its advantages and limitations under a set of csnditions. An method must therefore be used with conscious understanding of the available data, it reliability, and the limitations of the method.

The available major methods alongwith the data used in each method are given in Table No : 13. This is by no means a complete list. It however indicates the range of methods available and the utilisation of the data. It is neither possible nor necessary to discuss all the methods. Only five methods which are widely used and are relevent under Indian conditions are described here. These methods are :

- Blaney Criddle Method
- Radiation Method
- Pan Evaporation Method.
- Modified Pen men Method.
- Hergreaves Method.

Table No. 13

Climatological Methods For Estimation of Evapotranspiration

Method	Tempe-rature	Humidity	Wind	Sunshine hours	Radiation	Evapo-ration	Environ-ments	Rema
Blaney criddle Method	MD	GE	GE	GE	NR	NR	GE	
Radiation Method	MD	GE	GE	MD	IA	NR	GE	
Pan-Evaporation Method	NR	GE	GE	NR	NR	MD	GE	
Modified Pellman Method	MD	MD	MD	MD	IA	NR	GE	
Hargreaves Method	MD	NR	NR	NR	NR	NR	NR	

MD = Measured Data.
G E = General Estimate.
N.R = Not Required.
I A = If Available

Note = Only the methods used under Indian Condition are tabulated.

Table 14

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

Latitude North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
South1/	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60°	.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
58	.16	.21	.26	.32	.37	.40	.39	.34	.28	.23	.18	.15
56	.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
54	.18	.22	.26	.31	.36	.38	.37	.33	.28	.23	.19	.17
52	.19	.22	.27	.31	.35	.37	.36	.33	.28	.24	.20	.17
50	.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
48	.20	.23	.27	.31	.34	.36	.35	.32	.28	.24	.21	.19
46	.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
44	.21	.24	.27	.30	.33	.35	.34	.31	.28	.25	.22	.20
42	.21	.24	.27	.30	.33	.34	.33	.31	.28	.25	.22	.21
40	.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35	.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30	.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25	.24	26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20	.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15	.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10	.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0	.27	.27	.27	.27	.27	.27	.72	.27	.27	.27	.27	.27

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

Table – 15

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

Northern Hemisphere

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

Southern Hemisphere

Lat	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
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
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
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
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
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
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 – 16 Mean Daily Duration of Maximum Possible Sunshine Hours (N) for Different Months and Latitudes

Northern Lats	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.
Southern Lats	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apt.	May	June
50	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	1.6	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 – 17. 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
1000	.46	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.80	.82	.83	.85	.86	.87
2000	.49	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.87	.88
3000	.52	.55	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.81	.82	.84	.85	.86	.88	.88	.89
4000	.55	.58	.61	.64	.66	.69	.71	.73	.76	.78	.79	.81	.83	.84	.85	.86	.88	.89	.90	.90

Table 18. Saturation Vapour Pressure (ea) in mbar as Function of Mean Air Temperature (T) in °C 1/

Tempera-ture °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	.6	8.1	8.7	9.3	10.0	10.7	11.5	1 .3	13.1	14.0	15.0	16.1	17.0	18.2	19.4	20.6*	22.0

Tempera-ture °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.[illegible]	31.7	33.6	35.7	37.8*	40.1	42.4	44.9	47.6	50.3	53.2	56.2	59.4	62.8	66.3	69.9

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

Table 19 A Vapour Pressure (ed) in mbar from Dry and Wet Bulb Temperature Data in °C (Aspirated Psychrometer)

Depression wet bulb T °C altitude 0-1 000m

dry bulb T °C	0	2	4	6	8	10	12	14	16	18	20	22
40	73.8	64.9	56.8	49.2	42.2	35.8	29.8	24.3	19.2	14.4	10.1	6.0
38	66.3	58.1	50.5	43.6	37.1	31.1	25.6	20.5	15.8	11.4	7.3	
36	59.4	51.9	44.9	38.4	32.5	26.9	21.8	17.1	12.7	8.6	4.9	
34	53.2	46.2	39.8	33.8	28.3	23.2	18.4	14.0	10.0	6.2		
32	47.5	41.1	35.1	29.6	24.5	19.8	15.	11.3	7.5	4.0		
30	42.4	36.5	30.9	25.8	21.1	16.7	12.6	8.8	5.3			
28	37.8	32.3	27.2	22.4	18.0	14.0	10.2	6.7	3 4			
26	33.6	28.5	23.8	19.4	15 3	11.5	8.0	4.7	1.6			
24	29.8	25.1	20.7	16.6	12.8	9.3	6.0	2.9				
22	26.4	22.0	18 0	14.2	10.6	7.4	4 3	1.4				
20	23.4	19.3	15.5	12.0	8.7	5 6	2.7					
18	20.6	16.8	13.3	10.0	6.9	4.1	1.4					
16	18.2	14.6	11.4	8.3	5.4	2.7						
14	16.0	12.7	9.6	6.7	4.0	1.5						
12	14 0	10.9	8.1	5.3	2.8							
10	12.3	9.4	6.7	4.1	1.7							
8	10.7	8.0	5 5	3.1	0.8							
6	9.3	6.8	4.4	2.1								
4	8.1	5.7	3.2	1.6								
2	7.1	4.8	2 8	0.8								
0	6.1	4 0	2.0									

Depression wet bulb T °C altitude 1 000-2 000 m

dry bulb T °C	0	2	4	6	8	10	12	14	16	18	20	22
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
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
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
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
32	47.5	41.3	35.5	30.2	25.3	20.7	16.6	12.6	9.1	5.8	2.6	
30	42.4	36.7	31.3	26.4	21.9	17.7	13.8	10 2	6.2	3.8	0.9	
28	37 8	32.5	27.5	23.0	18.9	14.9	11.4	8.0	4.9	2.1		
26	33.6	28.7	24.1	20.0	16.1	12.5	9.2	6.0	3.2	0.5		
24	29.8	25.3	21.1	17.2	10.3	13.9	7.2	4.3	1.6			
22	26 4	22.3	18.3	14 3	11.5	8.3	5.5	2.7	0.2			
20	23.4	19.5	15.9	12.6	9.5	6.6	3.9	1.3				
18	20.6	17.1	13.7	10.6	7.8	5.0	2.5	0.1				
16	18 2	14.9	11.7	8.9	6.2	3.6	1.3					
14	16.0	12 9	10.0	7 3	4.8	2.4	0.3					
12	14 0	11.2	8.4	5.9	3.6	1.4						
10	12.3	9.6	7.0	4.7	2.6	0.4						
8	10.7	8.2	5.8	3.7	1.6							
6	9.3	7.0	4.8	2.7	0.7							
4	8.1	6.0	3.8	1.8								
2	7.1	5 0	2 9	1.0								
0	6.1	4.1	2.1									

Table 19 B 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 000m												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	64.7	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	1.4				26	33.6	28.4	23.7	19.3	15.1	11.4	7.8	4.5	1.4			
29.8	24.8	20.2	15.8	11.8	8.0	4.4	1.1					24	29.8	25.0	20.7	16.5	12.7	9.2	5.8	2.8				
26.4	21.8	17.4	13.4	9.6	6.0	2.7						22	26.4	22.0	17.9	14.1	10.5	7.2	4.1	1.2				
23.4	19.0	15.0	11.2	7.6	4.3	1.1						20	23.4	19.2	15.5	11.9	8.5	5.5	2.5					
20.6	16.6	12.8	9.2	5.9	2.7							18	20.6	16.8	13,3	9.9	6.8	3.9	1.1					
18.2	14.4	10.8	7.5	4.3	1.4							16	18.2	14.6	11.3	8.2	5.2	2.5						
16.0	12.4	9.1	5.9	3.0	0.1							14	16.0	12.6	9.6	6 6	3.8	1.3						
14.0	10.7	7.5	4.6	1.7								12	14.0	10.9	8.0	5.2	2.6	0.3						
12.3	9.1	6.1	3.3	0.7								10	12.3	9.3	6.7	4.0	1.6							
10.7	7.7	4.9	2.3									8	10.7	7.9	5.4	3.0	0.6							
9.3	6.5	3.9	1.5									6	9.3	6.7	4.4	2.0								
8.1	5.5	2.9	0.9									4	8.1	5.7	3.4	1.1								
7.1	4.5	2.3										2	7.1	4.7	2 5	0.3								
6.1	3.7	1.5										0	6.1	3.8	1.7									

Table – 20 Values of wiud Function $f(u) = 0.27 \left[1 + \frac{U_2}{100}\right]$

for wind Run at 2 m height in km / day

Wind km/day	0	10	20	30	40	50	60	70	80	90
	—	.30	.32	.35	.38	.41	.43	.46	.49	.51
100	.54	.57	.59	.62	.65	.67	.70	.73	.76	.78
200	.81	.84	.86	.89	.92	.94	.97	1.00	1.03	1.05
300	1.08	1.11	1.13	1.16	1.19	1.21	1.24	1.27	1.30	1.32
400	1.35	1.38	1,40	1.43	1.46	1.49	1.51	1.54	1.57	1.59
500	1.62	1.65	1.67	1.70	1.73	1.76	1.78	1.81	1.84	1.90
600	1.89	1 92	1.94	1.97	2.00	2.02	2.05	2.08	2.11	2.15
700	2.16	2.19	2 21	2.24	2.27	2.29	2.32	2.35	2.38	2.40
800	2.43	2.46	2 48	2.51	2.54	2 56	2.59	2.62	2.64	2.65
900	2.70									

Table – 21 Values of Weighting Factor (1–W) for the Effect of Wind and Humidity on ETo at Different Temperatures and Altitudes

Temperatuɹe °C	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
(1-W) at altitude m																				
0	0.57	.54	.51	.48	.45	.42	.39	.36	.34	.32	.29	.27	.25	.23	.22	.20	.19	.17	.16	.15
500	.56	.52	.49	.46	.43	.40	.38	.35	.33	.30	.28	.26	.24	.22	.21	.19	.18	.16	.15	.14
1000	.54	.51	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.20	.18	.17	.15	.14	.13
2000	.51	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12
3000	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12	.11
4000	.46	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12	.11	.10

Table : 22 Conversion Factor for Extra-Terrestrial Radiation (Ra) to Net Solar Radiation (Rns) for a Given Reflection ∝ of 0.25 and Different Ratios of Actual to Maximum Sunshine Hours (1− ∝) (0.25+0.50 n/N)

n/N	0.0	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90	.95	1.0
(1- ∝) (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 : 23 Effect of Temperature f(T) on Longwave Radiation (Rnl)

T°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 : 24 Effect of Vapour Pressure f(ed) on Longwave Radiation (Rnl)

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

Table : 25 Effect of the Ratio Actual and Maximum Bright Sunshine Hours f(n/N) on Longwave Radiation (Rnl)

n/N	0	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90	.95	1.0
f(n/N) =0.1 + 0.9 n/N	0.10	.15	.19	.24	.28	.33	.37	.42	.46	.51	.55	.60	.64	.69	.73	.78	.82	.87	.91	.96	1.0

Table 26 : Adjustment Factor (c) in Presented Penman Equation

	RHmax=30%				RHmax=60%				RHmax=90%			
Rs mm/day	3	6	9	12	3	6	9	12	3	6	9	12
Uday m/day	Uday/Unight=4.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.79	.84	.92	.97	.92	.100	1.11	1.19	.99	1.10	1.27	1.32
6	.68	.77	.87	.93	.85	.96	1.11	1.19	.94	1.10	1.26	1.33
9	.55	.65	.78	.90	.76	.88	1.02	1.14	.88	1.01	1.16	1.27
	Uday/Unight = 3.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.76	.81	.88	.94	.87	.96	1.06	1.12	.94	1.04	1.18	1.28
6	.61	.68	.81	.88	.77	.88	1.02	1.10	.86	1.01	1.15	1.22
9	.46	.56	.72	.82	.67	.79	.88	1.05	.78	.92	1.06	1.18
	Uday/Unight = 2.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.69	.76	.85	.92	.83	.91	.99	1.05	.89	.98	1.10	1.14
6	.53	.61	.74	.84	.70	.80	.94	1.02	.79	.92	1.05	1.12
9	.37	.48	.65	.76	.59	.70	.84	.95	.71	.81	.96	1.06
	Uday/Unight = 1.0											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.64	.71	.82	.89	.78	.86	.94	.99	.85	.92	1.01	1.05
6	.43	.53	.68	.79	.62	.70	.84	.93	.72	.82	.95	1.00
9	.27	.41	.59	.70	.50	.60	.75	.87	.62	.72	.87	.96

BLANEY CRIDDLE METHOD

The original Blaney - Criddle equation developed in 1950, gave directly the valu of "Consumptive water use." The equation was :

$$Cu = K \times f = K \left(P \times \frac{T}{100}\right) \text{ mm/day}$$

Where, Cu = Consumptive water use or ETc. mm/day

K = Crop coefficient (empirically determined)

T = Temperature in $^{\circ}$F.

P = Percentage of daylight hours to the annual daylight hours.

It Will be seen from the above quation that the effect of climatic conditions on value of K is not reflected in the relationship. K varies not only with crop but also v climatic conditions. It is therefore more convenient to estimate ETo.

The equation is therefore presented now in the modified form,

$$ETo = C\,P\,(0.46\,T + 8) \text{ mm/day}$$

Where, ETo = Daily reference crop evapotranspiration in mm/ day

C = Adjustment factor depending on RHmin, Sunshine hrs. and day wind estimate.

T = Mean daily Temderature over a month in $^{\circ}$C

P = Mean daily percentage af total annual day time hours.

There are three unknown factors in the right hand side of the equation viz: C, P

The value of T is available as data. P is taken from the Table 14 whicn gives percentage of day time hours to the annual day time hours at different lattitudes for month of the year. From this, the value of –

P (0. 46 T + 8) can be calculated.

Now, C depends on RHmin, day time wind velocity and sunshine hours. Gr are presented to show the value of ETo (duly considering C for different combinati against the value of P (0. 46 T+8). Twenty seven combinations are presented in Figure 18. where ETo is on Y axis and the value of P(0.46 T + 8 is on X axis. The ETo can thus be obtained from these graphs The ETc can be computed from the relationship.

$$ET_c = K \times ET_o$$

Nowmally, the values of wind velocity are avilable for 24 hrs. peirod. These are to be converted into Day velocities. In the absence of any specific data, the 24 hrs. velocity may be multiplied by 1.33 to obtain the day time velocity. For areas with either predominant night or day time wind this factor may vary from 1 to 1.6

The RHmin. referred in the estimation is minimum day time Humidity.

ETc = ETo x Kc where Kc is the crop coefficient. The procedure for determining Kc is discussed in later paragraphs, separately. A solved example will illustrate the procedure. The logical format for the solution is also given alongwith the soved example.

It may be noted that this method is adopted only for **monthly** average of ETo.

Example : Calculate ETo from the following data.

Station = Mahatma Phule Agricultural University, Rahuri.

Latitude = 19^{0} 53′ N.

Altitude = 502 m.

Period = January 1981.

Mean Maximum temperature = 27. 2 °C

Mean minimum Temperature = 11.0 °C

Mean Minimum Relative Humidity = 34%

Day time wind velocity (u_2) = 5.9 Kms/hr.

Mean actual sunshine hours (n) = 9.3

Maximum mean possible sunshine honrs in January = 11.0

Calculations

i) $ETo = C \times P\ (0.46\ T\,^{\circ}C + 8)$

ii) $T\,^{\circ}C = \text{Mean Temperature} = \frac{27.2 + 11}{2} = 19.1\ ^{\circ}C$

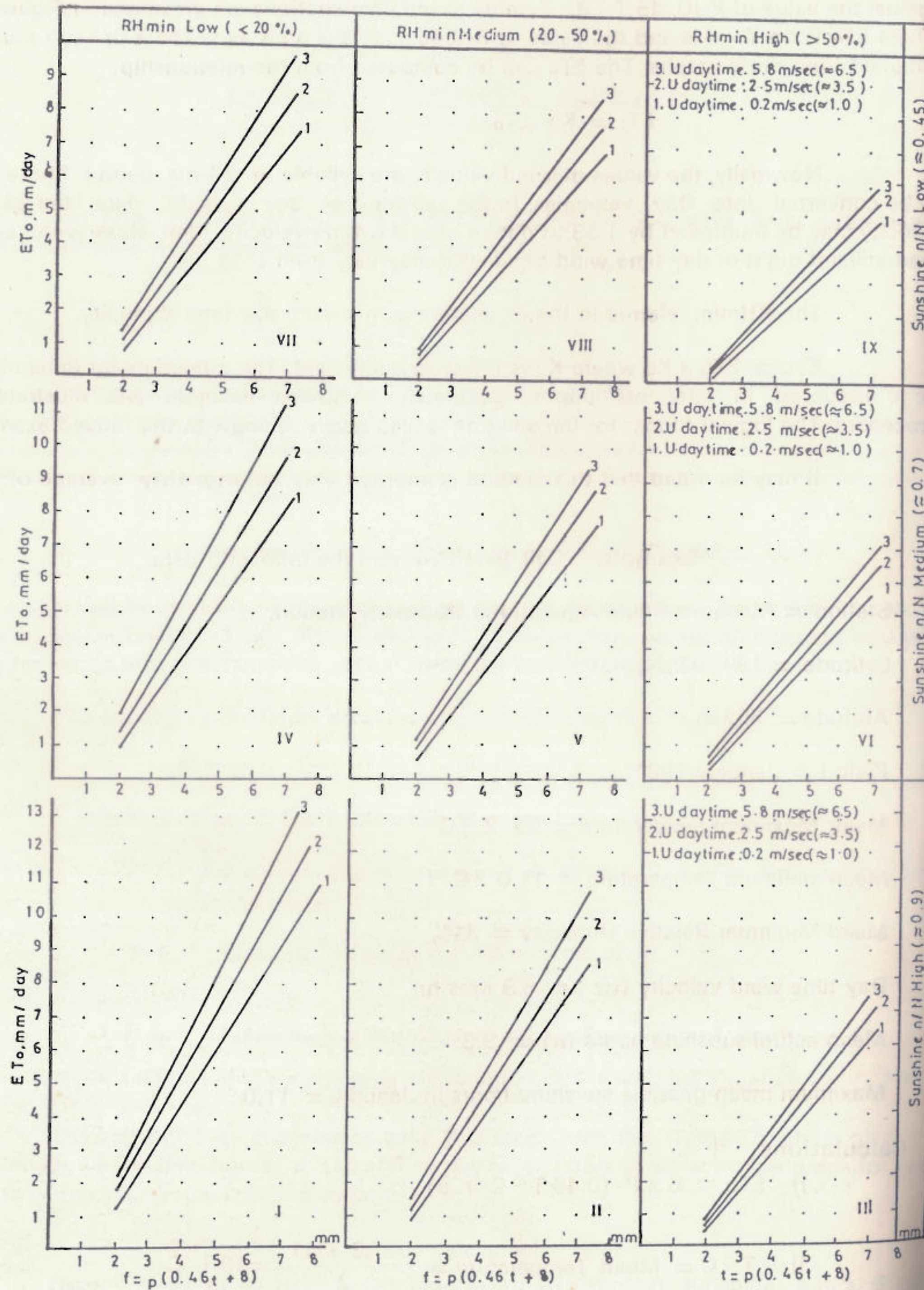
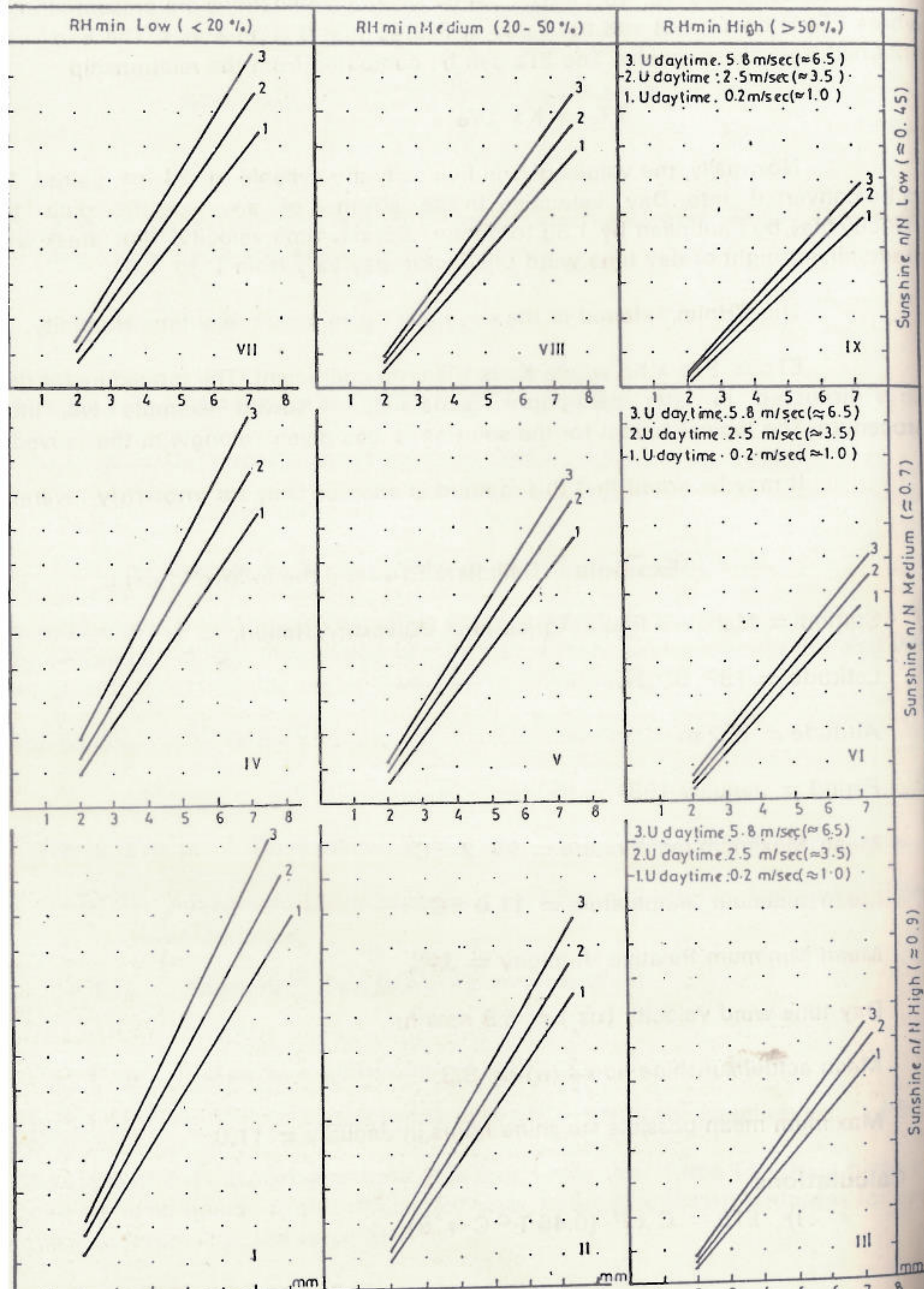


Fig.18 Prediction of ETo from Blaney-Criddle f factor for different conditions of minimum relative humidity, sunshine duration and day time wind.

Trd. by, B.S.Dulguch/ARU



iii) Mean daily percentage of total day time hours P (from table 14 for Lat. 20° N and Month January. = 0.25

iv) $P (0.46 T\,^\circ C + 8) = 0.25 (0.46 \times 19.1 + 8) = 4.196$

v) RHmin is 34% i. e. Medium

vi) $\frac{\text{Mean actual sunshine hours}}{\text{Maximum Possible Sunshine hrs}} = \frac{n}{N}$

$= \frac{9.3}{11.0} = 0.85$ i. e. high.

vii) The graphs consider velocity of wind in Mtrs/Sec. So convert wind velocity of 5.9 Kms./hr into velocity in m/sec.

$= \frac{5.9 \times 1000}{60 \times 60} = 1.64$ m/sec.

viii) The RHmin is medium. So block No. 2 is to be be used. Similarly $\frac{n}{N} = .85$

and hence the block II is to be used. In these three graphs the wind velocity of the Ist line i. e. 0 to 2 mtrs/sec. tallies with the data of 1.64 m/sec. So the graph No. 1 can be used.

The value of ET_o against the value of $P(0.46T\,^\circ C + 8) = 4.19$ on X – axis is 4.00. Therefore, $ET_o = 4$ mm/day.
A format for these calculation is given as Figure No. 19.

Application of Blaney Criddle Method

This method is useful where only the temperature data in precise terms is available and the other parameters can be available in general terms. While this is a great advantage, it also imposes some limitations which must be kept in view.

— Calculation of Mean ET_o (daily) should be made for periods not shorter than a month.

— Crop coefficients should be computed for actual field conditions. Kc values as originally reported are now rejected.

— The method is not very accurate where apart from the temperature, other parameters play an important, role. Such cases are equitorial regions, where temperature remaining the same ...

FORMAT FOR CALCULATIONS

(BLANEY CRIDDLE METHOD)

$$ETo = C \times P\ (0.46\,T^{\circ}C + 8)\ \text{mm/day}.$$

STATION: Rahuri	TALQ Rahuri	DIST: Ahmednagar	LATITUDE: 19° 53′ N ALTITUDE: 502 m
	Period: January 81.		

Requirement	Data	Source or Calculation	
T mean °C	Σ T max Σ T min (Daily for the month) Av. Tmax. 27.2 Av. Tmin. 11.2	$\frac{\Sigma T max + \Sigma T min}{2 \times \text{No. of Days}}$ OR $\frac{Av.\ Tmax. + Av.\ Tmin.}{2}$	19.1
P	Latitude 19° 53′ N. Month January 81	Table No. 14	0.25
P (0.46T + 8)	—	Calculate from P & T mean P (0.46T + 8)	4.196
Estimation of RHmin	RHmin % 34 %	Use Table No. 12	Medium
Estimate $\frac{n}{N}$	Actual Sunshaine hours. 9.3	Table 12 & Table 16	0.85 or High
Daytime wind velocity, m/sec	U_2 (DAY) 1.65	OR Table 12	1.65

FORMAT FOR CALCULATIONS

(BLANEY CRIDDLE METHOD)

$ETo = C \times P\ (0{\cdot}46\,T^{\circ}C + 8)$ mm/day.

STATION: Rahuri TALQ: Rahuri DIST: Ahmednagar LATITUDE: 19° 53' N

Period: January 81. ALTITUDE: 502 m

...ment	Data	Source or Calculation	
°C	Σ Tmax Σ Tmin (Daily for the month) Av. Tmax. 27·2 Av. Tmin. 11·2	(Σ Tmax + Σ T min) / (2 x No. of Days) OR (Av. Tmax. + Av. Tmin.) / 2	19·1
	Latitude 19° 53' N. Month January 81	Table No. 14	0·25
...T + 8)	—	Calculate from P & T mean P(0.46T + 8)	4·196
...on of RHmin	RHmin % 34 %	Use Table No. 12	Medium
n/N	Actual Sunshaine hours. 9·3	Table 12 & Table 16	0·35 or High
wind m/sec	U_2 (DAY) 1·65	OR Table 12	1·65
...day		Figure No. 18 Block 11	4 mm/day

— The methods cannot be used at high altitudes, without corrections factors. This is because the mean temperature is fairly low for cold nights but the radiation levels during day are sufficiently high. The ET_o soould be adjusted 10 percent, downwards for each 1000 m. altitude change above sea level.

— ET_o should be reducd by about 15% for latitudes of 55° or more.

Radiation method

The Radiation method considers the radiation reaching the earth as the major contributing or influence factor for evapotranspiration. The measured data required for this method is air temperature, and sunshine hours. In addition, general levels of humidity and wind velocity are necessary. If the measured data for sunshine hours is not available, the general level of cloudiness can be used, though with somewhat less accuracy. The relationship is is expressed by the equation.

$$ETo = C\ (W \times Rs)\ \text{mm/day}$$

where, ETo = Reference crop evapotranspiration expressed in mm/day

W = Weighing factor depending on temperature and altitude. Table No. 17 provides the values of W for different temperatures and altitudes.

Rs = Solar radiation reaching the earth.

$$= \left(0.25 + 0.50\,\frac{n}{N}\right) Ra$$

(Ra is the extraterrestrial radiation).

C = Adjustment factor depending on humidity and wind velocity in day.

There are only three unknowns in the right hand side of the equation. W can be obtained from the table No. 17 if temperature and altitude is known as data. The value of Rs is available either as measured value or can be computed. Normally, the measured value is not available and Rs has to be computed from –

$$Rs = \left(0.25 + 0.50\,\frac{n}{N}\right) Ra$$

Ra depends only on latitude and period of the year and can be obtained from Table No. 15. If the measurements for n i. e. the sunshine hours are available, Rs can be computed. Values of N i. e. maximum possible sunshie hours are given in Table 16 If however, the general levels or either sunshine or from cloudines, from Table 12. The approximate conversion of cloudiness in oktas or Tenths in given in Table No. 27.

Table No. 27

Indicative Conversion of Cloudiness

Cloudiness (Oktas	0	1	2	3	4	5	6	7		
n/N Ratio	0.95	0.85	0.75	0.65	0.55	0.45	0.35	0.15		
Cloudiness (Tenths)	0	1	2	3	4	5	6	7	8	
n/N Ratio	0.95	0.85	0.80	0.75	0.65	0.55	0.5	0.4	0.3	0.1

When the term (W × Rs) is computed, the value of ET_o can be obtained directly from the set of graphs in Figure No. 20. The adjustment factor C is taken into consideration and graphs are prepared for different levels, of RHmean and wind velocity. Sixteen different combinations are used and the nearest combination to the field conditions can be selected. For the solved example, the same data as in case of Blaney Criddle method is used, so that the results can be compared.

Example : Calculate ET_o in mm/day for the following data

Station	: M. P. A. University Rahuri
Latitude	: 19° 53′ N
Altitude	: 502 m
Period	: January–81
Mean Temperatures	: Max. 27. 2° C Min 11.0° C
Mean RHmin	: 34%
Mean RHmax	: 71 %

Day time wind velocity . 5.9 Kms/hr.
Mean Actual Sunshine hours : 9.3
Max. Possible Sunshine Hours : 11.0

Solution

(i) Ra from Table No. 15 for Latitude 19° 53′ N and month January = 11.2

(ii) $\frac{n}{N} = \frac{9.3}{11}$ = 0.85

(iii) $Rs = \left(0.25 + 0.50 \frac{n}{N}\right) Ra$

$= (0.25 + 0.50 \times 0.85)\ 11.2 = 7.56$

(iv) W from table No. 17 for altitude 502 m and mean temperature $\frac{27.2 + 11}{2}$ = 0.7

(v) W X Rs = 0.70 X 7.56 = 5.2

(xi) RHmax = 71 %

RHmin. = 34%

$RHmean = \frac{71 + 35}{2} = 52.5\%$

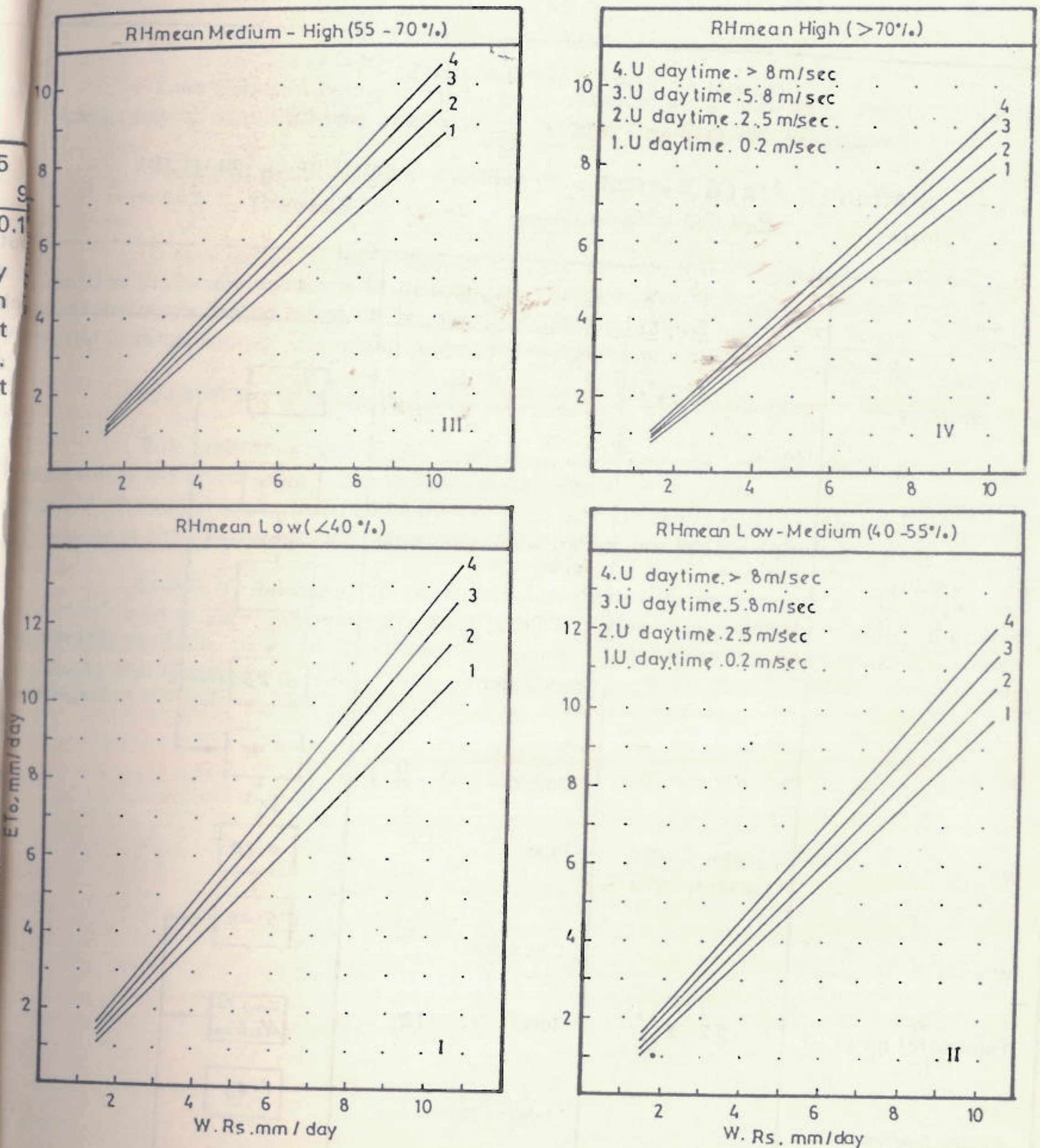


Fig.20 Prediction of ETo from W. RS for different conditions of mean relative humidity and day time wind.

Trd. by. B.S. Dulguch/ ARU.

FORMAT FOR CALCULATIONS.

Radiation Method $ETo = C \times W \times Rs$ mm / day

STATION	TALQ.	DIST.	PERIOD	LATITUDE	ALTITUDE
Rahuri.	Rahuri	Ahmednagar	Jan. 81	19°53' N.	502 m.

Requirement	observed DATA	Source / Calculation	Logic
Ra mm/day	Latitude 19°53' N. Month	Table No. 15	11.2
n hrs/day			9.3 (÷)
N hrs/day	Latitude Month.	Table No.	11.0
$\frac{n}{N}$		Calculation	0.85
Rs		Calculation $Ra(0.25 + 0.50\ \frac{n}{N})$	7.56 (x)
W	T mean 19.1 Altitude 502 m.	Table No. 17	0.70
W x Rs		Calculation	5.29
Estimate RH mean %	52.5%	Table No. 12.	Low To Medium
U_2 day time m/sec		Table No.	1.64
ETo mm/day		Figure No. 20 Block II Line 1	4.20 mm/day

Figure No. 21

Trd. by. B.S. Dulguch/ ARU.

Wind velocity in day time is 5.9 Kms/hr or $\dfrac{5.9 \times 1000}{60 \times 60}$

$\approx$ 1.94 m/ sec.

Thus RHmean is low to medium i. e between 40% and 55%. Hence block for RHmean low to medium and graph No. 1 for velocity 0 to 2 m/sec. is selected.

From this graph, value of ETo for (W $\times$ Rs) = 5. 29 is 4.20 mm day.

Therefore ETo = 4.20 mm/day

It may please be noted that in Radiation method the Mean Relative Humidity is used in the graphs, while in Blaney Criddle method, the minimum Relative Humidity is used. The value of ETo is slightly higher by Radiation method compared to the value by Blaney Criddle method. The useful format for calculations is given as figure No. 21.

Applications and Limitations :

This method is simple in application and can be conveniently used where radiation is the dominating factor in evapotranspiration. It can be used near equatorial regions, in coastal areas, in small islands or high altitude regions. It is somewhat inaccurate in planes in the interior regions, especially if the planes are at low altitudes.

Except for equatoriel zones, climatic conditions for each month or shorter periods vary from year to year. Consequently the ETo also varies. Calculations should therefore preferably be done for each month of each year of record, rather than using the mean radiation and temperature data of the years of record. Also, care must be taken while considering the general levels of Relative Humidity and wind velocity.

MODIFIED PENMAN METHOD

The original Penman Method was developed in England in 1948. It gave value evaporation losses related to Radiation, wind and humidity. A coefficent ranging f 0.6 in winter to 0.8 in summer gave the evapotranspiration of grass which is r the reference crop. The equation consisted of two terms, one the energy or radiation te and the other as aerodynamic term which gave the evaporation due to wind and humid considered together. Since only the Modified from of the equation is now used, the origi equation is not discussed here, However, the equation is given here only for the curio reader :

$$E_o = \frac{\Delta Q_n + \gamma E_a}{\Delta + \gamma} \text{ mm/day}$$

where, E_o = Evaporation from open water surface in mm/day

Δ = Slope of the vapour pressure vs. Temperature curve at the mean air Temper in mm H_g per $^\circ C$

Q_n = Net radiation (mm/day)

γ = Psychrometric Constant.

$E_a = 0.35\ (e_a - e_d)\ (1 + 0.0098\ u_2)$.

Here, $\frac{\Delta Q_n}{\Delta + \gamma}$ is the energy term and

$\frac{\gamma E_a}{\Delta + \gamma}$ is the aerodynamic term.

Under calm weather conditions, the energy term is more important while the aero ynamic terms is relatively more important under windy conditions. The predictions of was satisfactory under calm weather not only in cool humid regions like England but in hot, semi arid regions. Thus, in these regions $ET_o = 0.8\ E_o$. In arid regions, relationship was somewhat erroneous, as the aerodynamic term assumed more importan

A modified form of the method was presented in 1977 by J. Dorrenboss and W. Pruitt which introduced a somewhat simplified form of the equation alongwith correct factor considering day and night weather conditions. This modified form known as' Modif Penman Method (1977)" is now widely used and is discussed here in details. The origi Penman method calculates E_o i. e. evaporation from open water surface while Modif Penman method computes ET_o i. e. reference crop evapotranspiration. The formula giv above, for orginal Penman method has several components which have further relationships with weather parameters. All these have been accomodated in Modified formula. Several Tables are prepared for ease in computations which are referred during disucssions of each factor. The computations are not as difficult as they seem, if done in a systematic manner. Since this method is now widely used in India in general, and in Maharashtra in particular the factors are discussed at length, even at the risk of the discussions being repetitive.

The modified Penmen equation is -

$$ET_o = C\,[\,(W \times Rn) + (1 - W)\,f(u)\,(e_a - e_d)\,]$$

where, ET_o = Reference crap evapotranspiration (mm/day)

C = Adjustment factor for day and night wind velokities and different humidity levels.

W = Weighing factor for altitude and temperature effect on Radiation.

Rn = Net radiation in equivalent evaporation in mm/day.

(1 – W) = Weighing factor for altitude and temperature effect on wind and humidity

f(u) = Wind function or the effect of wind on ET_o, expressed in terms of equivalent evaporation in mm/day.

$(e_a - e_d)$ = Vapour pressure deficit expressed in m bar.

The term "W. R_n" is the radiation contribution to the evapotranspiration and is known as radiation or energy term. The term "(1 – W) f(u) $(e_a - e_d)$" is the cotribution of wind and humidity and is referred to as the aerodynamic term.

Let us examine each factor in the forumla and its significance.

(W) & (1-W) : These are the weightage factors for the Radiation and aerodynamic terms respectively. The original Penman equation is derived in England under calm weather conditions. The radiation term in the original equation was $\frac{\Delta Q_n}{\Delta + \gamma}$ The Q_n is equivolent to R_n in the modified equation and this term is simplified as W. Rn. Simiiarly, the aerodynamic term in the original penman equation was $\frac{\gamma Ea}{\Delta + \gamma}$ or $\frac{\gamma}{\Delta + \gamma}$ is equivalent to (1-W) in the modified equation. Thus, the penman equation engisages the ETo as the weighted average of the radiation term and the aerodynamic term. Δ is the slope of the curve of saturated vapour pressure Vs. Temperature. The curve for this is given as figure No. 22. It will be seen from this graph that the value of Δ increases from 0.50 @ 6°C to about 3 for 40° C.The change in the value of γ is comparatively negligible. Δ also increases with the increase in altitude. W, therefore, increases with increase in temperature and altitude, and approaches 1 though it cannot be equal to 1. This means that the Radiations term assu more and more influence on ETo as the temperature and altitudes increases. For convenie of computations, the values of W and (1-W) are given in Table Nos. 17 and 21 respecti

Adjustment factor C : There is no adjustment factor in the original penman equation. equation, was derived under calm weather conditions where the day and night wind was between 1.5 to 2. and Maximum relative humidity was about 70%. The equation found to predict erratic values where the wind conditions and Maximum Relative humi varied. It was also noticed that the errors were also related to the increases in Rs. Modified equation therefore suggested an adjustment factor for these variations. The mo

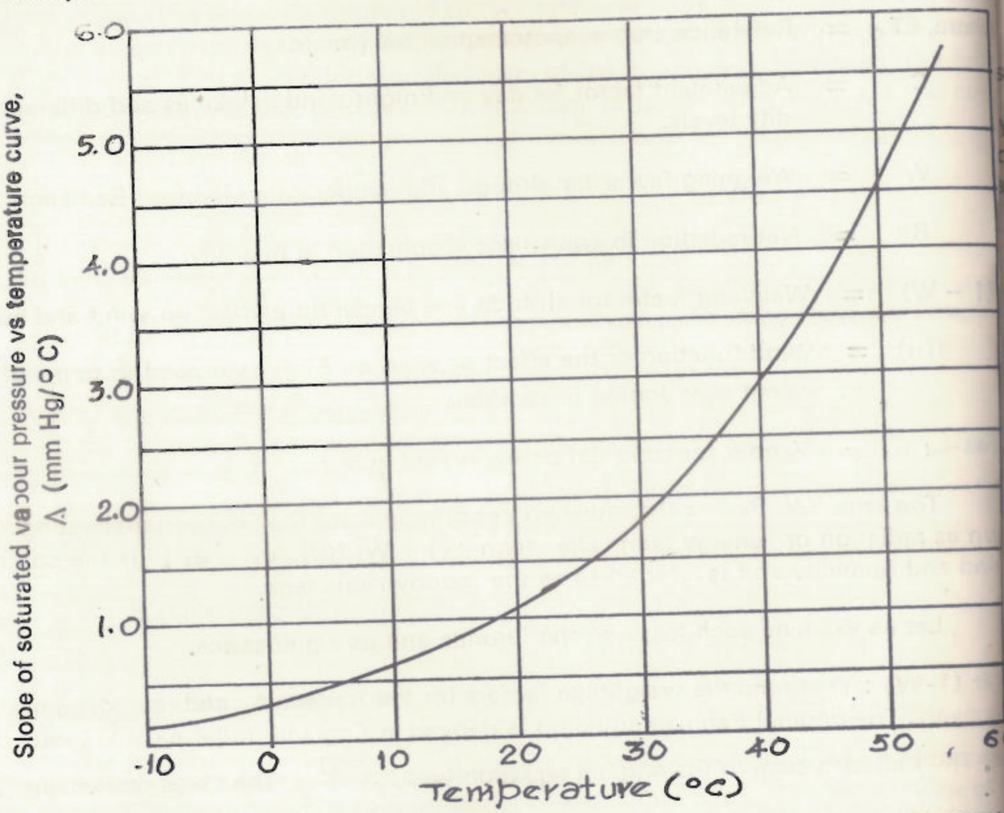


FIG. 22 SLOPE OF SATURATED VAPOUR PRESSURE VS TEMPERATURE CURV

ied Penman considers the average conditions for 24 hrs. Consequently if the wind con ions during day and night vary largely and the RHmax is more or less, than 60% to 7 the results are to be adjusted. Normally, there is underprediction if RHmax is more t 7o% and consequently the adjustment factor is more. Similarly, if the day wind to ni wind ratio is more than 1.5 to 2 or less then 1.5 to 2, the adjustment factor is to be adj ted. The overprediction increses with the decrease in the wind ratio. Four different levels Rs are also considered. The adjustment factors are to correct the over or underpredictions the ETo and are tabulated under table No. 26.

Radiation Term :

Rn : The first or radiation term of Modified Penman equation consists of W X Rn, where W is the weightage factor as explained above and Rn is the Net Radiation at earth surface. The Net Radiation has also been explained in the preceding paras. However, the concept is recapitulated in brief here.

Ra : is the extraterrestial Radiation depending only on latitude and time of the year. The values of Ra are given in table No. 15 for different latitudes and months.

Rs is the part of extraterrestial radiation reaching the earth and - $Rs = \left(0.25+0.50 \frac{n}{N}\right)$ Part of this radiation is reflected back into atmosphere, the quantity reflected being dependent on the nature of surface. The reflection coefficient for cropped soils is 0.25 i. e. 25% of Rs is reflected back into atmosphere. Therefore Net Solar Radiation denoted by :

$$Rns = (1 - \alpha)\ Rs$$

$$= (1 - 0.25)\left(0.25 + 0.50 \frac{n}{N}\right)$$

Table No. 22 provides values of conversion factors for Ra into Rns for different values of $\frac{n}{N}$ ratio. The values of n is obtainded as data while values of N are given in Table No. 16 for different latitudes and months.

Rn = (Rns - Rnl) where Rnl is longwave radiation from earth into the atmosphere. Rnl is dependent on temperature, (Tmean) vapour pressure (e_d) and ratio of actual and maximum possible sunshine hours $\left(\frac{n}{N}\right)$ i. e. $Rnl = f(T) \times f(e_d) \times f\left(\frac{n}{N}\right)$

The values of f(T) for temperatures ranging from o to 36° C are given in Table No. 23.

The values of f (e_d) are given in Table No. 24 for different values of e_d. The e_d can be obtained from Table No. 19 if dry and wet bulb readings are provided as data, and the altitude of the station is known. The procedure is further discussed while explaining the aerodynamic term.

The values of $f\left(\frac{n}{N}\right)$ are given in Table No. 25. The values of Rn can therefore be computed and the Radiation term is (W. Rn)

AERODYNAMIC TERM

The second or aerodynamic term of Modified Penman equation in (1-W) it is th weightage factor and has already been explained. The values of (1-W) can be obtaine directly from Table No. 21 if the mean Temperature and altitude is provided as data·

f (u) is the wind function where,

$$f((u) = 0.27 \left(1 + \frac{u2}{100}\right)$$

U_2 is the wind velocity in Kms/day. It may again be stressed that the modifie penman method uses the mean of 24 hrs. and u_2 is the wind run for 24 hours, at 2 m heig If the velocity is measured at a different height, the corrected value of velocity has to b adopted. The correction factors are given in Table No. 11.

The epxression ($e_a - e_d$) is the vapour pressure difficit i. e. the differen between the saturation vapour pressure and the actual vapour pressure. The staurati vapour pressure e_a is dependent on air Temperature. From the figures of Tmax and Tmi provided as data the mean air temperature Tmean is calculated. Values of e_a against Tme are provided in Table No. 18.

For evaluation of e_d the relative humidity data is required. The data is reported different climatological stations in the following three forms :

i) RHmax and RHmin. in % such as RHmax is 65 % RHmin is 35 %
in this case, the actual vapour pressure

e_d = RHmean x e_a . In the above case,

$$e_d = \frac{65 + 35}{2} \times \frac{1}{100} \times e_a = \frac{50}{100} \times e_a$$

ii) Dry bulb Tempertures in T °C are reported.

In this case the depression of the wet bulb thermometer is the difference the two readings, Values of e_d are available in Table No. 19A for dry bulb reading and w bulb depression. If the readings are from Non ventilated type thermometer. the table No.19 may be used.

iii) In many regions the Relative humidity during night is 100%. In such case the Tmin is approximately equal to T wet, bulb. This is the dew point Temperature and often reported as Tdewpoint. In this case e_d is equal to e_a at Tmin or e_a at Tdewpoint.

The temperatures are in T °C and the values of e_a and e_d are in m bar. the values are given in/mm Hg they may be converted into m bar by applying a conversi factor of 1.33.

Due to the interdependence of the variables used in the equation, the corroct use of units in which the variables are expressed is very important. It is only with the correct use of units that the correct conversion of energy in mm/day of Evapotranspiration is achieved.

It is also convenient to calculate the aerodynamic term first as the same values are again required in computation of the first term. A solved example illustrates the correct use of units and the tables.

Examples :

Calculate ETo from the following data by Modified Penman Method.

Station	:	M.P.A. Universiry, Rahuri
Latitude	:	19° 53′ N., Altitude : 502 m.
Period	:	January 1981.
Mean Maximum Temperature	:	27.2 °C
Mean Minimum Temperature	:	11.0 °C
Relative Humidity (Max)	:	71%
Relative Humidity (Min)	:	34%
Day time wind velocity	:	5.9 Kms/hr.
Day to night time wind ratio	:	1.5 (Assumed).
Mean actual sunshine hours	:	9.3

(The values of RH_{max} and Day to night wind ratio are assumed values for demonstrating the use in computations)

Solutions :

I) **Computation of ($e_a - e_d$)**

i) $T\ mean = \frac{Tmax + Tmin}{2} = \frac{27.2 + 11}{2} = 19.1\ ^\circ C$

ii) e_a (From Table No. 18 for 19.1 °C) is 22 m bar.

iii) $RHmean = \frac{71 + 34}{2} = 52.5\ \%$

iv) $e_d = \frac{ea \times RH\ mean}{100} = \frac{22 \times 52.5}{100} = 11.55$ m bar

v) $(ea - ed) = 22 - 11.55 = 10.45$ m bar

2) **Computation of f (u)**

vi) Day time velocity = 5.9 Km/hr.

Day to Night radio = 1.5

Night time velocity = $\frac{5.9}{1.5}$ = 3.93 Km/hr.

∴ 24 hr. wind run = $\frac{24\ (5.90 + 3.93)}{2}$

$$f(u) = \left(1 + \frac{U_2}{100}\right) = 0.27 \left(1 + \frac{117.96}{100}\right) = 0.51$$

vii) (1 – W) from Table No 21
for Tmean 19.1 and altitude 502 m is 0.315

viii) Aerodynamic term
(1 – W) x f (u) x (ea – ed) = 0.315 x 0.59 x 10.45 = 1.94 mm/day.

3) **Radiation Term :**

xi) Ra from Table No. 15 for Latitude 19°53′ N and month January — 11.1 mm/day

x) N from table No. 16 for Latitude 19°53′ and month January. = 11 hours

xi) n/N = $\frac{9.3}{11}$ = 0.845

xii) Rs = $\left(Ra\ 0.25 + 0.50 \frac{n}{N}\right)$

= 11.1 (0.25 + 0.50 x .845) = 7.46 mm/day.

xiii) Rns = (1—α) Rs = (1—0.25) x 7.46 = 5.595 mm/day.

xiv) f (T) from Table No. 23 for Tmean 19.1 °C is 14.4

xv) f (ed) From Table No. 24 for ed = 11.55 is 0.175

xvi) f $\left(\frac{n}{N}\right)$ from Table No. 25 for $\frac{n}{N}$ is 0.845 or 0.86

xvii) Rnl = f (T) X f (ed) X f $\left(\frac{n}{N}\right)$

= 14 4. X 0.175 X 0.85 = 2.17 mm/day

xviii) Rn = Rns — Rnl = 5.595 — 2.17 = 3.425 mm/day

xix) W from Table No. **17** for Tmean 19.1 and altitude 502 m is 0.685

xx) Radiation Term W. Rn = 0.685 X 3.425 = 2.07 mm/day

xxi) Day time velocity is 5.9 Kms/hr.
or 1.64 m/sec.
Rs = 7.64 mm/day
RHmax = 71% and u day/night = 1.5
Adjustment factor 'C' from Table No. 26 for above values.
Nearest values RHmax is 60%
u day/u night is 2
Average of 0.98 and 0.91 = 0.94

xxii) The ETo = C (W. Rn + (1—W f (u) (ea—ed))
= 0.94 (2.35 + 1.94) = 4.03 mm/day

In above computations. the following points may please be noted :

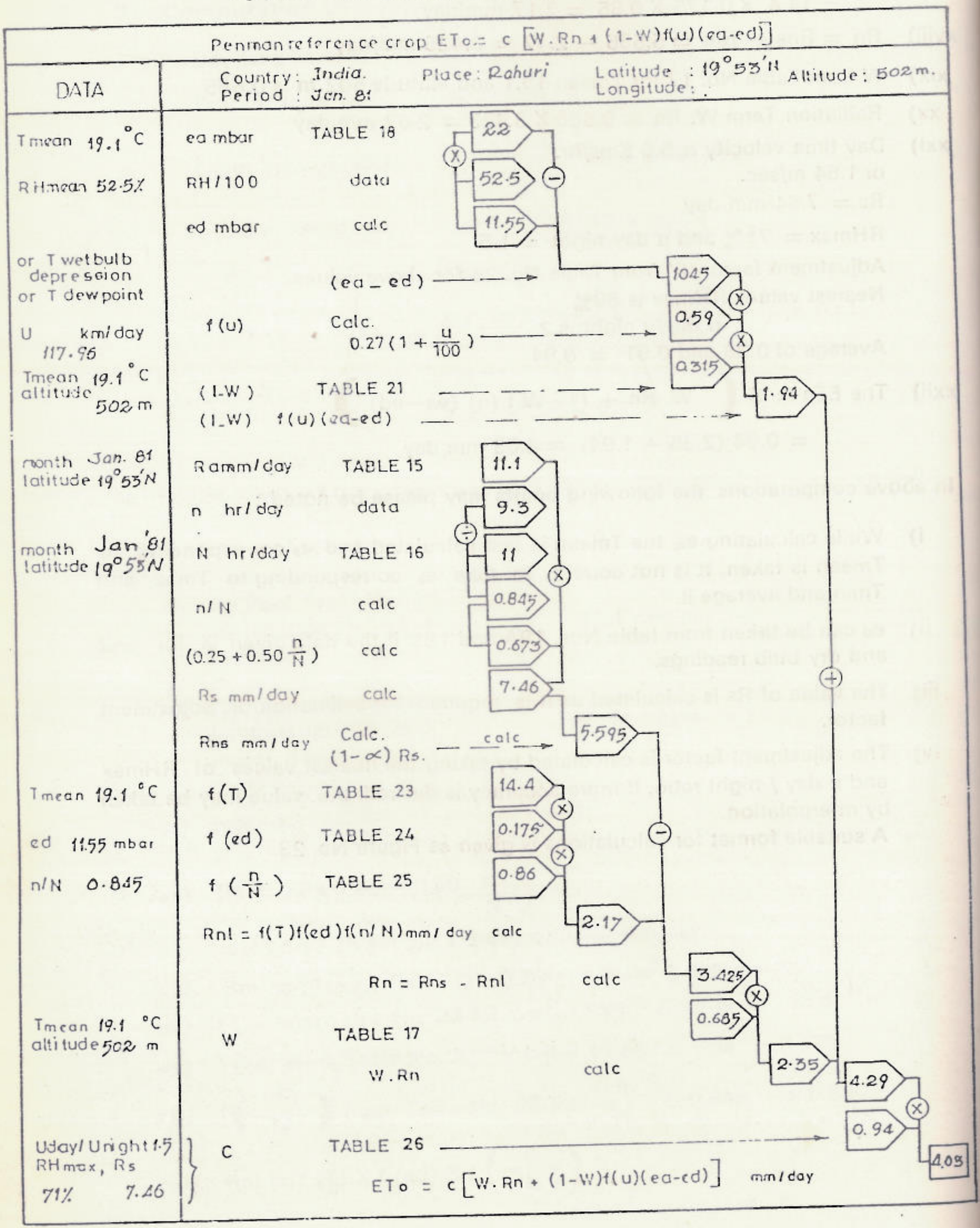
i) While calculating e_a, the Tmean is first calculated and e_a corresponding to Tmean is taken. It is not correct to take e_a corresponding to Tmax and Tmin and average it.

ii) e_d can be taken from table Nos. 19A and 19B if the data given is for wet and dry bulb readings.

iii) The value of Rs is calculated as it is required for estimation of adjustment factor.

iv) The adjustment factor is calculated by taking the nearest values of RHmax and u day / night ratio. If more accuracy is desired, the value may be taken by interpolation.
A suitable format for calculations is given as Figure No. 23

FORMAT FOR CALCULATION OF PENMAN METHOD



When Rs data are available Rns = 0.75 Rs.

FIGURE 23

Trd.by. B.S.Dulguch/ ARU.

HARGREAVE'S METHOD

In 1983, George H. Hargreaves and Zorab A Samani compared Lysimeter ETo data in Haiti with the results obtained from several equations. They have concluded that the results predicted fiom climatological data, limited only to Radiation and Temperature closely approach the ETo given by lysimeters. The original relationship suggested by Hargreaves in 1975 related the ETo to Rs and Temperature.

$$ETo = 0.0075 \times Rs \times T\ °F$$

Where, T °F is the mean air Temperature in degrees Faherenheit, and Rs is the solar radiation reaching the earth expressed in mm/day. ETo is also expressed in mm/day.

However, measured data for Rs is normally not available. Relationship between Ra, (which is almost independent of the variations in climate) and Rs was developed as :

$$Rs = K_t \times Ra \times TD^{0.50}$$

Where, K_t is a coefficient requiring some calibration

Ra is extraterrestrial radiation in mm/day

Rs is solar radiation reaching earth in mm/day

and TD is the difference in mean maximum and mean Minimum Temperatures in °C.

Measured and estimated values were used to calibrate K_t for Africa India, Brazil and U. S. A. The values of K_t are higher near ocean, due to the moderating effect on the temperature range, are approximately the same for plains, plateaus, and large valleys and tend to be low in high mountain valleys.

Combining the above two equations, the equation developed by Hargreaves for universal application is —

$$ETo = 0.0023 \times Ra\ (T\ °C + 17.8) \times TD^{0.50}$$

Where, ETo = Reference Crop evapotranspiration in mm/day.

Ra = Extrateresstrial Radiation in mm/day

T °C = Mean temperature in degrees centigrade

TD = Difference in Maximum and Minimum mean temperature in °C.

The equation is comparatively very simple and requires only the temperature d apart from the latitude. The temperature data is normally available. The equation claims be superior to many other equations at least for interior locations with plain topograp where the growing seasons of the crops are frost free.

A sample calculation with the same data in other is given below for illustratio

Example : Calculate ETo by Hargreaves method for the fol'owing data ;

Station = M. P. A. University, Rahuri.

Latitude = 19° 53′ N. Altitude 502 m.

Mean Max. Temperature = 27.2 °C

Mean Min. Temperature = 11.0 °C

Period = January 1981.

Solution : i) Ra from Table No. 15

for Latitude 19° 53′ N month Janury = 11.1 mm/day

ii) Mean Temperature

$$\frac{27.2 + 11}{2} = 19.1 \text{ °C}$$

ii) $TD = (27.2 - 11) = 16.2$ °C

Therefore,

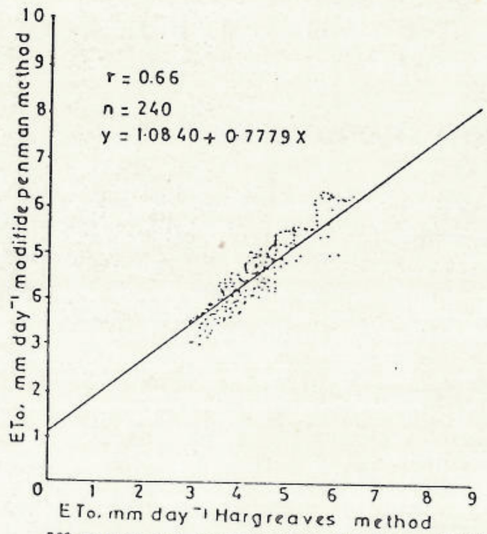
$$ETo = 0.0023 \times Ra\,(T\text{ °C} + 17.8)\; TD^{0.50}$$

$$= 0.0023 \times 11.1\;(19.1 + 17.8) \times 16.2^{0.5}$$

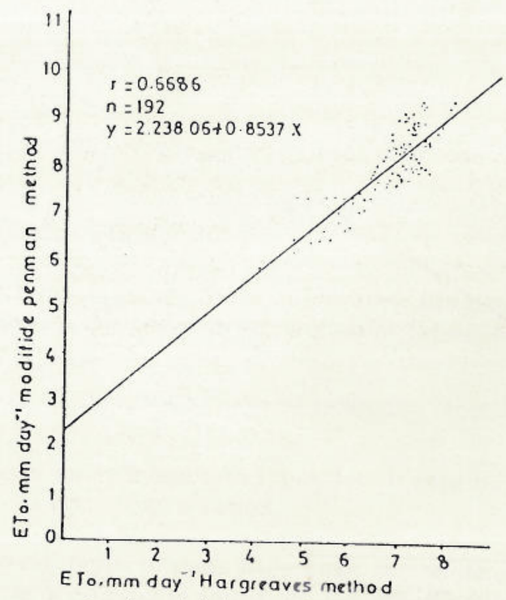
$$= 3.80 \text{ mm/day.}$$

Comparision Betwaen Modified Penman Method and Hargreave's Met

For estimation of crop water requirement, the Modified Penman method is wi used in Maharashtra State. This method requires meteorological data on many wea parameters. This data is many a times not easily available. In Hargreave's method the data required is Temperature data which is usually available for a long period A compar was made between the two methods by M/s. Chhabda, More, Palaskar and Va (Journal of Indian Society of Soil Science Vol. 34-696-700). The data for 24 years in command of Nira Project was analysed and it was concluded that the mean ratios of (Penman) and ETo (Hargreaves) were 1.11, 1.04 and 1.18 for Kharif, Rabi and Weather seasons respectively. The overall mean ratio for the whole analysis was

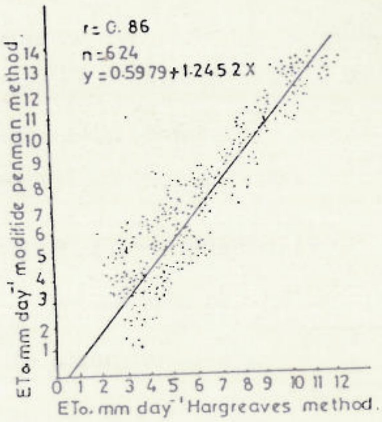


III. Relationship between ETo Penman and ETo Hargreaves for rabi season.

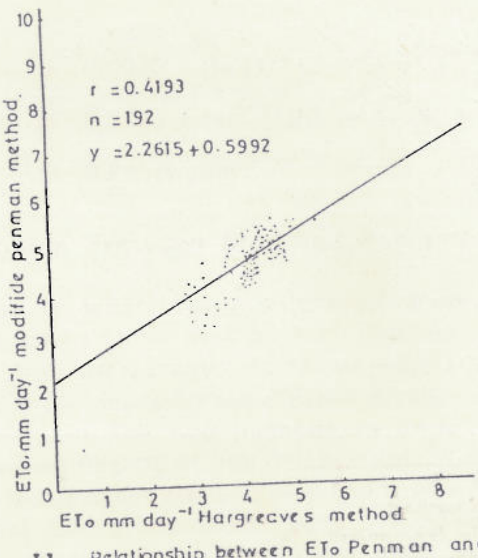


IV. Relationship between ETo Penman and ETo Hargreaves for hot-weather season.

FIGURE : 24.



I. Relationship between ETo Penman and ETo Hargreaves for all season.



II. Relationship between ETo Penman and ETo Hargreaves For Kharif season.

FIGURE : 24 (CONTINUED.)

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Table 28 — Pan Coefficient (Kp) for Class A Pan for Different Groundcover and Levels of Mean Relative Humidity and 24 hour Wind

Class A Pan	Case A : Pan placed in short green cropped area				Case B1 : Pan placed in dry fallow area		
RHmean %		low < 40	medium 40–70	high > 70		low < 40	medium 40–70
Wind km/day	Windward side distance of green crop m				Windward side distance of dry fallow m		
Light <175	1	.55	.65	.75	1	.7	.8
	10	.65	.75	.85	10	.6	.7
	100	.7	.8	.85	100	.55	.65
	1000	.75	.85	.85	1000	.5	.6
Moderate 175-425	1	.5	.6	.65	1	.65	.75
	10	.6	.7	.75	10	.55	.65
	100	.65	.75	.8	100	.5	.6
	1000	.7	.8	.8	1000	.45	.55
Strong 425-700	1	.45	.5	.6	1	.6	.65
	10	.55	.6	.65	10	.5	.55
	100	.6	.65	.7	100	.45	.5
	1000	.65	.7	.75	1000	.5	.45
Very strong > 700	1	.4	.45	.5	1	.5	.6
	10	.45	.55	.6	10	.45	.5
	100	.5	.6	.65	100	.4	.45
	1000	.55	.6	.65	1000	.35	.4

Table 29 — Pan Coefficient (Kp) for Colorado Sunken Pan for Different Groundcover and Levels of Mean Relative Humidity and 24 hour Wind

Sunken Colorado	Case A : Pan placed in short green cropped area				Case B 1/ : Pan placed in dry fallow area			
RHmean %		low <40	medium 40–70	high > 70		low <40	medium 40–70	high > 70
Wind km/day	Windward side distance of green crop m				Windward side distance of dry fallow m			
Light <175	1	.75	.75	.8	1	1.1	1.1	1.1
	10	1.0	1.0	1.0	10	.85	.85	.85
	≥ 100	1.1	1.1	1.1	100	.75	.75	.8
					1000	.7	.7	.75
Moderate 175–425	1	.65	.7	.7	1	.95	.95	.95
	10	.85	.85	.9	10	.75	.75	.75
	≥ 100	.95	.95	.95	100	.65	.65	.7
					1000	.6	.6	.65
Strong 425–700	1	.55	.6	.65	1	.8	.8	.8
	10	.75	.75	.75	10	.65	.65	.65
	≥ 100	.8	.8	.8	100	.55	.6	.65
					1000	.5	.55	.6
Very strong > 700	1	.5	.55	.6	1	.7	.75	.75
	10	.65	.7	.7	10	.55	.6	.65
	≥ 100	0.7	.75	.75	100	.5	.55	.6
					1000	.45	.5	.55

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

Table 30 — Ratios Between Evaporation from Sunken Pans mentioned and F
Colorado Sunken Pan for Different Climatic Conditions and
Environments

Climate		Ratio Epan mentioned and Epan Colorad			
		Humid-temperate climate		Arid to semi- (dry seaso	
Groundcover surrounding Pan (50 m or more)	Pan area m²	Short green cover	Dry fallow	Short green cover	Dry
CGI 20 dia. 5 m, depth 2 m (USSR)	20	1.0	1.1	1.05	1
Sunken Pan dia. 12 ft, depth 3.3 ft. (Israel)	10.5				
Symmons pan 6 ft², 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, debth 3 ft	0.7		1.0		
Aslyng Pan 0.33 m², depth 1 m (Denmark)	0.3			1.0	
CGI 3000 dia. 61.8 cm, depth 60-80 cm (USSR)	0.3				
Sunken Pan dia. 50 cm, depth 25 cm (Netherlands)	0.2	1.0	.95	1.0	

EXAMPLE : CGI 20 in semi-arid climate, dry season, placed in dry fallow land : for given month Epan CGI 20 = 8 mm/day.
Corresponding Epan sunken Colorado is 1, 25 x 8 = 10 mm/day.

U. S. Class A Pan :

This is a circular pan 121 cm in diameter and 25.5 cm deep. It is made of galvanised iron sheet of 22 guage or monel metal 0.8 mm thick sheet. The pan is mounted on a wooden open frame platform with its bottom 15 cm above ground level. The soil is built up within 5 cm of the bottom of the pan. The pan must be level. It is filled with water 5 cm below the rim. The water level is not allowed to drop below 7.5cm from the rim. Water is regularly renewed to eliminate turbidity. The pan if galvanised is painted annually with alluminium, paint. The dimensions mentioned are internal dimensions of the pan. The area of water surface is 1.1499 sq. mtr.

Sunken Colorado Pan :

The pan is 92 cm square and 46 cm deep made of galvanised iron sheet 22 guage. It is set in the ground with its rim 5 cm above the ground level. The water level in the pan is maintained 5 cm below the rim i.e. nearly at the ground level. It is claimed that this pan readings give a closer prediction of the evapotranspiration of grass, than other pans.

The pans are normally placed in green cropped areas and two cases may arise when (i) wind flows first over the dry surface and then over green crop, then over the pan and (ii) when wind flows first over the green crop then over dry sur-face and then over the pan. The K_p values for both these casess are different. The situations are illustrated in figure No. 25. The K_p values for both these cases for class A pan are given in Table No. 28. The values of K_p for Sunken Colorado Pan for similar cases are given in Table No. 29.

Table No. 30 provides relations of evaporation from different standard pans to the evaporation in sunken Colorado pan. The use of the tables and the formula is simple and needs no elaboration.

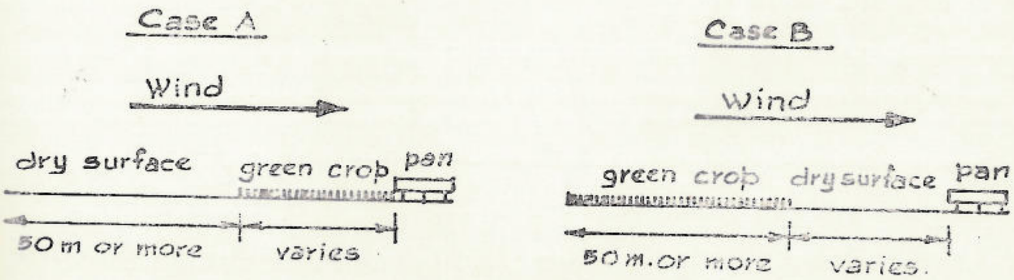


FIGURE No. 25

Additional Considerations :

The values given in the table are for semi arid or arid climates excluding rainy periods. These values are to be reduced by about 20% where the pan is placed in areas of extensive bare soils, and windy climate. Where the levels of wind, temperature and

relative humidity are moderate, the values may be reduced by 5 to 10%. No reduction i
needed in humid cool conditions.

when pan is placed in a small enclosure surrounded by tall crop of 2.5 m the K values need to be increased by 25 to 30 % for dry windy climates and by about 5 to 10% for calm humid conditions. The pans are painted with aluminium paint. An increase of upt 10% is observed when the pan is painted black. So the pans should be painted invariabl in white. Screens mounted over the pan reduce Ep. Values by about 10%. A seperate pa filled with water upto brim may be placed near the evaporation pan for birds. Normally bird prefer to drink from the pan filled upto the brim.

Comparision of pan-evaporation method and modified penman method

Pan-evaporation readings can be easily obtained as compared to other climat data readings. Attempts have been made to corelate the ETo values obtainned by Pan-eva poration method to the ETo values obtained by Modifed Penman method. Results of on such attempt by M/s. M. S. Palaskar, S. D. More and Dr. S. B. Varade show that the valu of ETo obtained by both methods tally closely. A table showing the ETo values by Modifie Penman method and ETo values by Pan-evaporation method for 14 years data at Padegac is given in Table No. 31. A corelation graph is given as figure No. 26. The relation est blished is expressed as –

$$\text{ETo by modified Penman} = 0.8828 + 0\ 9099 \text{ ETo (Pan)}.$$

Though the data base is not wide enough to take this as a standard relation, it c be safely assumed that the values predicted by both the methods agree very closely in se arid regions, with flat topography.

(Ref. Indian Journal of Agricultural Sciences 57 (3) (169-75) March 1987)

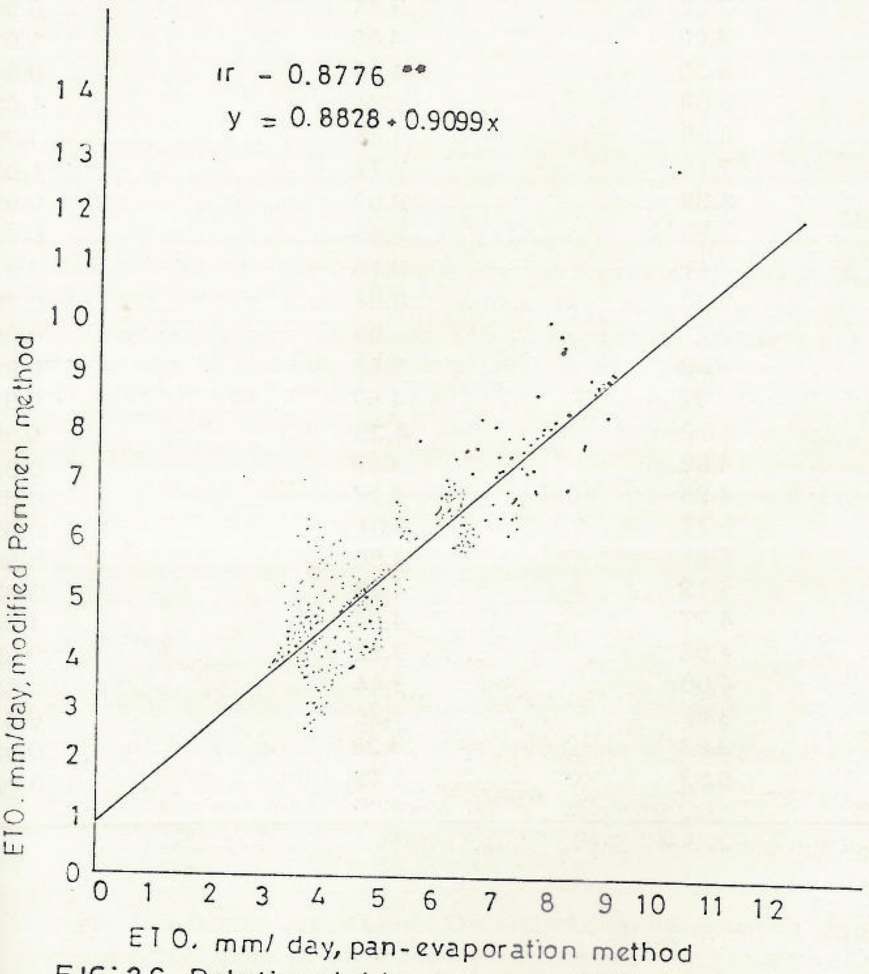


FIG: 26 Relationalship between ETO by Pan Evaporation method and modified Penman method.

Ird: B.S. Dulguch/A.R.U.

Table : 31 Seventy five per cent dependable values of reference crop evapotranspiration as estimated by pan-evaporation and modified Penman methods.

Month & half monthly period.		Modified Penman method (ETo Penman)	Pan-evaporation method (ETo Pan)	ETo pan/ ETo Penma ratio
Jan	I	3.82	3.44	0.90
	II	4.00	4.08	1.02
Feb	I	5.30	4.96	0.94
	II	5.69	5.84	1.03
Mar	I	6.50	6.88	1.06
	II	7.15	7.77	1.09
Apr	I	8.38	8.02	0.96
	II	9.03	8.55	0.95
May	I	9.41	9.15	0.97
	II	9.80	8.64	0.88
Jun	I	7.71	6.90	0.90
	II	6.59	5.57	0.85
Jul	I	4.97	4.57	0.92
	II	5 12	4.35	0.85
Aug	I	4.88	3.99	0.82
	II	4.95	4.27	0.86
Sep	I	5.27	5.01	0.95
	II	5.61	4.50	0.80
Oct	I	5.19	4.76	0.92
	II	4.77	4.96	1.04
Nov	I	4.62	3.92	0.85
	II	4.00	3.44	0.86
Dec	I	3.66	3.20	0.87
	II	3.58	3.28	0.92
Mean		5.83	5.42	0.92

CROP COEFFICIENT (Kc)

All the climatological methods discussed above, predict the value of ETo i. e. the evapotranspiration of reference crop per day. The evapotranspiration of any crop is related to the ETo by-

$$ETc = K_c \times ETo$$

Where, ETc is the evapotranspiration of crop in mm/day and Kc is the crop coefficient.

The crop coefficient varies according to crop characteristics, dates of planting, stage of growth and climatic conditions. The wide variation in the crop coefficients are due to resistance of different crops to transpiration, such as closing of stomatas during day (pineapple), Waxy leaves (Citrus) etc. Difference in crop heights, crop roughness, reflection from water and soil, canopy cover can also be reasons for difference in crop coefficients. The same crop planted in different seasons can have different growth periods and different crop coefficient in the growth period, as the rate of crop growth is different The frequency of availability of water either due to rains or due to irrigation also affects the crop coefficients especially in the early growth period. Figure No. 27 shows Kc values of sugarbeet for differ ent sowing dates. It may be noted that the growth period is different for the three seasons.

The crop coefficient of the crop is therefore to be decided for a particular set of conditions of sowing date etc. The procedure as per F. A. O. paper No. 24 is given below.

The crop coefficients are dependent on the stage of growth and the rate of growth of the crop. The growth period is therefore divided into four stages.

i) Initial Stage : Germination period and early growth of the crop when the soil cover by the crop is less than 10 %

ii) Crop Development Stage : The end of initial stage till the soil cover by the crop is about 70 to 80 %

iii) Mid Season Stage : From the end of crop development stage to the start of maturing, which is indicated by discolouring of leaves or falling off of the leaves. For most crops this may extend well past the flowering stage.

iv) Late Season Stage : From end of mid season stage to the full maturity or harvesting.

The period of these stages depend not only on the crop characteristics and soil, but also on the sowing dates. The stages are therefore, to be determined by local observa-

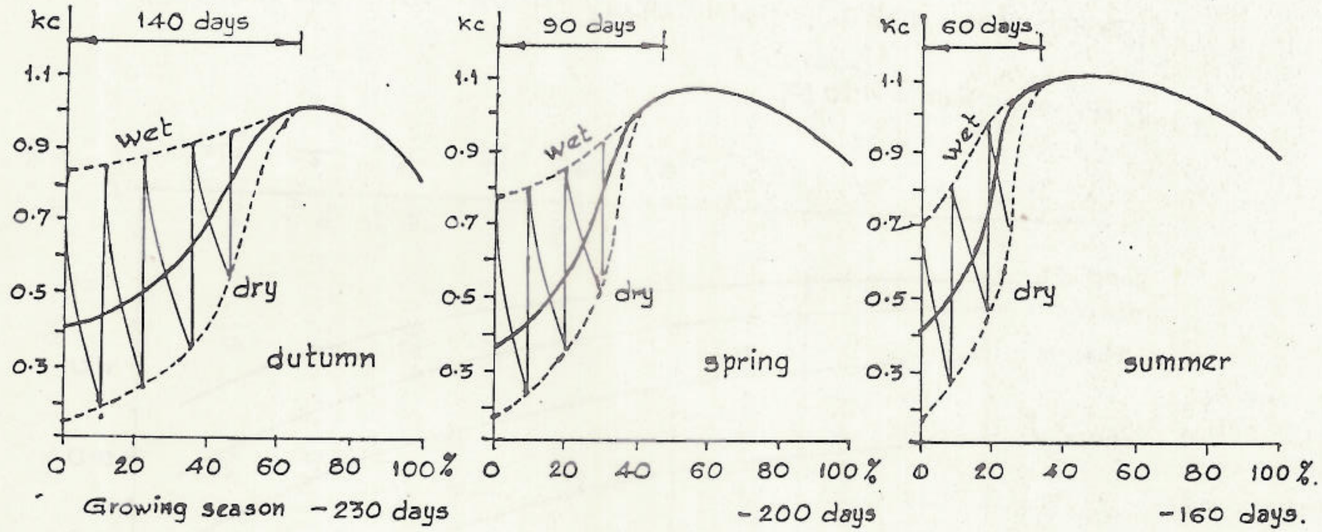


FIG.27. SUGARBEETS; kc VALUES FOR DIFFERENT SOWING DATES.

MML.

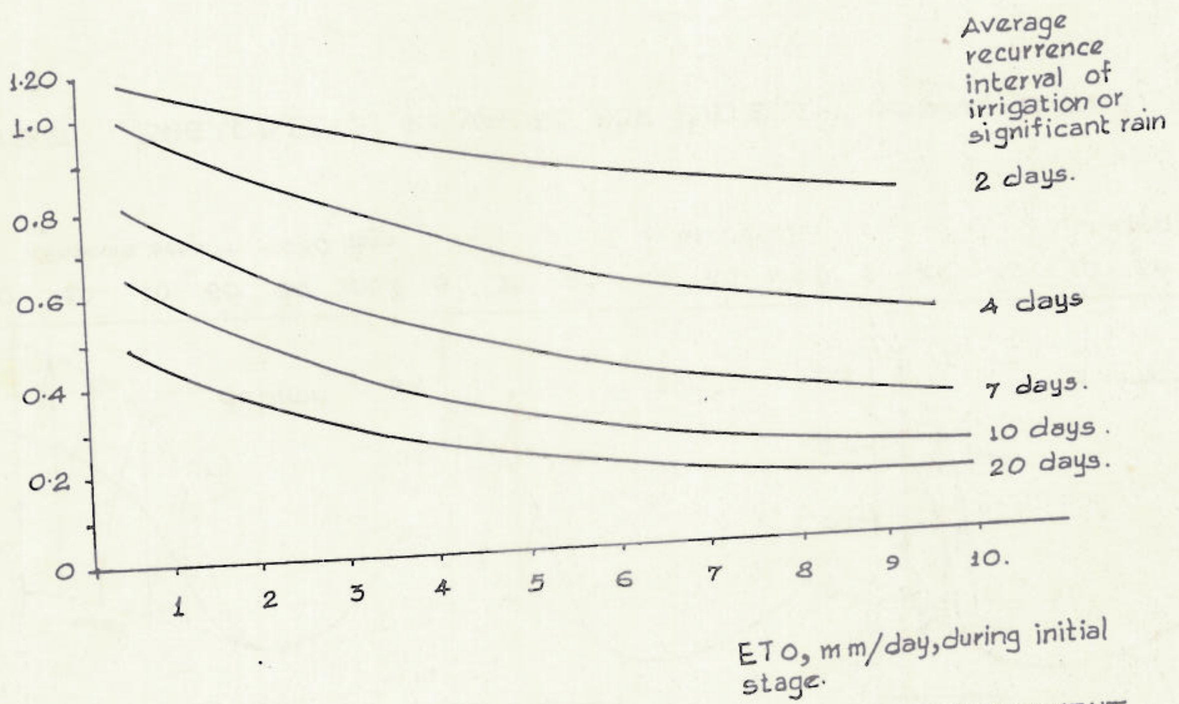


FIG.28. AVERAGE Kc VALUE FOR INITIAL CROP DEVELOPMENT STAGE AS RELATED TO LEVEL OF ETo AND FREQUENCY OF IRRIGATION AND/OR SIGNIFICANT RAIN.

MML.

Rabi Crops :							
1.	Wheat	1-30 Nov	15	25	50	30	120
2.	Jowar local	1 Sept 15 Oct	20	35	50	30	135
3.	Jowar hybrid	16 Sept 15 Oct	15	25	40	25	105
4.	Jowar Ratoon	16 Oct 15 Nov	10	20	35	25	90
5.	Maize	1-15 Oct	20	30	40	30	120
6.	Gram	16 Oct 15 Nov	20	25	30	30	105
7.	Safflower	16 Sept 15 Oct	20	30	45	25	120
8.	Potatoes	1-15 Nov	20	20	30	20	90
9.	Onions	1-15 Nov	15	25	40	25	105
10.	Vegetables	1-15 Nov	20	30	40	15	105
11.	Sunflower	1-30 Nov	15 to 20	20 to 30	30 to 40	25 to 30	90 to 120
Hot weather crops :							
1.	Ground nut	16 Jan 15 Fab	20	30	45	25	120
2.	Jowar Fodder	16 Fab 15 Mar	15	25	50	—	90
3.	Mung	16 Fab 30 Mar	10	15	20	15	60
Two Seasonal crops :							
1.	Cotton L. S.	1-30 May	30	50	60	55	195
2.	Chillies	1-15 Jan	30	40	50	30	150
3.	Turmeric	16-30 May	30	40	115	40	225
4.	Ginger	16-30 May	30	40	115	40	225
Perenial Crops :							
1.	Sugarcane	1-15 Jan	—	—	—	—	365
2.	Banana	1-15 July	—	—	—	—	450
3.	Oranges	1-15 Jan	—	—	—	—	365
4.	Lucerne	1-15 Jan	—	—	—	—	265

Table 33

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

ETo mm/day during initial stage	Frequency of irrigation/significant rain during initial stage 2 days	4	7	10	14	20
1.00	1.05	0.95	0.76	0.60	0.54	0.45
2.00	1.00	0.87	0.66	0.51	0.45	0.37
2.25	0.99	0.85	0.64	0.48	0.43	0.35
2.50	0.98	0.83	0.61	0.46	0.41	0.34
2.75	0.97	0.81	0.69	0.44	0.39	0.32
3.00	0.95	0.79	0.58	0.42	0.38	0.31
3.25	0.94	0.78	0.56	0.41	0.36	0.29
3.50	0.93	0.76	0.54	0.32	0.35	0.28
3.75	0.92	0.74	0.53	0.38	0.34	0.27
4.00	0.91	0.72	0.51	0.36	0.32	0.26
4.25	0.90	0.71	0.49	0.35	0.31	0.25
4.50	0.89	0.69	0.48	0.34	0.30	0.24
4.75	0.88	0.68	0.47	0.33	0.29	0.23
5.00	0.87	0.66	0.46	0.32	0.28	0.21
5.25	0.87	0.64	0.45	0.31	0.27	0.21
5.50	0.86	0.63	0.44	0.30	0.26	0.21
5.75	0.86	0.63	0.43	0.29	0.25	0.20
6.00	0.85	0.61	0.42	0.28	0.25	0.19
6.25	0.84	0.66	0.41	0.28	0.24	0.18
6.50	0.84	0.59	0.40	0.27	0.23	0.18
6.75	0.83	0.58	0.39	0.26	0.23	0.18
7.00	0.82	0.57	0.39	0.26	0.23	0.18
7.25	0.82	0.57	0.38	0.25	0.22	0.17
7.50	0.81	0.56	0.37	0.24	0.21	0.17
7.75	0.81	0.55	0.37	0.24	0.21	0.17
8.00	0.80	0.54	0.36	0.23	0.20	0.16
8.25	0.80	0.54	0.35	0.23	0.20	0.16
8.50	0.79	0.53	0.35	0.22	0.20	0.16
8.75	0.79	0.53	0.34	0.22	0.19	0.15
9.00	0.78	0.52	0.34	0.22	0.19	0.15
9.25	0.78	0.52	0.30	0.21	0.19	0.15
9.50	0.78	0.50	0.33	0.21	0.18	0.15
9.75	0.78	0.50	0.32	0.21	0.18	0.15
10.00	0.78	0.50	0.32	0.21	0.18	0.15

Kc values during the crop development stage :

The Kc value during this stage always varies with time, and reaches a stable value when it approaches the mid season stage. For any particular period it has to be interpolated from the Kc value of initial stage and the mid season stage.

Kc value during the midseason stage :

During this stage the transpiration by the crop and the evaporation from the soil both play an equal role on the Kc value. The Kc value is dependent on wind velocity and Humidity. A table showing the Kc values for different crops and for different wind and humidity conditions is given as table 34. The midseason value is almost constant for the stage.

Kc values for late season or maturity stage :

The Kc value decreases from the midseason stage to the end of the late season. The minimum values are again listed in the above table (No. 34) for various crops for different wind and humidity conditions.

Thus we can get three values of Kc, One from the graphs in the figure No. 28 or table No. 33 for the initial stage, one value from Table No. 34 for midseason stage and one value from the same table as the minimum value for late season stage. These values can be plotted with period on X-axis. For the initial stage the graph is a straight line parallel to the X-axis, Y being the Kc value of initial growth stage. The second part of the graph is the straight line joining the Kc value at the end of initial stage and the Kc value during the midseason stage. This line indicates the increasing Kc values during the crop development stage. The third part of the graph is again a straight line parallel to X-axis Y being the Kc value during the midseason stage. This indicates that the Kc value is almost constant during this stage.

The fourth section is a straight line from the midseason Kc value to the minimum Kc values at harvest indicating decreasing Kc values during the late season stage. A smooth curve is drawn to represent the Kc values during the whole period. A typical case study shows the procedure followed.

Table – 34

Crop Coefficient (kc) for field and Vegetable crops for Different Stages of Crop Growth and Prevailing Climatic Conditions :

Crop	Humidity / Wind (m/Sec)	Crop stage	RH min > 70%, 0-5	RH min > 70%, 5-8	RH min < 20%, 0–5	RH min < 20%, 5–8
All field crops	Crop stage : initial	1	Use Fig. 1			
	crop development	2	by interpolation			
Barley	mid season	3	1.05	1.1	1.15	1.2
	at harvest or maturity	4	.25	.25	.2	.2
Brinjal		3	.95	1.0	1.05	1.1
		4	.8	.85	.85	.9
Carrots		3	1.0	1.05	1.1	1.15
		4	.7	.75	.8	.85
Castor		3	1.05	1.1	1.15	1.2
		4	.5	.5	.5	.5
Chillies		3	.95	1.0	1.05	1.1
		4	.8	.85	.85	.9
Corn (Fodder) (maize)		3	1.05	1.1	1.15	1.2
		4	0.95	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)		3	.95	1.00	1.05	1.1
		4	.80	.85	.9	.95
Cucumber (Fresh)		3	.9	.9	.95	1.0
		4	.7	.7	.75	.8
Groundnut		3	.95	1.0	1.05	1.1
		4	.55	.55	.6	.6
Lentil		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25

Linseed	3	1.0	1.05	1.1	1.15
	4	.25	.25	.2	.2
Melons	3	.95	.95	1.0	1.05
	4	.65	.65	.75	.75
Millet	3	1.0	1.05	1.1	1.15
	4	0.3	0.3	0.25	0.25
Oats	3	1.05	1.1	1.15	1.2
	4	0.25	0.25	.2	.2
Onion (dry)	3	.95	.95	1.05	1.1
	4	.75	.75	.8	.85
Onion (Green)	3	.95	.95	1.0	1.05
	4	.95	.95	1.0	1.05
Peas	3	1.05	1.1	1.15	1.2
	4	.95	1.0	1.05	1.1
Potato	3	1.05	1.1	1.15	1.2
	4	.7	.7	.75	.75
Pulses	3	1.05	1.1	1.15	1.2
	4	0.3	0.3	.25	.25
Radish	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
Soyabean	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
Sugar beet	3	1.05	1.1	1.15	1.2
	4	.9	.95	1.0	1.0
no irrigation last month	4	.6	.6	.6	.6

Sunflower	3	1.05	1.1	1.15	1.2
	4	.4	.4	.35	.35
Tomato	3	1.05	1.1	1.2	1.25
	4	.6	.6	.65	.65
Wheat	3	1.05	1.1	1.1	1.2
	4	.25	.25	.2	.2

Example : Plot a graph for Kc values vs. period for wheat. The data is :

Sowing date	: 1st November	
Growth stages	: Ist Stage	: 15 days
	: IInd Stage	: 25 days
	: IIIrd Stage	: 50 days
	; IVth Stage	; 30 days
	Total :	120 days
Wind velocity	: 2 m/sec.	
Relative Humidity (minimum)	: 34%	
Irrigation interval ;	14 days.	
ET_o in intial stage	; 5.5 mm/day	

Solution :

(i) For the Kc value during initial stage we require information on two points viz; ET_o during the period and the irrigation interval. The ET_o calculated by any of the climatological methods described above can be used. In this case the ET_o is 5.5 mm/day. Now refer figure 28. The graphs are given for irrigation interval of 10 days and 20 days. For 10 days interval the Kc value for 5.5 mm/day is 0.3 while for 20 days it is 0.21, Therefore, for 14 days interval the value is 0.26. Thus for the first 15 days the Kc value is 0.26.

ii) For the midseason Kc value, refer table 34. For wheat, for wind velocity of 0 to 5 m/sec, the Kc values are 1.05 for RHmin 70% and 1.15 for RHmin 20. RHmin as per data is 34%. Interpolating. we get a value of $\left[\left(1.05 + \frac{36}{50}\right) \times 0.1)\right] = 1.118$ or say 1.12.

ii) Similarly, from table 34, the values are 0.25 and 0.2. Therefore for our conditions the Kc value is $\left(0.25 - \frac{34}{50} \times .05\right) = 0\ 216$ or say 0 22

Now, points can be plotted for the Kc values for.

Period in days starting from 1st November.	Kc
1	0 26
15	0.26
40	0.12
90	1.12
120	0.22

By approximately smoothening, we can get the curve as shown in figure No. 29 From this graph the value of Kc for any period, for which the crop water requirement is to be worked out, can be found. If necessary average value of Kc can be taken for that period. It is advisable to rely more on local data especially in case of water loving plants rice cane and Bananas. For these, the reader is referred to F. A. 24 for more information.

The Kc values of cane and Rice for Maharashtra are given below for ready refere-nce. These are general values and may be modified from local data if available.

Kc Values for Sugarcane

Crop age		Growth Stages	RHmin > 70%		RHmin < 20%	
12 months	18 Months		light to mod. wind	Strong wind	light to mod. wind	Strong wind
0–1	0–1.5	Planting to 0.25 full canopy	.55	.6	.4	.45
1–2	1.5–3.5	.25-.5 full canopy	.8	.85	.75	.8
2–2.5	3.0–3.75	.5–.75 full canopy	.9	.95	.95	1.8
2.5–4	3.75–6	.75 to full canopy	1.0	1.1	1.1	1.2
4–10	6–15	Peak use	1.05	1.15	1.25	1.8
10–11	15–16.5	early senescence	.8	.85	.95	1.25
11–12	16.5–18	ripening	.6	.65	.7	.75

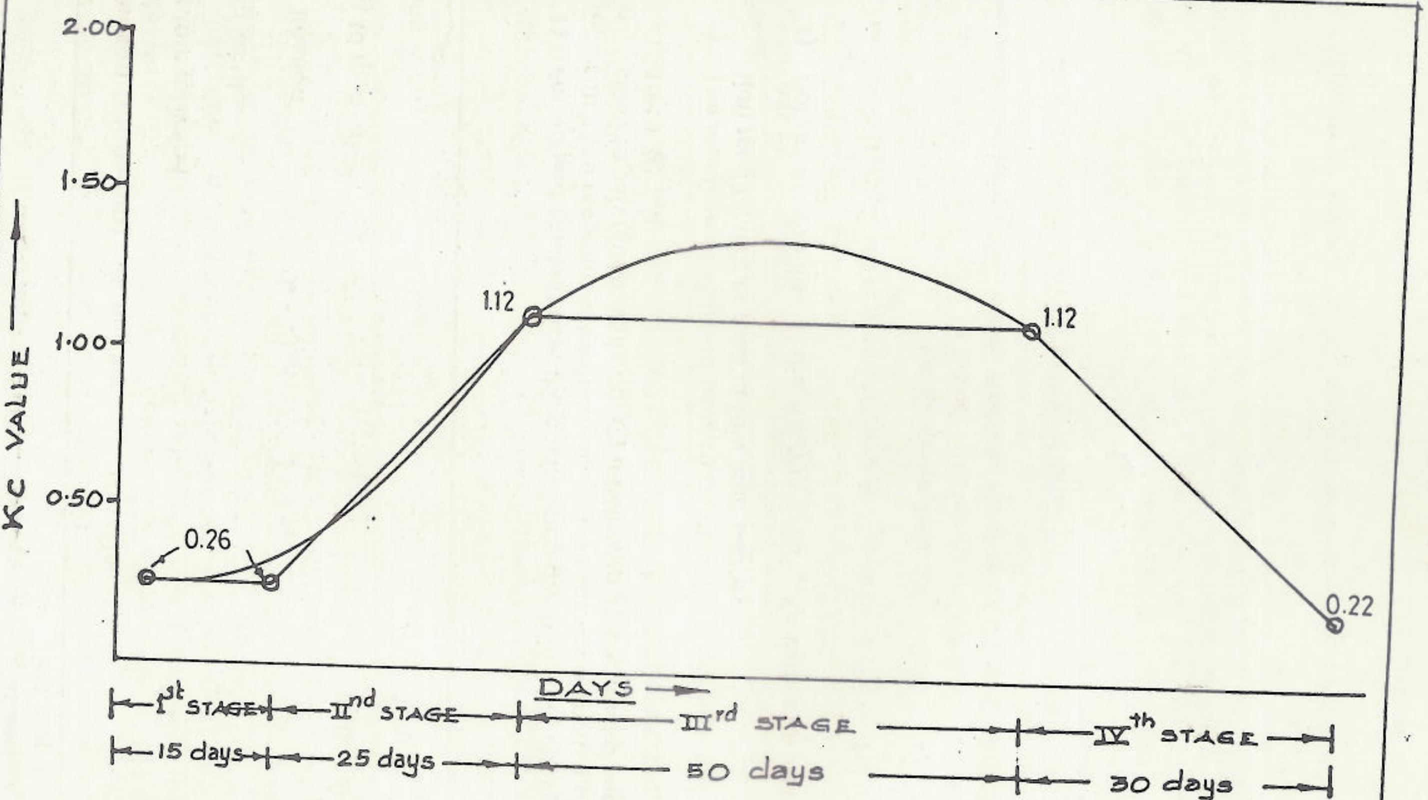


FIG. NO. 29. Kc VALUES OF WHEAT. (TYPE EXAMPLE).

MML.

Kc Values for Rice

	Planting	Harvest	Ist and IInd month	Mid season	Last 4 weeks
Wet Season (monsoon)	June-July	Nov-Dec.			
Light to mod-wind			1.10	1.05	0.95
Srong wind			1.15	1.10	1.00
Dry Season	Dec.-Jan	May			
Light to mod-wind			1.10	1.25	1.00
Strong wind			1.15	1.35	1.05

Notes :

1) For upland (drilled) rice, the coefficients given in the above table shall apply, since the recommended practices involve the maintenance of top soil layers very close to saturation. Only during initial crop stage, will kc need to be reduced by 15 to 20 %.

2) The drainage of soil will have to be considered while computing the Net Irrigation requirement in case of low land paddy.

3) For dry season also, if the RH min >70% Kc values for wet season may be used.

Crop Water Requirement and Net Irrigation Requirement

The formulae so far reviewed, give the evapotranspiration loss either of refetence crop or of other crop. The total water requirement however, may start right from land preparation for the crop. The water required may also include the water necessary for land leaching if the land is salt affected. Thus, the water required for cultivation of crop is not only the water required for its healthy gtowth dwing its life time, but also the water required for land preparation including water required for leaching.

This water requirement is satisfied by,

— Water balance at the beginning in root zone
— Rain water
— Irrigation
— Ground water

Since the rain water and groundwater is difficult to control, it is only irrigation water, the quantity of which can be varied. The requirement of water is first satisfied by rainwater and ground water and only the balance quantity is supplied as irrigation water, Thus,

Water requirement of crop = Leaching requirment + Land preparation requirements or other special requirements + Evapotranspiration requirements.

OR $WR_c = LR + SP + ET_c$. and this requirement is met with by

$WR_c = ER + G_e + NIR$ — Water Balance in soil

Where, ER is the part of rainfall contribution useful to the water requirments, G_e is the contribution of underground water table and NIR is the net irrigation requirement.

Or

NIR - (Leaching Requirement + Land preparation requirement + Evapotranspiration requirments)

— (Effective Rainfall + Groundwater contribution + Stored water balance)

The effective rainfall and ground water contribution is explained separately in further paras. The net irrigation requirement thus worked out is at the root zone and irrigation requirement at any point in the system can be worked out by applying proper efficiency factor.

The special requirement such as land preparation et. have to be decided as per site conditions. The The approximate leaching requirement can be worked out by the relationship.

$$\text{Leaching requirement} = \text{Irrigation application depth.} \times \frac{EC_i}{EC_d} \text{ in mm/day}$$

Where, EC_i and EC_d are the electrical conductivities of irrigation and drainage water respectively. The leaching requirement is primarily met with from deep percolation of rainfall. If the earlier rainfall is adequate, the leaching requirement can be neglected while calculating the Net Irrigation Requirement.

Effective Rainfall

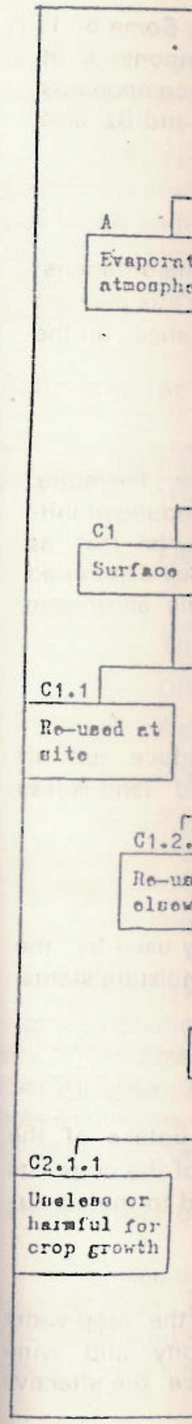
The primary source of water for habitation is rains. All the water from the rainfall cannot however be useful for some specific purpose. The part of rainfall which is useful for that purpose is the effectiva rainfall for that purpose. Thus the concept of effective rainfall is relative. The effective rainfall for one need not be effective rainfall to others. For an engineer planning irrigation on storage reservoirs, only that potion of the rainfall, which reaches the reservoir directly or indirectly, is the effective rainfall. For a geohydrologist, the portion of rainfall which contributes to the groundwater storage may be the effective rainfall, for an agriculturist. only tha portion of rainfall which contributes to the crop water needs, is the effective rainfall.

An individual farmer considers that the effective rainfall is that portion of total rainfall which is useful in raising crops planted on his soil, under his management. Water which moves out of his field by surface run off is ineffective unless he plans to pump back some of the run off for utilisation. Also, the water that moves below root zone as deep percolation is ineffective. Sometimes, the water may remain stagnant on his field and though it is neither a part of run-off nor, deep percolation, it may not be useful for his crops. On the other hand, it may be harmful to the crops. This is also ineffective rainfall.

It is therefore imperative that when effective rainfall is considered, the purpose for which the effective rainfall is considered, must, be clearly defined and kept in view.

For the present discussions, our purpose is to work out the irrigation requirements of crops. With this limited purpose the effective rainfall is the portion of the rainfall, which contributes to the crop water needs, without harming the crop in any way.

It is interesting to trace the pathway of rain water. The rainwater coming from the clouds strikes the soil surface. But before it strikes the soil surface, a neglible part is evaporated in the atmosphere and some part is intercepted by vegetation. Of the part intercepted by vegetation, a part is retained and evaporated by the vegetation while the remaining is drained on soil surface. Some of the water stiking the soil surface is lost as surface run off while the part of it infiltrates into the soil. This component can again be divided into two parts, viz part retained by soil in the root zone and the part wh ch percolates below the root zone. Not all tha water in the rootzone is utilised for crop growth. Some cf it may be



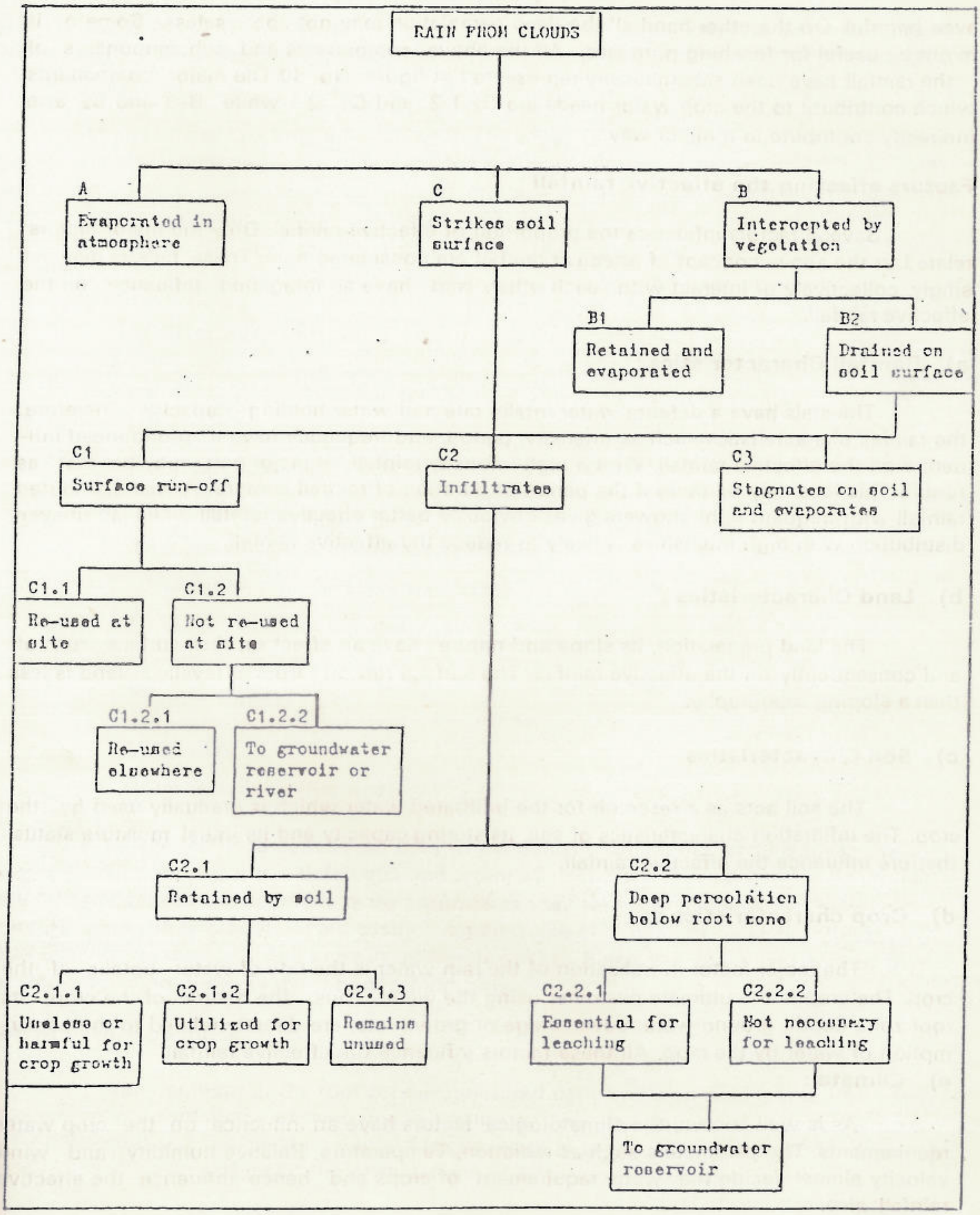


FIG. 30 PATHWAY OF RAINWATER.

even harmful. On the other hand all the deep pereolation may not be useless. Some of it might be useful for leaching purposes. All the above components and subcomponents of the rainfall have been schematically represented in figure No. 30 The major components which contribute to the crop water needs are C_2 1.2 and C_2 2.1 while B–1 and B_2 also indirectly contribute in a minor way.

Factors affecting the effective rainfall

Several factors influenca the proportion of effective rainfall. Only the major factors' related to the above concept of effective rainfall are considered here. These factors may act singly, collectively or interact with each other, and have an integrated influence on the effective rainfall.

a) Rainfall Characteristics :

The soils have a definite water intake rate and water holding capacity. Therefore, the rainfall characteristics such as intensity, period, and frequency have a pronounced influence on the effective rainfall. With a high intensity rainfall, a major part may be lost as runoff. This loss may be more if the period or duration of rainfall is more. A well distributed rainfall with frequent light showers gives obviously better effective rainfall while an uneven distribution with high intensities is likely to reduce the effective rainfall.

b) Land Characteristics :

The land preparation, its slope and nature have an effect on the surface run off and consequently on the effective rainfall. The surface run off from a levelled land is less than a sloping topography.

c) Soil Characterlstics

The soil acts as a reservoir for the infiltrated water which is gradually used by the crop. The infiltration characteristics of soil, its storing capacity and its initial moisture status, therfore influence the effective rainfall.

d) Crop characteristics :

The major factor in utilisation of the rain water is the rate of water uptake of the crop. The crop is the ultimate customer using the water. Thus, the nature of the crop, its root zone depth, ground water cover, stage of growth etc. are directly related to the consumption of water by the crop. All these factors influence the effective rainfall.

e) Climate :

As is well known, the climatological factors have an influence on the crop water rqeuirements. The parameters such as radiation, Temperature, Relative humidity and wind velocity almost decide the water requirement of crops and hence influence the effective rainfall also.

f) Other minor factors, such as mangement practices, drainage arrangements, ground water quality etc. have also an indirect effect on the utility of the rainwater for crop consumption.

With so many factors, influencing the effective rainfall and variable nature of these factors, it is almost impossible to determine the effective rainfall mathematically. Many methods based on field observations or empirical formulae are evolved to determine the effective rainfall, but the limitations of these methods must be borne in mind during application. The choice depends on the local available data and availibility of resources such as funds and facilities.

Estimation of Effective Rainfall

Several methods are available for the assessment of effective rainfall. They can be divided into two groups.

— Field observation methods

— Empirical relationships.

The field obsarvation methods include,

— Observation of soil moisture changes.

— Daily soil moisture balance method

— Integrating guage

— Ramdas method

— Lysimeters

— Drum technique (For rice)

All these methods depend on daily or periodical observations of moisture in the soil evapotranspiration of plants, rainfall etc. and computing the effective rainfall from this field data. These methods are definitely more accurate as they take into account the field conditions. However, they are often very costly, cumbersome and location specific. Because of these limitations, they are used more in research works. Since the practical utility of these methods is limited, they are described in brief only.

Soil moisture changes :

Water content in the root zone is measured daily and also before and after heavy showers, by soil sampling and oven drying the same. The dry density of the soil is previously deteimind and the moisture content is converted in to mm depth/root zone depth. A class A pan is kept nearby and the observations of Epan are also noted.

$$\text{Effective Rainfall} = M_2 - M_1 + k_p E_{pan}.$$

Where, M_2 and M_1 are the initial and final moisture contents in mm, K_p is the pan coefficient and E_{pan} is the evaporation of pan in mm for the period under observation. If desired the rainguage is also installed nearly and the effective rainfall is related to actual rainfall. The method is apparently simple but involves labourious work of soil sampling and constant attention.

Daily Soil moisture balance method :

In this method a daily account of soil moisture balance is maintained. Any addition of water either due to rains or due to irrigation is credit and soil moisture depletion is debit. The maximum water holding capacity is precisely determined beforehand. Any amount of surplus soil moisture over the water holding capacity is treated as drainage. The runoff measurements are either neglected or are separately estimated. The effective rainfall can be computed from this data. The proforma to maintain the data is given as table No. 35. The sample calculation in the proforma can illustrate the procedure. The data in the sample calculations is assumed as :

Field capacity of root zone : 100 mm

M. D. Depletion : 50 mm

Table No. 35 – Daily soil water Balance Account

Date	Rainfnll	ETP	Storage change in soil	Storage balance in soil	Irrigation	Water surplus (Drainage)
1	100	6	94	94	—	0
2	25	8	17	100	—	11
3	0	9	—9	91	—	0
4	0	9	—9	82	—	0
5	0	8	—8	74	—	0
6	0	9	—9	65	—	0
7	100	5	95	100	—	60
8	100	4	96	100	—	96
9	50	8	42	100	—	42
10	0	10	—10	90	—	0
11	0	11	—11	79	—	0
12	0	11	—11	68	—	0
13	0	12	—12	56	—	0
14	0	12	—12	44	50	0
15	0	11	—11	83	—	0
16	0	11	—11	72	—	0
17	0	10	—10	62	—	0
18	0	11	—11	51	—	0
19	0	10	—10	41	50	0
20	0	10	—10	81	—	0
21	0	11	—11	70	—	0
22	0	12	—12	58	—	0
23	0	12	—12	46	—	0
24	50	8	42	—	88	0
25	100	6	94	100	—	82
26	100	5	59	100	—	95
27	0	10	—10	90	—	0
28	0	10	—10	80	—	0
29	0	10	—10	70	—	0
30	0	10	—10	60	—	0
Total	625	279			188	386

Lysimeters :

Perhaps the best method available for keeping the water balance account is the lysimeter. Lysimeter (described elsewhere in details) is a large container with soil in which crop is grown, similar to the surrounding field crop. The container is fitted with inlet and outlet for irrigation and drainage water. Arrangements are made for accurate measurements of soil water, addition or depletion. From this data, a daily water balance account can be maintained and effective rainfall can be computed. Though this method is accurate, the advantage is outweighed by the cost and it is limited to research work only.

Integraiing Guage :

In this method an integrting guage, which is a combination of rainwater receiver, a water reservoir, and a evaporation pan (not to be confused with the standard evaporation pans) is used. The rainfall receiver is connected to the reservoir vessel. The reservoir vessel is provided with an outlet in the side wall. The outlet level is so adjusted that the quantity held by the reservoir is equal to the maximum water holding capacity of soil. This reservoir is again connected to a evaporation vessel. The evaporating surface represents the crop evaporation. The size of the pan is accordingly adjusted. The evaporating surface looses moisture equal to crop evapotranspiration, and creates a fall in the reservoir level. The outflow from the reservoir is collected and measured as ineffective rainfall. The main drawback in the guage is that surface runoff is not taken into account and has to be separately estimated. The schematic arrangement is shown in Figure No. 31

Ramdas Method :

Ramdas (1960) has suggested a direct field method using a portable device containing the soil of the field compacted to the field density. The apparatus is shown in figure No. 32 It cousists of two cylinders. Tho inner cyliuder is 30 cms in dia with a perforated base at a depth equal to the root zone of crop. A funnel is fitted to this base which leads to a bottle occupying the lower part of the cylinder, The upper part of the cylinder is filled with soil compacted to field density, and the crop as in the field is raised in this soil also. The cylinder is placed in the outer cylincer and buried in the soil. The crop in the field is exactly under the same conditions as the crop in the cylinder. Excess rainwater drains into the bottle 'H' and is peiodically measured. This is the amount of ineffective rainfall The device is simple and gives direct measurements for a set of conditions.With a suitable number of replications, a reasonably accurate measurement of effective rainfall can be obtained.

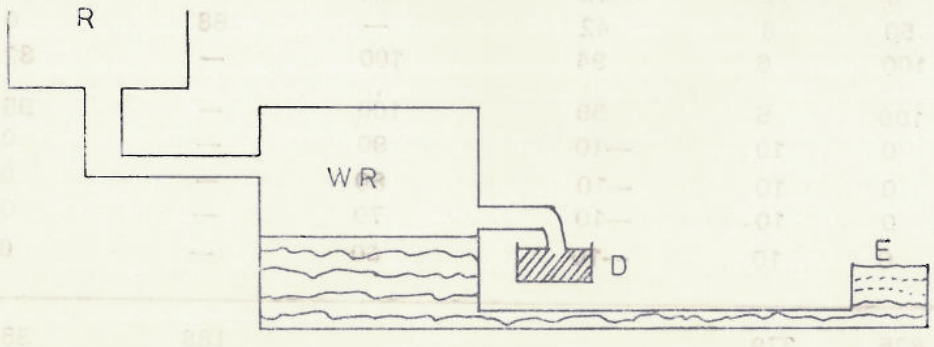


Fig. 31 INTEGRATING GAUGE FOR MEASURING EFFECTIVE RAINFALL

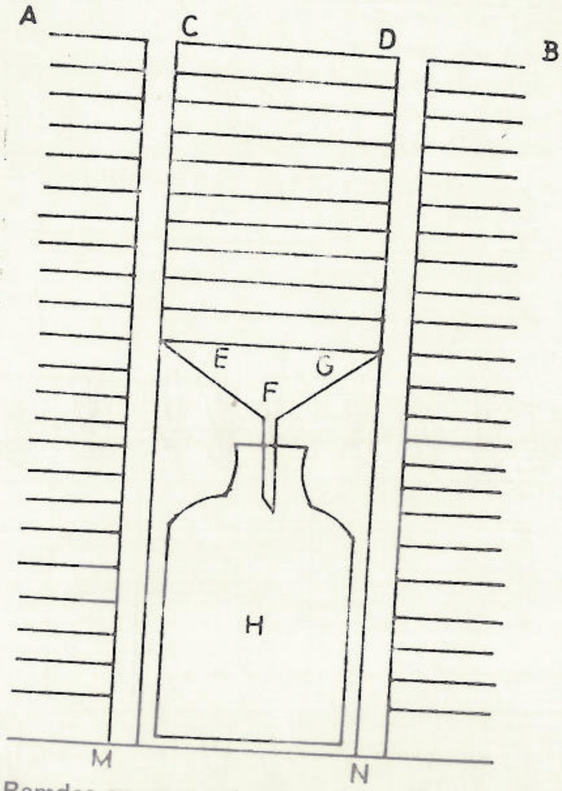
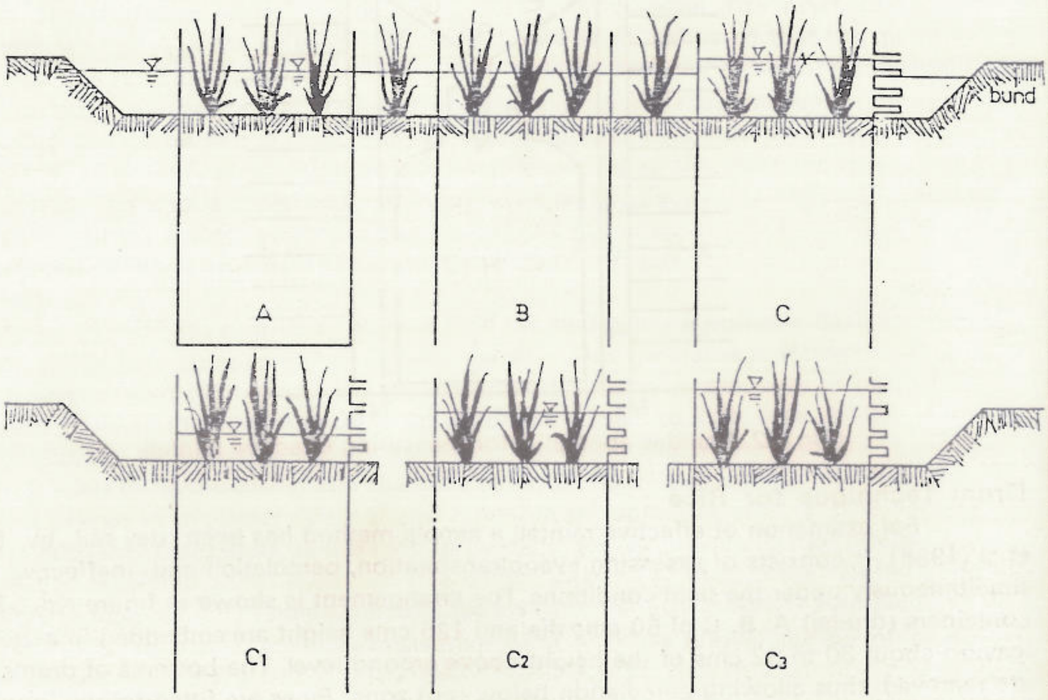


Fig. 32. Ramdas apparatus for measuring effective rainfall.

Drum Technique for Rice :

For estimation of effective rainfall a simple method has been dev sed by Dastane et al (1966). It consists of assessing evapotranspiration, percolation and ineffective rainfall simultaneously under the field conditions. The arrangement is shown in figure No. 32. Three containers (drums) A, B, C of 50 cms dia and 125 cms height are embedded in a rice field, leaving about 30 to 32 cms of the height above ground level. The bottoms of drums B & C are removed, thus allowing percolation below root zone. Pipes are fitted to the drum C, at 0.5 cm interval in height above the ground level. The drums are filled with the field soil compacted at field density and rice is grown inside the drums under exact field conditions. Water levels in the drums are maintained as the water level outside. The difference in water levels on successive days in drums 'A' represents evapotranspiration of crop. The difference in drums 'B' represents the daily total needs of crop water including percolation. The container 'C' determines the ineffective rainfall. The maximum submergence is determined by the height of the crop and the field bund height whichever is less.Any rainfall which submerges the crop beyond this submergence is ineffective. The outlets are plugged or opened so as the submergence level is kept to this height. The water level in drum'C' is kept at a selected height. This heiget is adjusted with the increase in the height of crop. Evapotranspiration & percolation create a deficit every day.The rain fall first makes up this deficit and the



A: ET; B: ET + percolation: C: ET + percolation + run-off

Fig: No. 33. Container Technique for Determination of Effective Rain fall In Rice.

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excess flows out through the pipe. This is ineffective rainfall. Thus the difference in levels of drums B and C is ineffective rainfall. If there is no rain, the water level in C will reach the soil surface and the crop will be irrigated according to the practice. The technique is easy, inexpensive and practicable.The daily water balance can then be computed in the proforma given in table 36. The values used are assumed values to illustrate the procedure.

Table No. 36 — Computations for ineffective rainfall by drum technique

All figures in mm

Date	Irrigation	Daily Rainfall	Drum A	Drum B	Drum C	Evapotranspiration	Evapotranspiration plus percolation	Percolation	Ineffective rainfall
1	2	3	4	5	6	7	8	9	10
Previous day	0	0	75	75	75	0	0	0	0
1	0	20	90	80	75	5	15	10	5
2	0	40	107	97	75	8	18	10	22
3	0	100	170	160	75	5	15	10	85
4	0	15	85	75	75	5	15	10	0
5	0	0	67	75	57	8	18	10	0
6	0	0	48	38	38	9	19	10	0
7	0	20	51	41	41	7	17	10	0
8	0	60	95	85	75	6	16	10	10
9	0	70	140	130	75	5	15	10	55
10	0	0	67	57	57	8	18	10	0
11	0	0	49	39	39	8	18	10	0
12	0	0	32	22	22	7	17	10	0
13	0	0	17	7	7	5	15	10	0
14	75	0	75	65	65	7	17	10	0
15	0	30	90	80	75	5	15	10	5
Total	75	355	—	—	—	98	248	150	182

Notes : Permissible water depth	:	75 mm
Column 2	:	Reading
3	:	Rain guage record
4) 5)	:	To be adjusted to Col. 6 reading and to be observed next day.
6	:	Observation
7	:	Previous day Col. 6 + Col. 3 — Col. 4.
8	:	Previous day Col. 6 + Col. 3 — Col. 5.
9	:	Col. 8 — Col. 7
10	:	Col. 5 — Col. 6

The empirical methods available are :

— Renfro equation
— U. S. B. R. method
— Evapotranspiration / Precipitation ratio method
— U. S. D. A. (SCS) method
— Empirical relationships for crops other than rice
— Empirical relationships for rice

All these methods are based mostly on experience and have their own limitations. A judicious application is therefore necessary.

Renfro equation :

Renfro (1964) has suggested the following relationship :

$$ER = E \times R_g + A$$

Where,
ER is effective rainfall in mm
R_g is the rainfall during the growing season of the crop in mm.
A is the irrigation application in mm.
E is the coefficient depending on ratio of consumptive use of crop to the rain fall during growing season.

The values of E are given in Table No. 37. The value of E denotes the degree of utilisation of rains for consumptive use. The greater the value of E, greater is the effective rainfall,This method is simple but cannot be used unless corroborated by some field method.

Table No. 37

Value of E for Uue in Estimating Effective rainfall by Renfro Equation

Cu / Rg	E	Cu / Rg	E
0.0	0	2.2	0.69
0.2	0.10	2.4	0.72
0.4	0.19	2.6	0.75
0.6	0.27	2.8	0.77
0.8	0.35	3.0	0.80
1.0	0.41	3 5	0.84
1.2	0.47	4.0	0.88
1.6	0.57	5.0	0.93
1.8	0.61	6.0	0.96
2.0	0.65		

U. S. Bureau of Reclaimation Method :

This method, recommended for arid and semi arid zones considers the rainfall in five driest consecutive years. The monthly rainfall figures, for a particular month is taken for computation. A ready table is given for range of rainfall. (table no 38). The method considers only the rainfall but not the soil type, nature of crop, or frequency distribution of rains. The method is therefore not considered very satisfactory.

Table No. 38

Effective rainfall based on increments of Monthly Rainfall (U. S. B. R. Method)

Rainfall Range in mm	Percent	Effective Rainfall range in mm
0.0 to 25.4	90 — 100	22.9 to 25.4
25.4 to 50.8	85 — 95	44.4 to 49.5
50.8 to 76.2	75 — 90	63.5 to 72.4
76.2 to 101.6	50 — 80	76.2 to 92.7
101.6 to 127.0	30 — 60	83.8 to 107.9
127.0 to 152.4	10 — 40	86.4 to 118.1
Over 152.4	—	86.4 to 120.6

For example, if montholy rainfall for 5 driest consecutive years, for the month of July are, 100, 125, 150, 225 and 175 mm effective rainfall is 120.6 mm.

Evapotranspiration / Precipitation Ratio Method :

This is a semi empirical method widely used in India. In this method, ecapotranspiration to rainfall ratio is calculated for a particular period of days ranging from 2 to 30 days depending upon crop mean monthly evapotranspiration and soil type. Average ratio for each month of the growing period and total growing period is calculated. This ratio is taken as the ratio of effective rainfall to total rainfall in the growing period. Rainless periods are deleted from the computations.

A table showing the uumber of days for each calculation for different crop, soils and mean monthly ETo is given in Table No. 39. The evapotranspiration values are for reference crop and are usually taken as 0.8 of panevapotranspiration Data from U. S. Class 'A' pan.

Table No. 39

Number of days in a group for different soil types and climatic conditions

Crop	Mean monthly ETo mm/day	Soil Texture and water storage capacity (mm/m)			
		Light (below 40)	Medium (40 to 80)	Heavy (80 to 120)	Very heavy 120 and above
Rice	3 to 12	2	3	4	7
Other	Over 6	4	7	10	15
Crops	Below 6	7	10	15	30

In case of rice, instead of ETo, total water loss i. e. evapotranspiration plus percolation is sometimes used. This method is simple, inexpensive and does not need very precise data. Broad knowledge of soil characteristics and pan evaporation data is sufficient. For broad planning, this method is very useful.

Taking crop characteristics into account, necessaty correction can be applied for undesirable or harmful kind of rainfall, such as that causing lodging or flower drop etc.

U. S. D. A. (SCS) METHOD

The U. S. Department of Agriculture, Soil Conservation Service has developed tables relating the effective rainfall to the mean monthly rainfall and mean monthly consumptive use of the crops. These tables are the result of a comprechensive analysis of rainfall records at 22 stations in different climatic and soil zones for 50 years. The soil moisture balance account was prepared for these periods assuming a storage capacity of the soil as 75 mm. at the irrigation application. It is also assumed that the net irrrgation application is 75 mm. Based on this data, table No 40 gives the values of effective rainfall for different consumptive Use and rainfalls. Of course the effective rainfal cannot exced the consumptive use. If it does, the lower value of the two is adopted as effective rainfall.

If the irrigation application is other than 75 mm. a correction factor is to be applied to the effective depth obtained from table No. 40. The correction factors for different depths of application varying from 10 mm to 170 mm are given in table. 41

This method takes into account the climatological factors, moisture holding capacity of the soils, irrigation application depth etc. This is probably the best method available today and is widely used in many countries.

Empirical relations :

Apart from the above methods, some empirical practices are followed in different countries. These practices are based mostly on long experience and are useful under the conditions where they are developed. Before using anywhere else, i. e. where they are not in vougue, the verification by accurate field methods is necessary. These practices are enlisted below.

For Crops Other Than Rice :

INDIA

i) Effective rainfall is taken as 70% of seasonal rainfall

ii) Effective rainfall is taken as mean rainfall neglecting 75 mm in one day and 125 mm in 10 days.

iii) Effective rainfall is taken as the lowest monsoon rainfall occuring in three out of five years.

iv) The Kharif season is divided in to 10 day's periods. Rainfall in each period, exceeding the consumptive use of crops is treated as ineffective.

Table – 40 Average Monthly Effective Rainfall As Related to Mean Monthly Rainfall and Mean Monthly Consumptive Use (USDA, SCS)

Monthly mean rainfall mm	Mean monthly consumptive us mm													
	25	50	75	100	125	150	175	200	225	250	275	300	325	350
	Mean monthly effective rainfall mm													
12.5	7.5	8.0	8.7	9.0	9.2	10.0	10.5	11.2	11.7	12.5	12.5	12.5	12.5	12.5
25.0	15.0	16.2	17.5	18.0	18.5	19.7	20.5	22.0	24.5	25.0	25.0	25.0	25.0	25.0
37.5	22.5	24.0	26.2	27.5	28.2	29.2	30.5	33.0	36.2	37.5	37.5	37.5	37.5	37.5
50.0	25	32.2	34.5	35.7	36.7	39.0	40.5	43.7	47.0	50.0	50.0	50.0	50.0	50.0
62.5	at 41.7	39.7	42.5	44.5	46.0	48.5	50.5	53.7	57.5	62.5	62.5	62.5	62.5	62.5
75.0	|	46.2	49.7	52.7	55.0	57.5	60.2	63.7	67.5	73.7	75.0	75.0	75.0	75.0
87.5	|	50.0	56.7	60.2	63.7	66.0	69.7	73.7	77.7	84.5	87.5	87.5	87.5	87.5
100.0	|	at 80.7	63.7	67.7	72.0	74.2	78.7	83.0	87.7	95.0	100	100	100	100
112.5	|	|	70.5	75.0	80.2	82.5	87.2	92.7	98.0	105	111	112	112	112
125.0	|	|	75.0	81.5	87.7	90.5	95.7	102	108	115	121	125	125	125
137.5	|	|	at 122	88.7	95.2	98.7	104	111	118	126	132	137	137	137
150.0	|	|	|	95.2	102	106	112	120	127	136	143	150	150	150
162.5	|	|	|	100	109	113	120	128	135	145	153	160	162	162
175.0	|	|	|	at 160	115	120	127	135	143	154	164	170	175	175
187.5	|	|	|	|	121	126	134	142	151	161	170	179	185	187
200.0	|	|	|	|	125	133	140	148	158	168	178	188	196	200
225	|	|	|	|	at 197	144	151	160	171	182				
250	|	|	|	|	|	150	161	170	183	194				
275	|	|	|	|	|	at 240	171	181	194	205				
300	|	|	|	|	|	|	175	190	203	215				
325	|	|	|	|	|	|	at 287	198	213	224				
350	|	|	|	|	|	|	|	200	220	232				
375	|	|	|	|	|	|	|	at 331	225	240				
400	|	|	|	|	|	|	|	|	at 372	247				
425	|	|	|	|	|	|	|	|	|	250				
	|	|	|	|	|	|	|	|	|	at 412				
450	25	50	75	100	125	150	175	200	225	250				

Table – 41 Multiplication Factors to Relate Monthly Effective Rainfall Value Obtained From Table 40 to Net Depth of Irrigation Application (d), In mm.

Table – 41 Multiplication Factors to Relate Monthly Effective Rainfall Value Obtained From Table 40 to Net Depth of Irrigation Application (d), In mm.

d mm	factor	d mm	factor	d mm	factor
10.00	0.620	31.25	0.818	70.00	0.990
12.50	0.650	32.50	0.826	75.00	1.000
15.00	0.676	35.00	0.842	80.00	1.004
17.50	0.703	37.50	0.860	85.00	1.008
18.75	0.720	40.00	0.876	90.00	1.012
20.00	0.728	45.00	0.905	95.00	1.016
22.50	0.749	50.00	0.930	100.00	1.020
25.00	0.770	55.00	0.947	125.00	1.040
27.50	0.790	60.00	0.963	150.00	1.060
30.00	0.808	65.00	0.977	175.00	1.070

BURMA

During rainy season. rainfall less than 12 mm/day is treated as ineffective. 65% of the rainfall above this figure is considered as effective rainfall. During other seasons 65% above 25 mm/day rainfall is treated as effective rainfall

THAILAND

80% of the November rainfall and 90% of rainfall from December fo March is treated as effective rainfall.

For Rice :

Rice thrive under conditions of abundant . water. Hence the land is kept under submergence for the growth period of rice. The crop water requirement of rice therefore, includes the evapotranspiration plus percolation.Measuring or estimation of effective rainfall is therefore more complicated. The practices adopted in three rice growing countries are enlisted :

INDIA

i) 50% to 80% of rainfall is treated as effective rainfall depending upon the nature of soil.

ii) Rainfall less than 6 mm/day, or more than 75 mm/day or 125 mm in 10 days is treated as ineffective

JAPAN

From the rainfall records of 15 days, the rains of 50 to 80 mm/day is considered ineffective.

VIETNAM

Daily rainfall below 5 mm or above 50 mm is treated ineffective. If the evapotranspiration rate is 10 mm or more, two days 'successive rainfall up to 60 mm or 3 days' successive rainfall upto 70 mm is treated as effective. Rainfall above this is considered as ineffective.

A study was carried out by M/s Ramkrishnarao, Kadam, Shinde, and Varade in Marathwada region of Maharashtra State where the water holding capacity of the soils was 250 mm and the infiltration rate of 2 cms/hr. The criteria for effective rainfall evolved for each month is as under :

Month	Criteria
June	a) Less than 10 mm/day is ineffective. b) More than 100 mm/day is ineffective.

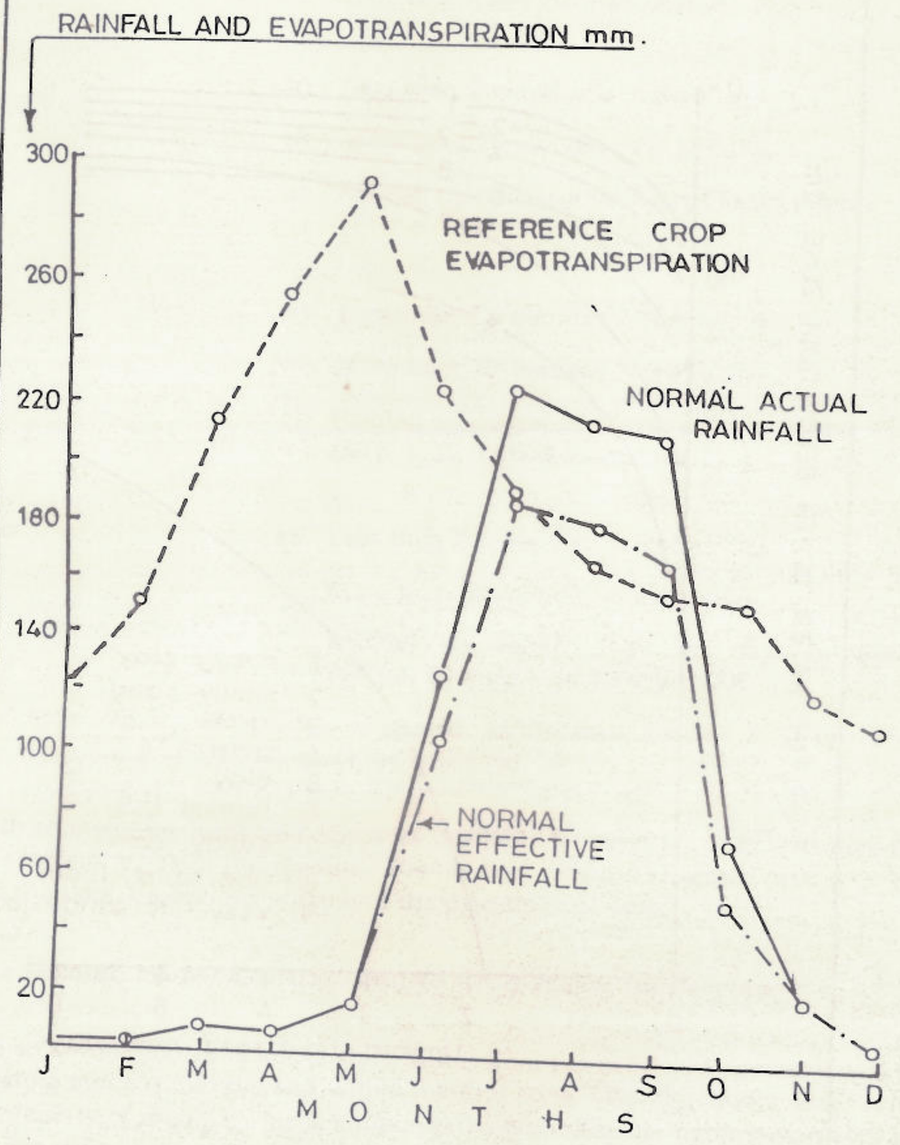

FIG. NO. 34 ACTUAL RAINFALL, EFFECTIVE RAINFALL AND EVAPOTRANSPIRATION (ETo)

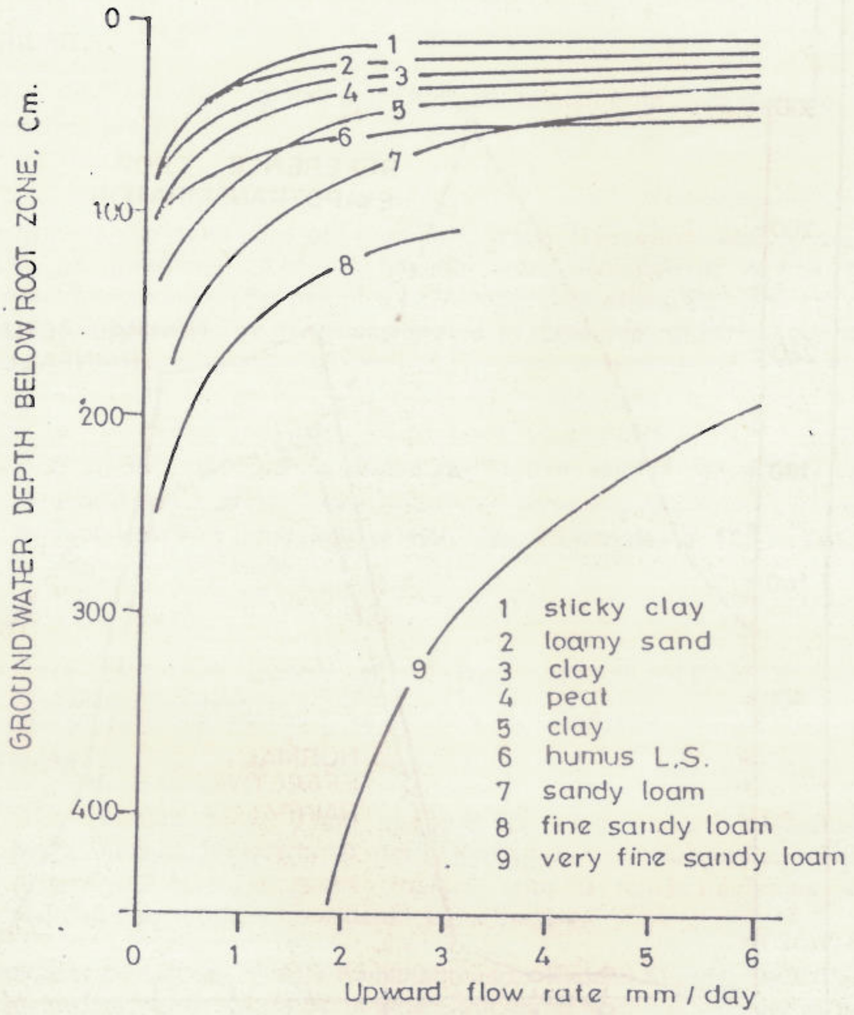

FIG. NO.35. UPWARD FLOW RATES FOR DIFFERENT SOILS AND GROUND WATER DEPTHS

July

August

September

For other

rainfall, effective r

With so m

it is often a proble

avilability of the d

Grou

The soil in

a higher moisture c

by capillary propert

contribution depen

below root zone, a

movement of moistu

soils, the distance o

tribution is so small

showing upward flo

Figure No. 35.

c) Rainfall on consecutive two days in excess of (Eto + 100 mm) is ineffective.

July

a) Less than 5 mm/day is ineffective

b) More than 75 mm/day is ineffective

c) Rainfall on consecutive 2 days in excess of (ETo + 75 mm) is ineffective.

August

a) Less than 2.5 mm/day is ineffective

b) More than 75 mm/day is ineffective

c) Rainfall on consecutive two days in excess of (ETo + 75 mm) is ineffective

September

a) Less than 2.5 mm/day is ineffective.

b) More than 50 mm/day is ineffective.

c) Rainfall on consecutive two days in excess of (ETo + 50 mm) is ineffective.

For other months all the rain is treated as effective rainfall. A graph showing rainfall, effective rainfall and ET_o is given as figure No. 34

With so many methods and practices available for assessment of effective rainfall, it is often a problem to select the method. The method is to be selected accroding to the availability of the data, desired accuracy and the predominant crop.

Ground Water Contribution to Crop Water Requirement

The soil in the rootzone sucks some water from the soil below rootzone which is at a higher moisture content that the soil within the root zone. This "Suction action" is mostly by capillary property of the soil, This is known as the ground water contribution (G_e). This contribution depends upon the capillary properties of soil, depth of the ground water table below root zone, and the moisture status of the soil. For heavy soils, the distance of movement of moisture is high while the rate is low, while conversely, for light textured soils, the distance of movement is small but the rate is high. Usually, the groundwater contribution is so small that,detailed measurements or experiments are not worthwhile. A graph showing upward flow rate for different ground water depths for different soils is given in Figure No. 35.

Stress or Deficit Irrigation

The methods discussed in the foregoing paras determine the crop water requirements fot the healthy growth of crop. The crop draws this water requirements form the soil, through its root system, provided sufficient water is available in the so called'Soil Reservoir'. While this reservoir starts depleting, the crop continues to draw the requirements. For some evel of depletion, the crop can draw the total requirement (Let us call it ETm), but after, some depletion level, though the crop can still draw the water, the water drawn is less than the total requirement. The crop is then said to be under water stress. More commonly, this condition is known as stress or deficit condition. The actual water that can be drawn by the crop is called actual evapotranspiration or ETa. Thus value of the ratio ETa/ETm gets progressively reduced with the depletion level. The maximum value of ET_a /ETm is obviousiy 1. The irrigation enginseer always tries to avoid the stress condition, but this condition has to be faced sometimes because of :

— Inadequate water availability

or

— Longer irrigation interval imposed by system constraints.

The study of stress conditions, can enable the optimum use of available water within the system constraints. The study mainly revolves around two questions viz :

— Quantitive estimations of ETa.

— Effect of Stress on yield.

Actual Evapotranspiration (ETa) :

The actual evapotranspiration depends on the crop, and the level of depletion of the available soil water and the value of ET_m. Most vegetable crops require relatively wet soils to mantain ETa = ET_m Other crops such as cotton, sorghum, Maize can maintain $ET_a = ET_m$ at much lower level of depletion. In general, the crops whose harvested part is fleshy or leafy (such as fruits, vegetables etc.) require a narrow range of depletion while for crops, whose harvested part is dry, (such as grain, cotton, oil seeds etc.) the lower level of depletion is tolerably wider The type of soil does have some effect on the level of depletion when ETa starts becoming less than ETm. But the effect is negligible.

Soil Water Depletion Factor (P)

The proportion of the total soil water that can be depieted without causing the ETa to become less than ETm is called P. P thus depends on (i) Crop, (ii) The magnitude of ETm and (iii) Soil (Slight effect).

The values of 'P' have been experimentlly decided for various crops for different values of ETm. For this purpose, the crops are divided into 4 groups indicated in Table 42.

Table - 42 : Crop Groups According to Soil Water Depletion.

Group No.	Crops
(I)	Onion, Pepper, Potato
(II)	Bannana, Cabbage, Grape, Peas, Tomato
(III)	Alfalfa, Beans, Citrus, Groundnut, Sunflower, Wheat, Water melons
(IV)	Cotton, Maize, Safflower, Sorghum, Soyabean, Sugarcane, Sugarbeat, Tobacco.

Ref. : FAO Publication No 33

The soil water depletion factor P according to crop groups and ETm/day is indicated in Table 43.

Table – 43 : Soil Water Depletion Factor 'P'

Crop groups	ETm mm/day								
	2	3	4	5	6	7	8	9	10
1	0.500	0.425	0.350	0.300	0 250	0.225	0.200	0.200	0.175
2	0.675	0.575	0.475	0.400	0.350	0.325	0.275	0.250	0.225
3	0.800	0.700	0.600	0.500	0.450	0.425	0.375	0.350	0.300
4	0.875	0.800	0.700	0.600	0.550	0.500	0.450	0.425	0.400

Ref. : F. A. O. Publication No. 33

It will be observed that as the value of ETm increases, the value of 'P' decreases.

ETa is related to the available soil moisture and ETm. Normally the available soil oisture is known from the soil type and the value is available in mm/m depth of soil. Roots n utilise the moisture from root zone only. Therefore the available soil moisture at a rticular time is –

D. Sa where D in meters is the root zone depth of crop at that time and Sa is the l moisture in mm/mtr. Generalised values of root depths of various growth stages are own in table 44.

A table showing the values of ETa for various values of D.Sa (in mm), P, and ETm iven as Table No. 45.

The use of the tables is illustrated below :

Example : Wheat is grown in medium Textured soil with Sa value 100 mm/m. The gation is applied at an interval of 14 days. Calculate average ETa on 10th day after gation when the Root zone depth is 60 Cm and ETm is 5 mm/day.

TABLE : 44 ROOT GROWTH OF DIFFERENT CROPS AT DIFFERENT STAGES

Sr. No.	Crops	Rooting depth in cm at different stages of crops (days after sowing) 15	30	45	60	75	90	105	120	135	150	160	190
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	Jowar	20	60	90	100	O	—	—	—	—	—	—	—
2.	Groundnut	20	35	50	60	O	—	—	—	—	—	—	—
3.	Maize	20	50	75	100	O	—	—	—	—	—	—	—
4.	Rice, Lowland	10	20	25	35	O	—	—	—	—	—	—	—
5.	Rice, upland	10	15	20	25	O	—	—	—	—	—	—	—
6.	Wheat	20	40	60	90	O	—	—	—	—	—	—	—
7.	Rabi-Jowar	20	50	75	100	O	—	—	—	—	—	—	—
8.	Gram	20	40	60	80	O	—	—	—	—	—	—	—
9.	Potato	15	25	35	40	O	—	—	—	—	—	—	—
10.	Onion	15	30	40	O	—	—	—	—	—	—	—	—
11.	Sugarcane	20	40	60	75	95	100	O	—	—	—	—	—
12.	Ginger and Turmeric	15	25	40	50	60	—	—	—	—	—	—	—
13.	Chillies	18	35	50	75	O	—	—	—	—	—	—	—
14.	Tomato	20	45	70	90	100	O	—	—	—	—	—	—
15.	Cabbage	15	30	45	O	—	—	—	—	—	—	—	—
16.	Bajra	40	75	100	O	—	—	—	—	—	—	—	—
17.	Cotton	25	50	75	100	—	—	—	—	—	—	—	—
18.	Safflower	40	80	100	O	—	—	—	—	—	—	—	—
19.	Tobacco	20	45	70	75	—	—	—	—	—	—	—	—
20.	Banana	5	10	15	20	25	25	35	40	45	50	55	60
21.	Citrus	15	30	100	O	—	—	—	—	—	—	—	—
22.	Sunflower	35	70	100	O	—	—	—	—	—	—	—	—
23.	Lucerne	20	70	90	100	—	—	—	—	—	—	—	—
24.	Tur	20	45	90	100	—	—	—	—	—	—	—	—
25.	Green & Black Gram	25	50	60	O	—	—	—	—	—	—	—	—

O Indicates same rooting depth for the other crop period.

Table : 45 Mean Actual Evapotranspiration (ETa) in mm/day over the Irrigation Interval for Different Yields of ETm (mm/day), D. Sa (mm) and p (fraction)

ETm = 2.0 mm/day

D. Sa p 2 4 6 8 10 ...

Table : 45 Mean Actual Evapotranspiration (ETa) in mm/day over the Irrigation Interval for Different Yields of ETm (mm/day), D. Sa (mm) and p (fraction)

D. Sa	p	ETm = 2.0 mm/day																
		2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	35	40
25	0.2	2.0	2.0	1.8	1.7	1.6	1.4	1.3	1.2	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.6
	0.4	2.0	2.0	2.0	1.9	1.7	1.6	1.5	1.4	1.2	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.6
	0.6	2.0		2.0	2.0	1.9	1.7	1.6	1.5	1.3	1.2	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	2.0			2.0	2.0	1.9	1.7	1.5	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	2.0	2.0	2.0	2.0	1.9	1.8	1.8	1.7	1.6	1.6	1.5	1.4	1.4	1.3	1.3	1.2	1.1
	0.4	2.0			2.0	2.0	2.0	1.9	1.9	1.8	1.7	1.7	1.6	1.5	1.5	1.4	1.3	1.1
	0.6	2.0					2.0	2.0	2.0	2.0	1.9	1.8	1.7	1.7	1.6	1.5	1.4	1.2
	0.8	2.0								2.0	2.0	2.0	1.9	1.8	1.7	1.6	1.4	1.2
100	0.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.8	1.8	1.7	1.7	1.6	1.6
	0.4	2.0							2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.8	1.7
	0.6	2.0												2.0	2.0	2.0	2.0	1.9
	0.8	2.0														2.0	2.0	2.0
150	0.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.8	1.8
	0.4	2.0											2.0	2.0	2.0	2.0	2.0	1.9
	0.6	2.0															2.0	2.0
	0.8	2.0																2.0
200	0.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9
	0.4	2.0														2.0	2.0	2.0
	0.6	2.0																2.0
	0.8	2.0																2.0
300	0.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	0.4	2.0																2.0
	0.6	2.0																2.0
	0.8	2.0																2.0

Table : 45 Continued

D.Sa	P	ETm = 4.0 mm/day																
		2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	35	40
25	0.2	3.9	3.4	2.9	2.5	2.2	1.9	1.7	1.5	1.4	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.6
	0.4	4.0	3.7	3.2	2.7	2.3	2.0	1.7	1.5	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.6	4.0	4.0	3.5	2.9	2.4	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	4.0	4.0	3.8	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	4.0	3.9	3.6	3.4	3.1	2.9	2.7	2.5	2.3	2.2	2.0	1.9	1.8	1.7	1.6	1.4	1.2
	0.4	4.0	4.0	4.0	3.7	3.5	3.2	2.9	2.7	2.5	2.3	2.1	2.0	1.9	1.7	1.6	1.4	1.2
	0.6	4.0		4.0	4.0	3.8	3.5	3.2	2.9	2.6	2.4	2.2	2.1	1.9	1.8	1.6	1.4	1.2
	0.8	4.0			4.0	4.0	3.8	3.4	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.6	1.4	1.2
100	0.2	4.0	4.0	4.0	3.9	3.8	3.6	3.5	3.4	3.2	3.1	3.0	2.9	2.8	2.7	2.6	2.3	2.2
	0.4	4.0		4.0	4.0	4.0	4.0	3.9	3.7	3.6	3.5	3.3	3.2	3.1	2.9	2.8	2.5	2.3
	0.6	4.0					4.0	4.0	4.0	3.9	3.8	3.6	3.5	3.3	3.2	3.0	2.7	2.4
	0.8	4.0							4.0	4.0	4.0	3.9	3.8	3.6	3.4	3.2	2.8	2.5
150	0.2	4.0	4.0	4.0	4.0	4.0	3.9	3.8	3.7	3.6	3.5	3.5	3.4	3.3	3.2	3.1	2.9	2.7
	0.4	4.0				4.0	4.0	4.0	4.0	4.0	3.9	3.8	3.7	3.7	3.6	3.5	3.2	3.0
	0.9	4.0								4.0	4.0	4.0	4.0	3.9	3.9	3.8	3.5	3.3
	0.8	4.0											4.0	4.0	4.0	4.0	3.8	3.6
200	0.2	4.0	4.0	4.0	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.6	3.6	3.5	3.4	3.3	3.1
	0.4	4.0					4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.9	3.9	3.8	3.6	3.5
	0.6	4.0											4.0	4.0	4.0	4.0	3.9	3.8
	0.8	4.0														4.0	4.0	4.0
300	0.2	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.9	3.9	3.9	3.8	3.8	3.7	3.5
	0.4	4.0									4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.9
	0.6	4.0															4.0	4.0
	0.8	4.0																4.0

Table: 45 Continued

D. Sa	P	ETm = 6.0 mm/day										
		2	4	6	8	10	12	14	16	18	20	22	24

Table: 45 Continued

D. Sa	P	ETm = 6.0 mm/day 2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	35	40
25	0.2	5.5	4.3	3.5	2.8	2.4	2.0	1.8	1.6	1.4	1.2	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.4	5.9	4.8	3.7	3.0	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.6	6.0	5.2	4.0	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	6.0	5.7	4.1	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	6.0	5.5	4.9	4.3	3.9	3.5	3.1	2.8	2.6	2.4	2.2	2.0	1.9	1.8	1.7	1.4	1.3
	0.4	6.0	5.9	5.4	4.8	4.2	3.7	3.3	3.0	2.7	2.5	2.2	2.1	1.9	1.8	1.7	1.4	1.3
	0.6	6.0	6.0	5.9	5.2	4.6	4.0	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.5	1.3
	0.8	6.0	6.0	6.0	5.7	4.9	4.1	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
100	0.2	6.0	6.0	5.8	5.5	5.2	4.9	4.6	4.3	4.1	3.9	3.7	3.5	3.3	3.1	3.0	2.6	2.4
	0.4	6.0	6.0	6.0	5.9	5.7	5.4	5.1	4.8	4.5	4.2	4.0	3.7	3.5	3.3	3.1	2.8	2.4
	0.6	6.0		6.0	6.0	6.0	5.9	5.6	5.2	4.9	4.6	4.3	4.0	3.7	3.5	3.3	2.8	2.5
	0.8	6.0				6.0	6.0	6.0	5.7	5.3	4.9	4.5	4.1	3.8	3.6	3.3	2.9	2.5
150	0.2	6.0	6.0	6.0	5.8	5.7	5.5	5.3	5.1	4.9	4.7	4.5	4.3	4.2	4.0	3.9	3.5	3.2
	0.4	6.0		6.0	6.0	6.0	5.9	5.8	5.6	5.4	5.2	5.0	4.8	4.6	4.4	4.2	3.8	3.3
	0.6	6.0				6.0	6.0	6.0	6.0	5.9	5.7	5.5	5.2	5.0	4.8	4.6	4.1	3.6
	0.8	6.0							6.0	6.0	6.0	5.9	5.7	5.4	5.1	4.9	4.2	3.7
200	0.2	6.0	6.0	6.0	6.0	5.9	5.8	5.6	5.5	5.3	5.2	5.0	4.9	4.7	4.6	4.4	4.1	3.9
	0.4	6.0			6.0	6.0	6.0	6.0	5.9	5.8	5.7	5.6	5.4	5.2	5.1	4.9	4.6	4.2
	0.6	6.0						6.0	6.0	6.0	6.0	6.0	5.9	5.7	5.6	5.4	5.0	4.6
	0.8	6.0										6.0	6.0	6.0	6.0	5.9	5.4	4.9
300	0.2	6.0	6.0	6.0	6.0	6.0	6.0	5.9	5.8	5.8	5.7	5.6	5.5	5.4	5.3	5.2	4.9	4.7
	0.4	6.0					6.0	6.0	6.0	6.0	6.0	6.0	5.9	5.9	5.8	5.7	5.4	5.2
	0.6	6.0										6.0	6.0	6.0	6.0	6.0	5.9	5.7
	0.8	6.0														6.0	6.0	6.0

Table 45 Continued

D.Sa	P	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	35	40
		ETm = 8.0 mm/day																
25	0.2	6.7	5.0	3.8	3.0	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.4	7.5	5.4	4.0	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.6	8.0	5.8	4.1	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	8.0	6.1	4.2	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	7.8	6.7	5.8	5.0	4.3	3.8	3.4	3.0	2.7	2.5	2.2	2.1	1.9	1.8	1.7	1.4	1.3
	0.4	7.9	7.5	6.4	5.4	4.6	4.0	3.5	3.1	2.8	2.5	2.2	2.1	1.9	1.8	1.7	1.4	1.3
	0.6	8.0	8.0	7.0	5.8	4.8	4.1	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
	0.8	8.0	8.0	7.6	6.1	5.0	4.2	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
100	0.2	8.0	7.8	7.3	6.7	6.2	5.8	5.3	5.0	4.6	4.3	4.0	3.8	3.6	3.4	3.2	2.8	2.5
	0.4	8.0	8.0	7.9	7.5	6.9	6.4	5.9	5.4	5.0	4.6	4.3	4.0	3.7	3.5	3.3	2.8	2.5
	0.6	8.0	8.0	8.0	8.0	7.6	7.0	6.4	5.8	5.3	4.9	4.5	4.1	3.8	3.6	3.3	2.9	2.5
	0.8	8.0			8.0	8.0	7.6	6.9	6.1	5.5	5.0	4.5	4.1	3.8	3.6	3.3	2.9	2.5
150	0.2	8.0	8.0	7.8	7.5	7.1	6.7	6.4	6.1	5.8	5.5	5.2	5.0	4.7	4.5	4.3	3.9	3.5
	0.4	8.0	8.0	8.0	8.0	7.8	7.5	7.1	6.7	6.4	6.0	5.7	5.4	5.1	4.8	4.6	4.1	3.6
	0.6	8.0			8.0	8.0	8.0	7.7	7.4	7.0	6.6	6.2	5.8	5.5	5.1	4.8	4.2	3.7
	0.8	8.0					8.0	8.0	7.9	7.6	7.1	6.6	6.1	5.7	5.3	5.0	4.3	3.7
200	0.2	8.0	8.0	8.0	7.8	7.5	7.2	7.0	6.7	6.5	6.2	6.0	5.7	5.5	5.3	5.1	4.7	4.3
	0.4	8.0		8.0	8.0	8.0	7.9	7.7	7.5	7.2	6.9	6.6	6.4	6.1	5.9	5.6	5.1	4.6
	0.6	8.0				8.0	8.0	8.0	8.0	7.8	7.6	7.3	7.0	6.7	6.4	6.1	5.4	4.8
	0.8	8.0							8.0	8.0	8.0	7.9	7.6	7.2	6.9	6.5	5.7	5.0
300	0.2	8.0	8.0	8.0	8.0	7.9	7.8	7.6	7.5	7.3	7.1	6.9	6.7	6.6	6.4	6.2	5.8	5.5
	0.4	8.0			8.0	8.0	8.0	8.0	8.0	7.9	7.8	7.6	7.5	7.3	7.1	6.9	6.5	6.0
	0.6	8.0							8.0	8.0	8.0	8.0	8.0	7.9	7.7	7.6	7.1	6.7
	0.8	8.0											8.0	8.0	8.0	8.0	7.7	7.1

Table 45 Continued

D. Sa		ETm 10.0 mm/day 2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	35	40
25	0.2	7.8	5.4	4.0	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.4	8.7	5.7	4.1	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.6	9.5	6.0	4.2	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
	0.8	10.0	6.2	4.2	3.1	2.5	2.1	1.1	1.6	1.4	1.3	1.1	1.0	1.0	0.9	0.8	0.7	0.6
50	0.2	9.4	7.8	6.4	5.4	4.6	4.0	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
	0.4	10.0	8.7	7.0	5.7	4.8	4.1	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
	0.6	10.0	9.5	7.6	6.0	4.9	4.2	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
	0.8	10.0	10.0	8.1	6.2	5.0	4.2	3.6	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.4	1.3
100	0.2	10.0	9.4	8.6	7.8	7.1	6.4	5.9	5.4	5.0	4.6	4.3	4.0	3.7	3.5	3.3	2.8	2.5
	0.4	10.0	10.0	9.5	8.7	7.8	7.0	6.3	5.7	5.2	4.8	4.4	4.1	3.8	3.6	3.3	2.8	2.5
	0.6	10.0	10.0	10.0	9.5	8.5	7.6	6.8	6.0	5.4	4.9	4.5	4.2	3.8	3.9	3.3	2.9	2.5
	0.8	10.0		10.0	10.0	9.3	8.1	7.1	6.2	5.6	5.0	4.5	4.2	3.9	3.6	3.3	2.9	2.5
150	0.2	10.0	9.9	9.4	9.9	8.3	7.8	7.3	6.8	6.4	6.0	5.7	5.4	5.1	4.8	4.6	4.0	3.7
	0.4	10.0	10.0	10.0	8.7	9.2	8.7	8.1	7.5	7.0	6.6	6.1	5.7	5.4	5.1	4.8	4.2	3.7
	0.6	10.0		10.0	10.0	9.9	9.5	8.9	8.2	7.6	7.0	6.5	6.0	5.6	5.3	4.9	4.3	3.7
	0.8	10.0			10.0	10.0	10.0	9.6	8.9	8.1	7.4	6.8	6.2	5.8	5.4	5.0	4.3	3.7
200	0.2	10.0	10.0	9.8	9.4	9.0	8.6	8.2	7.8	7.4	7.1	6.7	6.4	6.1	5.9	5.6	5.1	4.6
	0.4	10.0	10.0	10.0	10.0	9.8	9.5	9.1	8.7	8.2	7.8	7.4	7.0	6.7	6.3	6.0	5.4	4.8
	0.6	10.0			10.0	10.0	10.0	9.8	9.5	9.0	8.5	8.1	7.6	7.2	6.8	6.4	5.6	4.9
	0.8	10.0					10.0	10.0	10.0	9.8	9.3	8.7	8.1	7.6	7.1	6.6	5.7	5.0
300	0.2	10.0	10.0	10.0	9.9	9.7	9.4	9.2	8.9	8.6	8.3	8.0	7.8	7.5	7.3	7.1	6.5	6.0
	0.4	10.0		10.0	10.0	10.0	10.0	9.9	9.7	9.5	9.2	8.9	8.7	8.4	8.1	7.8	7.1	6.5
	0.6	10.0					10.0	10.0	10.0	10.0	9.9	9.7	9.5	9.2	8.9	8.5	7.7	7.0
	0.8	10.0								10.0	10.0	10.0	10.0	9.9	9.6	9.3	8.3	7.4

Calculations Steps :

(a) D. Sa = $0.6 \times 100 = 60$ mm or say 50 mm

(b) Wheat group is III.
P for group III when ETm = 5 mm is 0.50 (Tables 42 and 43).

(c) Average ETa on 10th day $= \dfrac{3.5+3.8+4.2+4.6}{4} = 4.25$ mm/day

(Average for P and ETm from Table 45)

Irrigation Interval :

In the above example, the irrigation interval for the crop is given by :

$$\text{Irrigation Interval} = \frac{\text{D. Sa}}{\text{ETm}} = \text{P}$$

$$= \frac{60 \times 0.50}{5} = 6 \text{ days}$$

Of course this is only an academic exercise as rotation cannot be designed for a particular crop at a particular stage. This illustration is given to understand the logic for further use.

Yield Response to Stress

Yield of crop depends on many factors, such as crop variety, soil, climatic conditions, Irrigation, Use of fertilizers and pesticides, level of management etc. Maximum yield will be obtained when all these factors contribute to their optimum level. Other factors being unrestricted, the yield is maximum when Ea = ETm i. e. when the crop draws water equal to its evapotranspiration needs. When ETa drops below ETm, the yield also decreases and this yield decrease is proportional to the deficit in ETm. The ratio of deficit in yield to the deficit in ETm is called the yield response factor Ky. The relation can be mathematically expressed as–

$$\left(1 - \frac{Ya}{Ym}\right) = Ky \left(1 - \frac{ETa}{ETm}\right)$$

Where Ya = Actual yield

Ym = Maximum yield.

ETa = Actual water used by crop

ETm = Evapotranspiration needs of crop

'a and ETm can be for the entire growth periods or for a specific part of crop and Ym will accordingly be for the entire growth periods or for specific part of period. The values of Ky vary with crop and growth periods.

e reduction in yield can be computed for the entire period if the deficit in water read over the growth period. However, if the deficit is different over different ods, the deficit in yield for each period has to be calculated and then summed

: us first consider the case where water stress is uniformly distributed over the :h period.

crops are divided into 7 groups, if the Ya is to be estimated trom graphs given 36. These groups are indicated in the figure itself. From the value of deficit re period, the value of deficit in yield can be calculated.

mple : The total requirement of wheat is 580 mm. The average ETa over the d of 125 days was 3.45 mm/day. Calculate the probable yield reduction.

a) Average ETm : 580 - 125 = 4.64 mm/day

b) ETa : Data = 3.45 mm/day

c) $\left(1 - \frac{ETa}{ETm}\right) = \left(1 = \frac{3.45}{4.64}\right) = 0.256$

d) $\left(1 - \frac{Ya}{Ym}\right)$ = From graph = 0.250

. the yield reduction will be 25% (approximately) of the maximum yield.

;ame can be calculated form Table No. 46 also. The Ky factor for winter wheat

$$\left(1 - \frac{Ya}{Ym}\right) = Ky\left(1 - \frac{ETa}{ETm}\right)$$

$$- \frac{ya}{ym} \quad) = 1 \times 0.256$$

$$- \frac{Ya}{Ym}) = 0.256$$ i. e The yield reduction is 25.63 %

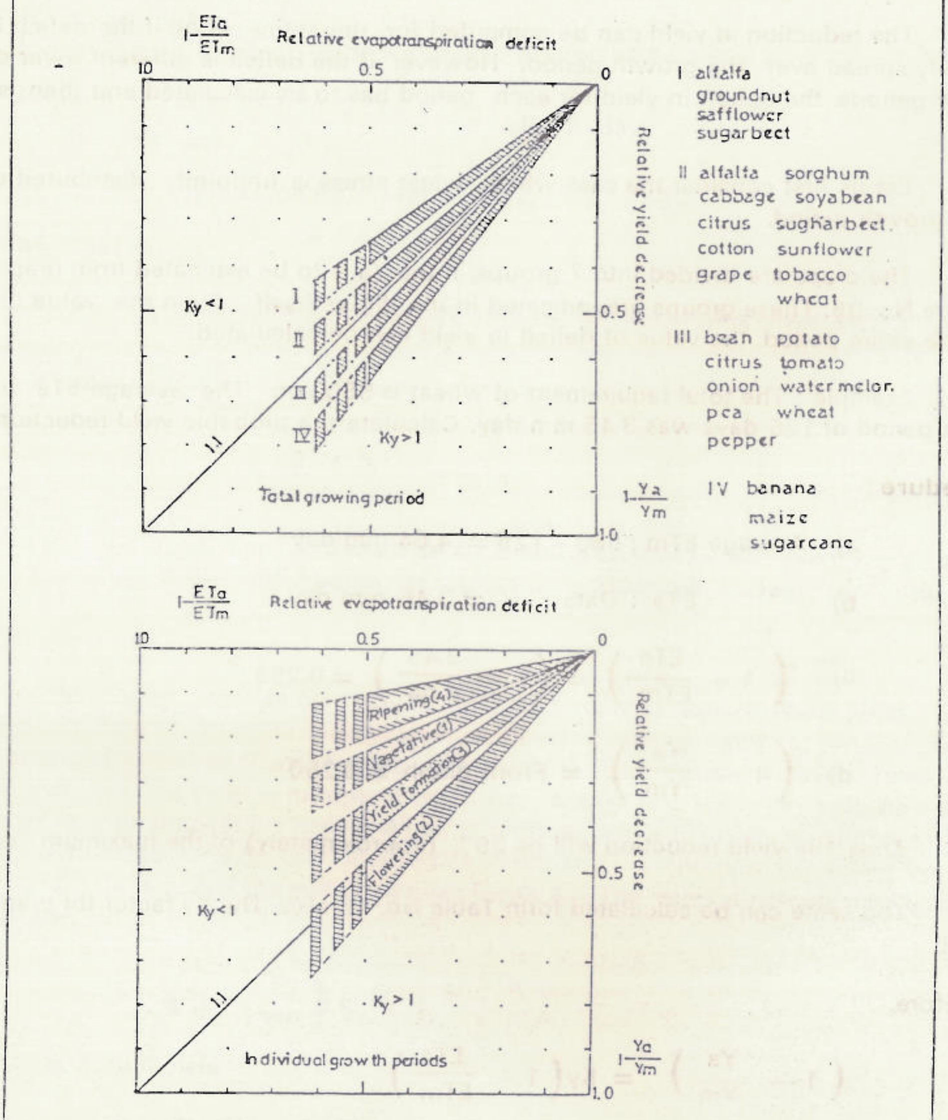

FIG.36. GENERALIZED RELATIONSHIP BETWEEN RELATIVE YIELD DECREASE (1-Ya / Ym) AND RELATIVE EVAPOTRANSPIRATION (1-ETa / ETm)

Trd: B.S. Dulguch

Crop
Alfalfa
Banana
Bean
Cabbage
Citrus
Cotton
Grape
Groundnut
Maize
Onion
Pea
Pepper
Potato
Safflower
Sorghum
Soybean
Sugarbeet
beet
sugar
Sugarcane
Sunflower
Tobacco
Tomato
Water melon
Wheat
winter
spring

Table 46

Yield Response Factor (ky)

Crop	Vegetative period (1)			Flowering period	Yield formation	Ripening	Total growing period
	early (Ia)	late (Ib)	total	(2)	(3)	(4)	(5)
Alfalfa			0.7-1.1				0.7-1.1
Banana							1.2-1.35
Bean			0.2	1.1	0.75	0.2	1.15
Cabbage	0.2				0.45	0.6	0.95
Citrus							0.8-1.1
Cotton			0.2	0.5		0.25	0.85
Grape							0.85
Groundnut			0.2	0.8	0.6	0.2	0.7
Maize			0.4	1.5	0.5	0.2	1.25
Onion			0.45		0.8	0.3	1.1
Pea	0.2			0.9	0.7	0.2	1.15
Pepper							1.1
Potato	0.45	0.8			0.7	0.2	1.1
Safflower		0.3		0.55	0.6		0.8
Sorghum			0.2	0.55	0.45	0.2	0.9
Soybean			0.2	0.8	1.0		0.85
Sugarbeet							
beet							0.6-1.0
sugar							0.7-1.1
Sugarcane			0.75		0.5	0.1	1.2
Sunflower	0.25	0.5		1.0	0.8		0.95
Tobacco	0.25	1.0			0.5		0.9
Tomato			0.4	1.1	0.8	0.4	1.05
Water melon	0.45	0.7		0.8	0.8	0.3	1.1
Wheat							
winter			0.2	0.6	0.5		1.0
spring			0.2	0.65	0.55		1.15

Stress in a Particular growth period :

The crop has the following growth stages :

a) Establishment Period

b) Vegetative growth period

c) Flowering period

d) Grain formation period

e) Ripening period

The establishment period is sometimes called early vegetative period. The Ky factors in each of these stages is different. Hence the reduction in yield due to stress in each period will be different.

For the growth periods of the above variety of wheat, the water requirements and ETa values during each period are as under.

	Est. Period	Veg. Growth	Flowering	Yield Formation	Ripening	Total
Growth period in days	12	45	20	35	13	125
Water requirements in mm.	17	180	124	220	39	580
ETa in mm	17	130	78	170	35	430

The yield reduction in this case can be calculated as under :

	Est. Period	Veg. Growth	Flowering	Yield Formation	Ripening	Total
$\frac{ETa}{ETm}$	$\frac{17}{17}$	0.72	0.63	0.78	0.90	
$1 - \frac{ETa}{ETm}$	0	0.28	0.37	0 22	0.10	
Ky (from table)	–	0.20	0.60	0.5	0.00	
Yield reduction %	Nil	5.60	22.20	11.00	0.00	38.80

Thus, with the stress distribution not being uniform, the yield reduction has changed. In this particular distribution of stress, the yield reduction has increased because of high stress during flowering and yield formation stages. Let us consider a case of stress distribution where stress during the above two stages is comparatively small.

	Est. Period	Veg. Growth	Flowering	Yield formation	Repening	Total
Growth period in days	12	45	20	35	13	125
Water requiremet in mm	17	180	124	2˜0	39	580
ETa in mm	17	50	120	220	23	430
$\left(\frac{ETa}{ETm}\right)$	1	0.28	0.97	1 00	12	
$\left(1 - \frac{ETa}{ETm}\right)$	0	0.72	0.03	0.00	0.41	
Ky (from Table)	0 20	0.20	0.60	0 50	0.00	
Yield reduction%	0.00	14.40	2.00	0.00	0.00	16.40

Thus we have three cases for the same deficit of water -

— When, the stress of 26% is uniformity distributed over the growth period, the yield reduction ic about 25.5%.

— When the stress is dominantly in vegetative, flowering and yield formation stages, the yield reduction is about 39%.

— When the stress is dominantly in vegetative and ripening period, the yield reduction is only 16.5%.

This shows the importance of the stress in a particular stage or the sensitivity of the crop to water stress in a particular period. Most crops are sensitive to water stress during the flowering and yield formation stage. A table showing the values of Ky for different growth periods of crops is given as table No. 46. The crop is more sensitive to the water stress when the value of Ky is more. Graphical representation of the generalised relationship between yield decrease and relative evapotranspiration can be seen in figure 36. However, for individual crops, it is better to refer to individual Ky factors.

The stress can be distributed over the desired period by irrigation scheduling, when the constraint of water is known in advance. Even if there is no constraint of water, the saving in the water caused by inducing the stress can be utilised on additional land, and total yield per m^3 of water can be optimised. In this case the yield per ha of land may be somewhat less but the yield per m^3 of water is more. These factors are discussed in more details in further paras under practical applications.

Potential Yield (Ym) :

In the above discussions, the yield reduction is computed in terms of percentage, of maximum yield. On practice, the actual values of Ym are necessary. A table (No. 47) showing the generalised values of the harvest yield (not the dry matter) are shown. The potential yield at a specific location can be computed if the climatic data is available. For computation methods, the reoder is invited to refer to F.A.O. Publication No. 33.

Table : 47 Good Yields of High-producing Varieties adapted to the Climatic Conditions of the Available Growing Season under Adequate Water Supply and High Level of Agricultural Inputs under Irrigated Farming Conditions (ton/ha)

<table>
<tr><th rowspan="3" colspan="2">CROP</th><th colspan="6">Climatic Regions</th></tr>
<tr><th colspan="2">Tropics 1/</th><th colspan="2">Subtropics 2/</th><th colspan="2">Temperate 3/</th></tr>
<tr><th><20°C 4/</th><th>>20°C</th><th><20°C</th><th>>20°C</th><th><20°C</th><th>>20°C</th></tr>
<tr><td>Alfalfa</td><td>hay</td><td colspan="2">15</td><td colspan="2">25</td><td colspan="2">10</td></tr>
<tr><td>Banana</td><td>fruil</td><td></td><td>40-60</td><td></td><td>30-40</td><td></td><td></td></tr>
<tr><td>Bean : fresh</td><td>pod</td><td>6-8</td><td></td><td>6-8</td><td></td><td>6-8</td><td></td></tr>
<tr><td>dry</td><td>grain</td><td>1.5-2.5</td><td></td><td>1.5-2.5</td><td></td><td>1.5-2.5</td><td></td></tr>
<tr><td>Cabbage</td><td>head</td><td>40-60</td><td></td><td>40-60</td><td></td><td>40-60</td><td></td></tr>
<tr><td>Citrus :</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>grapefruit</td><td>fruit</td><td></td><td>35-50</td><td></td><td>40-60</td><td></td><td></td></tr>
<tr><td>lemon</td><td>fruit</td><td></td><td>25-30</td><td></td><td>30-45</td><td></td><td></td></tr>
<tr><td>orange</td><td>fruit</td><td></td><td>20-35</td><td></td><td>25-40</td><td></td><td></td></tr>
<tr><td>Cotton</td><td>seed cotton</td><td></td><td>3-4</td><td></td><td>3-4.5</td><td></td><td></td></tr>
<tr><td>Grape</td><td>fruit</td><td colspan="2">5-10</td><td colspan="2">15-30</td><td colspan="2">15-25</td></tr>
<tr><td>Groundnut</td><td>nut</td><td></td><td>3-4</td><td></td><td>3.5-4.5</td><td></td><td>1.5-2</td></tr>
<tr><td>Maize</td><td>grain</td><td>7-9</td><td>6-8</td><td>9-10</td><td>7-9</td><td></td><td>4-6</td></tr>
<tr><td>Olive</td><td>fruit</td><td></td><td></td><td></td><td>7-10</td><td></td><td></td></tr>
<tr><td>Onion</td><td>bulb</td><td>35-45</td><td></td><td>35-45</td><td></td><td>35-45</td><td></td></tr>
<tr><td>Poa : fresh</td><td>pod</td><td>2-3</td><td></td><td>2-3</td><td></td><td>2–3</td><td></td></tr>
<tr><td>dry</td><td>grain</td><td>0.6-0.8</td><td></td><td>0.6-0.8</td><td></td><td>0.6-0.8</td><td></td></tr>
<tr><td>Fresh pepper</td><td>fruit</td><td colspan="2">15-20</td><td colspan="2">15-25</td><td colspan="2">15-20</td></tr>
<tr><td>Pincapple</td><td>fruit</td><td></td><td>75-90</td><td></td><td>65-75</td><td></td><td></td></tr>
<tr><td>Potato</td><td>tuber</td><td>15-20</td><td></td><td>25-35</td><td></td><td>30-40</td><td></td></tr>
<tr><td>Rice</td><td>paddy</td><td></td><td>6-8</td><td></td><td>5-7</td><td></td><td>4-6</td></tr>
<tr><td>Safflower</td><td>seed</td><td></td><td></td><td colspan="2">2-4</td><td></td><td></td></tr>
<tr><td>Sorghum</td><td>grain</td><td>3-4</td><td>3.5-5</td><td>3-4</td><td>3.5-5</td><td></td><td>2-3</td></tr>
<tr><td>Soybean</td><td>grain</td><td colspan="2">2.5-3.5</td><td colspan="2">2.5-3.5</td><td></td><td></td></tr>
<tr><td>Sugarbeet</td><td>beet</td><td></td><td></td><td colspan="2">40-60</td><td colspan="2">35-55</td></tr>
<tr><td>Sugarcane</td><td>cane</td><td></td><td>110-150</td><td></td><td>100-140</td><td></td><td></td></tr>
<tr><td>Sunflower</td><td>seed</td><td colspan="2">2.5-3.5</td><td colspan="2">2.5-3.5</td><td colspan="2">2-2.5</td></tr>
<tr><td>Tobacco</td><td>leaf</td><td></td><td>2-2.5</td><td></td><td>2-2.5</td><td></td><td>1.5-2</td></tr>
<tr><td>Tomato</td><td>fruit</td><td colspan="2">45-65</td><td colspan="2">55-75</td><td colspan="2">45-65</td></tr>
<tr><td>Water melon</td><td>fruit</td><td></td><td>25-35</td><td></td><td>25-35</td><td></td><td></td></tr>
<tr><td>Wheat</td><td>grain</td><td>4-6</td><td></td><td>4-6</td><td></td><td>4–6</td><td></td></tr>
</table>

1) Semi-arid and arid areas only.
2) Oceanic and winter rainfall areas.
3) Oceanic and continental areas.
4) Mean temperature.

Net Irrigation Requirement With Consideration of Soil Moisture

The crop water requirements are satisfied either by natural precipitation, or by irrigation or from moisture stored in soil. In fact, the crops draw water only from the soil through their root system. The rain water or the irrigation water is added to the soil moisture first and then it can find its way to the crop roots. The soil moisture is thus a reservoir from which the crop draws its requirement of water and to which water is added either of rains or of irrigation. This concept is already explained under "Water Balance", and can be used to estimate the "Net Irrigation Reqirements" more accurately.

It is already established that the crop can draw water from the soil in sufficient quantity if the soil moisture is between the field capacity stage and the management allowed deficit stage. Thus the soil moisture in between these two stages is useful and available to the crop. Conversely, if the soil moisture is maintained within this range' the crop can maintain a healhy growth.

Every irrigation system has its own constraints. These are mainly in the fixed irrigation dose and the fixed time of irrigation. Let us consider that the irrigation dose is 70 mm at root zone in a irrigation system. Let us assume that the soil to be irrgated is of 200 mm Field Capacity with allowable depletion level of 50% or the avilable moisture can be 100 mm (maximum). The root zone depth is assumed to be 1 m. Before the irrigation begins. the soil may be at any moisture content. The avilable moisture may be 100 mm., O, or even less i. e. below the allowed depletion level. Let us analyse these different situations for understanding the problem.

a) When the available moisture is 100 mm.

In this case, any irrigation that we apply is wasted as the soil is not able to hold any additional water. It would be like pouring water in a bucket, which is already full of water. The applied irrigation water may be lost as deep percolation and may add to the under-ground water table. The irrigation in this case is purpcseless. The crop water demand is met with, from the 100 mm that the soil is already holding.

b) When the available water is 50 mm.

The soil will accomodate 50 mm of irrigation water and 20 mm will be lost as deep percolation. Extending the same reasoning, the ideal situation is if the soil has an available moisture of 30 mm. The soil will accomodate all the 70 mm and be at its maximum capacity of 100 mm. after irrigation

The situation slightly changes when the available moisture is less than 30 mm. The soil will be able to accomodate all the irrigation water of 70 mm but will not reach the maximum holding capacity of 100 mm. It may still be possible to meet the crop water demand, depending upon the ETc of the crop grown.

c) The situation when the available moisture content is zero or the moisture content is less than the allowable depletion level is similar to the one avove. The irrigation will have to make good the deficit up to the depletion level and only the balance will be available for crop growth. Such situation is very rare and hence not discussed in detail.

A specific example of cotton sown in 2nd fortnight of may is worked out in details in table No. 48. This will illustrate the procecdure. The water holding capacity of the soil is 200 mm and the MAD level is 50%. The soil is presoaked in f rst fortnight of May. The Etc effective rainfall figres are only indicative as the main purpose of exercise is to illustrate the procedure. The available moisture content will vary with the root zone depth of the crop, but this aspect is also disregarded for simplification.

Tabie No 48 : NIR FOR COTTON CROP

Period		Soil Moisture in the begi-nning in mm.	Effective Rainfall in mm.	Total	ETc in mm.	Irrigation necessary (mm)	Soil moisture at the end (mm) Limited to 100 mm.
May	I	—	—	—	—	100*	100
	II	100	3	103	25	—	78
June	I	78	44	122	28	—	94
	II	94	45	139	30	—	109(100)
July	I	100	55	155	35	—	120(100)
	II	100	56	156	40	—	116(100)
Aug.	I	100	64	164	45	—	119(100)
	II	100	64	164	63	—	101(100)
Sept.	I	100	62	162	77	—	85
	II	85	63	148	84	—	64
Oct.	I	64	2)	84	92	70**	62
	II	62	20	82	81	70**	71
Nov.	I	71	5	76	80	70**	66
	II	66	5	71	66	70**	75
Dec.	I	75	—	75	55		20
	II	20	—	—	—	—	
					811	330	
					+ 100		
					911		

* Presoaking requirement

** Minimum irrigation practicable.

Practical Applications

The techniques for computing the Crop Water Requirements/Net Irrigation Requirements and the logic behind these techniques have been discussed so far. The development of these methods started in the late fifties and reached the confidence level in late seventies. It is now an accepted fact for about two decades that these methods predict the crop water requirements with reasonable degree of accuracy. Yet, the field irrigation engineer is somewhat shy in introducing these techniques in his daily use. His reluctance to use of these techniques arises from two attitudes.

a) We have been practicing irrigation for the last so many decades without these techniques, and we are doing well. Why start using these methods now ?

b) These metods may be more accurate and realistic, but our systems have been designed with certain methodology and assumptions. How can these methods be used within the system constraints ?

The first atitude can be waived away. Even a good system can be made better by assimilating new concepts and technologies. With time, the aim of irrigation has changed from protective to productive. With the introduction of new crop varieties, the optimisation of benefits in relation to all inputs is now aimed at. We have to adopt these concepts and techniques to turn our good system into a better one.

The second objection does have some substance in it. We have a system and its constraints. Whatever improvements we desire, must be within these constraints of system and other resources. The foliwing paras discuss how better results in use of water may be possible with the use of these methods within the existing system constraints. The main objective of these discussions is to start thinking in this direction.

a) Verification of the assumptions in design :

The water requirements of crops are being traditionally worked out by assuming certain duties of crops. These assumed values depend on the experience of the planning engineer. His experience may not be in the same climatological region where the planning is being done. In this case, the assumption of values may depend on his experience and skill.

On the other hand, the crop water requirement can be worked out at the desired probability level with the climatological data of the region. This is now mostly practiced where the extensive data is avilable. The question arises when extensive data is not avilable. It is suggested that Hargreave 's equation which requires only latitude and the temperature data, may be used in such cases. The details of the procedure are given in earlier paragraphs.

Table - 49 Evapotranspiration Values for Proposed Cropping Pattern (mm)

	June		July		Aug.		Sept.		Oct.		Nov.		Dec.		Jan.		Feb.		Mar.		Apr.		May	
ETo	124	99	85	74	74	73	73	76	83	83	76	70	66	66	70	78	83	97	112	131	140	153	166	151
Etcrop																								
Sugarcane	130	104	90	80	81	84	88	86	86	79	70	62	57	57	57	68	76	91	108	130	144	161	174	159
Banana	104	77	139	121	111	111	105	105	56	59	56	53	54	57	64	75	83	102	122	144	154	164	166	134
Paddy			71	66	75	78	80	84	86	82														
Sorghum(k)	48	49	54	67	78	77	70	49																
Wheat										75	34	39	67	76	81	90	78	41						
Sorghum(R)								21	32	56	78	80	73	70	68	54								
Gram									24	32	65	77	73	55	30									
Cotton	28	30	35	40	45	63	77	86	92	91	80	66	55										100	26
Chillies			41	39	48	62	75	84	91	90	72	51												
Groundnuta																	100	67	114	138	147	148	129	

Pre-somking requirements.

Table – 50 Crop Water Requirements in m3/ha at Crop for Proposed Cropping Pattern

Crop	%	June		July		Aug.		Sept.		Oct.		Nov.		Dec.		Jan.		Feb.		Mar.		Apr.		May	
Sugarcane	3	39	31	27	24	24	25	27	26	26	24	21	19	17	17	17	20	23	27	32	39	43	48	52	48
Banana	1.5	16	12	21	18	17	17	16	16	8	9	8	8	8	9	10	11	12	15	18	22	23	25	25	20
Paddy	10	—	—	71	66	75	78	80	81	86	82														
Sorghum(k)	12	58	59	64	80	94	92	84	59																
Wheat	25										187	85	98	167	190	202	225	195	102						
Sorghum(R)	15								32	48	84	117	120	110	105	102	81								
Gram	5									12	16	33	39	37	28	15									
Cotton	25	70	75	88	100	113	158	193	210	230	228	200	165	138										250	63
Chillies	3			12	12	14	19	23	25	27	27	22	15												
Grondnuts	3																	30	20	34	41	44	44	36	
Total	102.5	183	177	283	300	337	389	423	452	437	657	486	464	477	349	346	337	260	164	84	102	110	117	363	131

Table No. 51 **Water Requirement for each Fortnight**

Fortnight	Water Requirement m³ /ha.	Irrigation Intensity	Water Requirement in m³ /ha.	Water Requirement in mm	Effective Rainfall in mm.	Water Requirement in mm	Water Requirement in mm (efficiency 0.7%) cutlet	AI/DC	
1	2	3	4	5	6	7	8	9	
Jan. I	346	0.495	699	69.9	—	69.9	100	6.10	
II	337	0.445	757	75.7	—	75.7	108	5.64	
Feb. I	260	0.325	800	80.0	—	80.0	114	5.34	
II	164	0.325	505	50.5	—	50.5	72	8.46	
							883		
Mar. I	84	0.075	1120	112.0	—	112.0	160	3.81	
II	102	0.075	1360	136.0	—	136.0	194	3.14	
Apr. I	110	0.075	1467	146.7	—	140.7	209	2.91	
II	117	0.075	1560	156.0	—	156.0	223	2.73	
May I	363	0.325	1117	111.7	—	111.7	160	3.81	
II	131	0.295	444	44.0	—	44.0	63	9.66	
June I	183	0.415	441	44.1	—	44.0	63	9.66	
II	177	0.415	426	42.6	45	—	64	9.5	
							1136		
July I	283	0.545	519	51.9	55	—	78.6	7.75	
II	300	0.545	550	55.0	56	—	—	7.70	
Aug. I	337	0.545	618	61.8	62	—	—	—	
II	389	0.545	714	71.4	64	7.4	11	55	Rainy Season
Sept. I	453	0.545	776	77.6	61	16.6	24	25	
II	452	0.695	650	65.0	63	2.0	3	203	
Oct. I	437	0.625	699	69.9	20	49.9	71	8.58	
II	657	0.875	750	75.0	20	55.0	78	8.81	
Nov. I	486	0.775	627	62.7	—	62.7	90	6.77	
II	464	0.775	599	59.9	—	59.9	86	7.10	
Dec. I	477	0.745	640	64.0	—	64.0	91	6.77	
II	349	0.495	705	70.5	—	70.5	100	6.10	
Total :	7428				490				

A set cf simple tables can verify the design assumptions of duties, AI/DC etc. ample set of tables is shown as Table Nos. 49 to 51. Table No. 49 shows the ETo and values of the project crops for every fortnight. Table No. 50 shows the values of gross er requirements of every crop for every fortnight. This does not include effective rainfall. e No. 51 shows the water requirements in m^3 /ha effective rainfall, and AI/DC for y fortnight. These tables will naturally vary with every project. The total water require– t of the project according to these tables (Column 2 of Table 51) is 7428 m^3 /ha while effective rainfall is 490 mm or 4900 m^3 /ha The water requirements at outlet distri– ry head or canal head can be worked out by applying proper efficiencies.

provements in Operation :

Once we compare the actual requirements with the design assumptious, opera- l imprcvements are possible.

The net water requirements in Rabi (15 th Oct. to end of Feb.) are 833 mm in 9 rotations or 98 mm/rotation at out let head.

This corresponds to 6 acres/cusec day or the value of AI/DC during Rabi at outlet head for this **mixed cropping** pattern is 6 acres. We can adjust our value to 6, and meet the actual requirements.

A look at col. nos. 8 and 9 can suggest a further improvement. The net water requirements per fortnight vary from 71 to 114 mm. The corresponding AI/DC values are 8.58 acres and 5.34 acres. A graph showing the values of water requirements in mm aginst the period is given as figure No. 37 It can be seen from the figure that for sometime we are underirrigating and for some time we are overirrigating. The suggested water supply schedule matches the actual water requirements to a better degree. It may be noted that the total water supplied is the same.

Further refinement is possible if the growth stages of crops are also taken in to t. However, that exercise is a bit complicated and hence not attempted here.

The main difficulty often pointed out is that meterelogical data of command is lable and hence during actual operation the water requirements cannot be actually d out. A study★ carried out by M/s. S. B. Varade, M. S. Palaskar and S. D. More tes that the ratio of NIR by pan-evaporation method to NIR by Modified Penman from 0. 82 to 1.00 for crops including wheat, sorghum, cotton, groundnut, sugarcane graph showing the ETo values by penman method aginst the ETo velues of pan ation method is given as figure No. 25.

ndian Journal of Agricultural Sciences 57 (3) pages 169-75, March 1987.

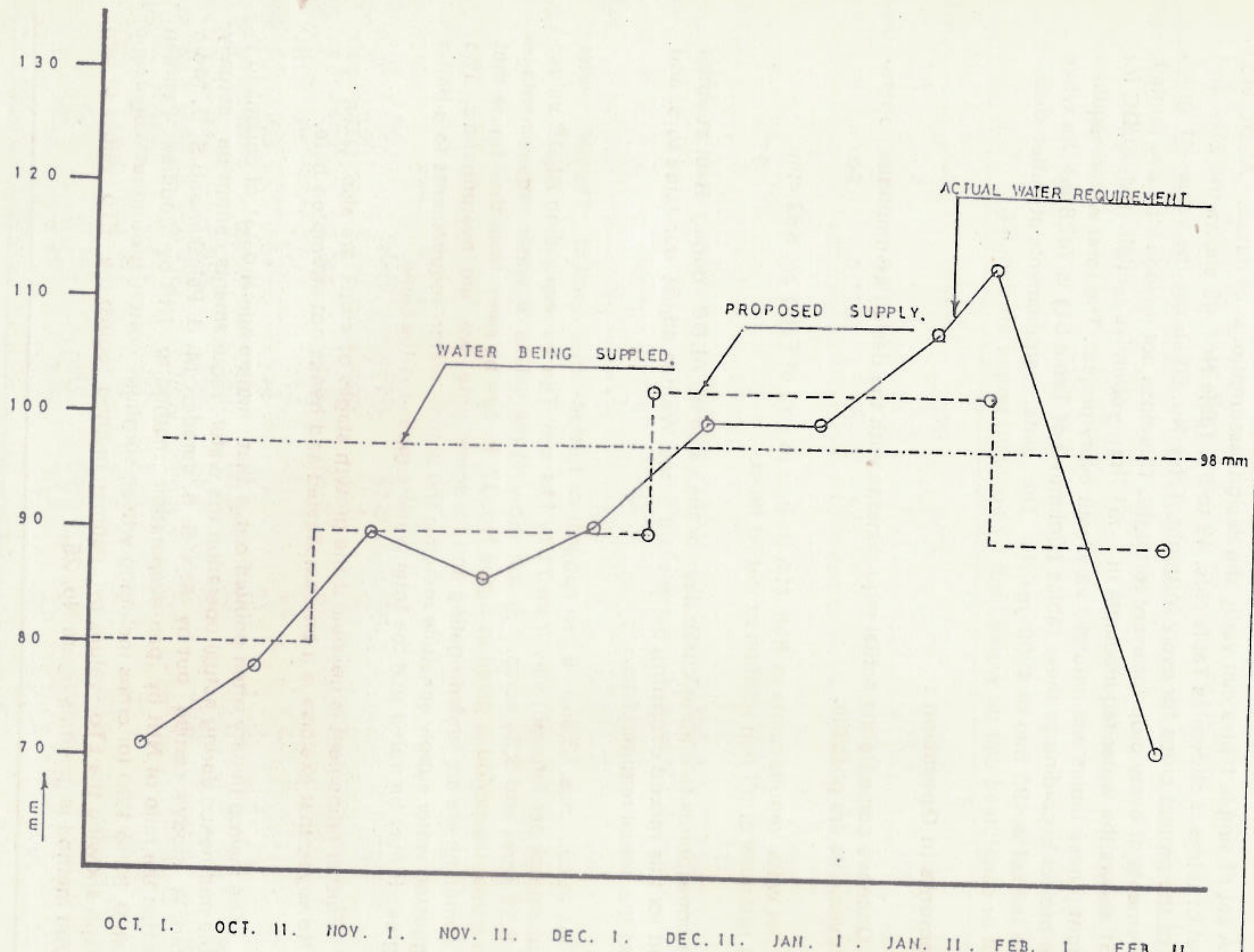

FIG. No. 37. WATER REQUIREMENT AND SUPPLY DURING RABI PERIOD.

Trd. by. B.S.Dulguch/WL /ARU/ DGR No.9. Dt:5.2.1988

Pan evaporation data can be easily observed in the command and this difficulty can be overcome, by corelating the pan evaporation values to modified penman values.

A similar comparisom between modified penman method and Har greaves method is given in earlier paras.

Canal Capacity

Usually, the canal capacity is designed for the peak water demand for rotation. This maximum demand is normally mnch higher than the demads of the neighbouring. rotations. If the soil moisture content is considered, the maximum demand can be partially met with from the soil moisture at the beginning of the rotation and the required canal capacity is much less than the maximum or peak demand This can be done by charging the soil water reservoir in the earlier two or three rotations by providing water more than the irrigation requirements. The excess water is stored in the soil and is utilised in the rotation of peak demand The reduction in the canal capacity can result in considerable economy. An example will illustrate the procedure. Table No. 52 gives the Net Irrigation Requirements in m^3 /ha of the irrigated area for the fortnight. In this, the effective rainfall is considered The crucial month is October. As a factor of safety, the Effective Rainfall is NOT CONSIDERED in October onwards. The available soil moisture is restricted to 80 mm or 800 m^3 /ha. which is a safe assumption. Even with these safe assumptions, canal capacity of 437 m^3 /ha is sufficient aginst a maximum demand of 657 m^3 /ha.

Conversely, the same technique can be adopted if the present water demand is more than the existing cannl capacity. This can happen when the crop pattern is changed or when new varieties of crops with more water requirements are introduced. The peak water demand can be evened by supplying more water in earl er rotations and utilising the soil moisture in the rotation of peak demand. Of course, the excess supply must be limited to the avilable moisture stotrge of the soil.

Deficit or Stress Irrigation :

When the avilable water is limited as in drought years, it must be used to the best advantage to the crops. The irrigation must be so planned that the water deficit occures mostly in the crop growth stages when the yield response factor is the least. Normally, the crops, especially the grain crops are less sensitive to the stress during vegetative growth period and the ripening peirod and more sensitive during the flowering stage and yield formation stage. In our mixed cropping pattern, the growth stages of different crops may be different. In a particular period, one crop may be in the vegetative growth stage while another may be in yield formation stage. While adjusting the rotations and the water supply, the dominant crop during the period will have to be considered. Personal discretion is necessary in this case. The growth stages of different crops in Maharashtra State, along- with their Ky factors in each growth stage are shown in figure No. 35. This may be useful in deciding the stress periods to be allowed. Each case will have to be individually studied.

TABLE – 52 Table showing Demand and Supply of Irrigation,

Fortnight		Soil moisture at start (m^3 / ha)	NIR m^3 / ha of actual irrigation	Irrigation proposed m^3 / ha of actual irrigation	Balance soil moisture m^3 / ha	Irrigation intensity	Water requirement m^3 / ha of I. C. A. (Col. 4 × Col. 6).
1		2	3	4	5	6	7
June	I	—	440	500	60	0.415	207.5
	II	60	—	—	60	0·415	—
July	I	60	—	—	60	0.545	—
	II	60	—	500	560	0.545	272.5
Aug.	I	560	—	—	560	0.545	
	II	560	74	—	486	0.545	
Sept.	I	486	166	—	320	0.545	
	II	320	20	500	800	0.695	347.5
Oct.	I	800	499	500	800	0.625	312.5
	II	800	750	500	550	0.875	437.5
Nov.	I	550	627	500	423	0.775	387.5
	II	423	599	500	324	0.775	387.5
Dec.	I	324	640	500	184	0.745	372.5
	II	184	705	700	179	0.495	297.5
Jan.	I	179	699	700	180	0.495	346.5
	II	180	757	700	123	0.445	311.5
Feb.	I	123	800	700	23	0.325	260.0
	II	23	505	600	118	0.325	195.0

nduced Stress For Optimum Yield :

In the planning of Irrigation projects, the optimum water requirements of crops considered i e. it is aimed to provide ETa =ETm while fixing the rotation period. This es optimum yield per ha of irrigated land. Another way of looking at optimisation is to sider optimum yield per unit of irrigation water.

Suppose, the project has X units of water which is sufficient to irrigate N_1 ha of d if the full water requirement of crop is considered. If the yield of crop is Y_1 tonnes/ha total yield is $N_1 \times Y_1$. Now, if the same quantity of water is supplied to N_2 ha where $> N_1$, the quantity of water supplied per ha will be less than the optimum requirements rops and the Yield Y_2 in this case will be less than Y_1 . However, the total yield of the ect, $N_2 Y_2$ may be more than $N_1 Y_1$. This is because the saving in water has irrigated itional land and the yield from this additional land has outweighed the reduction in yield sed by deficit supply of water. The maximum value of the product of N and Y will give optimum yield of the project. In this case, we provide ETa which is less than ETm i.e. s or deficit irrigation is resorted to and maximum yield per unit of water is aimed. Other ntages of induced stress irrigation are :

— Application efficiency is increased.

— The benefits are dispersed over a larger area and population.

— Drainage and water logging problems, especially in Heavy soils are reduced.

The deficit irrigation can be achieved by reducing the depth of water application in xisting rotation or by increasing the rotation period without altering the depth of appli- n. Since, the reduction in depth of application has other limiting factors, the later od is more convenient. Yet another method usually practised is to select the the deple- evel and then compute the rotation period and depth of application. This method has dvantage of ensuring the available water at a definite level of depletion.

The method uses the relationship between the depletion level and the AVERAGE factor during the time required to reach that depletion level.

The stress factor Kavs $= \frac{ETa}{ETm} = 1 - 0.204\ (DL^2)$

Where DL is the desired depletion level in percentage. Thus for a depletion level of

$\frac{ETa}{ETm}$ will be $1 - 0.204\ (0.75)^2$

$= 1 - 0.204 \times 0.56 = 1 - 0.115$

$= 0.885$

$ETa = 0.885\ ETm$.

A case study presented by M/s A. R. Suryawanshi, S. B. Varade. M.M. Patwardhan and D. G. Holsambre during "National Seminar on Irrigation Study" illustrates the case. Table Nos. 53 & 56 give the details of the case study. The advantages of low frequency defict irrigation have been presented in Table 56.

More research and study in this directions is however needed.

Some of the areas where the knowledge of precise crop water requirement can be applied, are discussed above. This is by no means a complete review of these areas and many more areas may be available where this knowledge can be fruitfully applied.

Table No. 53
Rabi Cropping Pattern Of a Project
(100 ha Of Irrigable Area)

Sr. No.	Crop	Percentage	Area ha	Crop Water requirement in Rabi (Based on Modi fied Penman Method (Total ET_m)mm
1.	Sugarcane including other perinnials	4.5	4.5	548
2.	Wheat	25	25	536
3.	Hy. Jawar (Sorghum)	15	15	450
4.	Gram	5	5	394

Other datails required for scheduling are

Field Capacity (FC) — 35% (on weight basis)

Bulk Density — 1.2 gms / cc.

Soil depth considered is 0.9 m. Root zone depths of Various crops considered are as follows though the growth is not full in the initial stage.

Sugarcane	—	1.2
Wheat	—	0.9
Sorghum	—	1.0
Gram	—	0.6

Frequency of Irrigation

Sr. No.	Crop	Root zone depth or soil depth whichever is less (m)	Available water (★) (mm) col 3 × 180	Frequency for 40% depletion (Case I): Available water at 40 % depletion (mm) col.4 × 0.4	Peak use Rate ET_m (mm/day)	Frequency (days) col. 5 ÷ col.6	Frequency for 75 % depletion (Case II): Available water at 75% depletion (mm) col.4 × 0.75	Peak use rate ET_a ET = 0.88 ETm) col.6 X 0 88	Frequency days. col. 8 ÷ col. 9
1	2	3	4	5	6	7	8	9	10
1.	Sugarcane	0.9	162	65	6.0	11	122	5.3	23
2.	Wheat	0.9	162	65	6.2	10	122	5.5	22
3.	Sorghum	0.9	162	65	6.0	11	152	5.3	23
4.	Gram	0.6	108	43	5.4	8	81	4.8	17

(★) A vailable water = F. C. — Pwp) ★ Bulk Density

= (35–20) ★ 1.2

= 18 cm/m depth of soil.

= 180 mm/m depth of soil.

Table No. 55

Equivalent Wheat Area

Sr. No.	Crop	Area ha	ET_m (mm)	Conversion factor	Equivalent wheat Area (ha) (3) ★ (5)
1	2	3	4	5	6
1.	Sugarcane	4.5	543	1.02	4.6
2.	Wheat	25	536	1.0	25 0
3.	Sorghum	15	450	0.84	12.0
4.	Gram	5	394	0.75	3.8
				TOTAL	46.0

Table 56

Advantages in Low frequency Deficit irrigatim

		CASE I High frequency full irrigation	CASE II low frequency deficit irrigation	Remark
1.	Water available at field head [ha. mm]	35233	35233	
2.	Field application efficiency	0.7	0.8	
3.	Water available at root zone (ha. mm. (1) ★ (2)	24663	28186	
4.	Water requirement at root zone per ha. of wheat in mm	536 (ET_m)	472 ($ET_a = 0.88\ ET_m$)	
5.	Area which can be irrigated with akailable water a-t root zone (ha) (3) ÷ (4)	46.0	59.7	Increase in area in case II by 30%
6.	Yield of wheat per ha. in quintals	20	18	
7.	Total yield (quintals) (5) ★ (6)	920	1075	Increase in total yield in case II by1 7%
8.	Field water use efficiency (Kg/ha. mm) (7) ★ 100 ÷ (1)	1.6	3.05	Increase in Field water use efficiency in case II by 17%

APPENDIX I (B)

Crop Coefficient (kc) for different crops

Crop	Crop Development stages					Total
	Initial	Crop develop-ment	Mid seasn	Late season	At harvest	growing period
Cabbage	0.4-0.5	0.7–0.8	0.95–1.1	0.9-1.0	0.8-0.95	0.7-0.8
Cotton	0:4-0.5	0.7–0.8	1.05–1.25	0.8-0.9	0.65-0 7	0.8-0.9
Groundnut	0.4-0.5	0.7–0.8	0.95–1.1	0.75-0.85	0 55-0.6	0.75-0 8
Maize grain	0.3-0.5	0.7–0.85	1 05–1.2	0.8-0.95	(.55-0 6	0 75-0 9
Onion dry	0.4-0.6	0.7–0.8	0.95–1.1	0 85-0.9	0.75-0.85	0.8-0.9
green	0.4-0.6	).6-0.75	0.95–1.05	0.95-1.05	0.95-1.05	0.65-0.8
Potato	0.4-0.5	0.7-0.8	1.05–1.2	0.85-0.95	0.7-0.75	0.75-0.9
Rice	1.1-1.15	1.1.1 5	1.1-1.3	0.95-1.05	0 95-1.05	05-1.20
Safflower	0 3-0.4	0.7-0.8	1.05-1.2	0.65-0.7	0.2-0 25	0 65 0.7
Sorghum	0.3-0.4	0.7-0.75	1.0-1.15	0.75-0.8	0.5-0 55	0.75-0.85
Soyabean	0.3-0.4	0.7-0.8	1.0-1.15	0.7-0.8	0.4-0.5	0.75-0.9
Sunflower	0.3-0.4	0.7-0.8	1.05-1.2	0.7-0.8	0 35-0.45	0.75-0.85
Tomato	0.4-0.5	0.7-0.8	1.05-1.25	0.8-0.95	0.6-0.65	0.75-0.9
Wheat	0.3-0.4	0.7-0.8	1.05-1.2	0.65-0.75	0.20-0 25	0 8-0.9

First figure : Under high humidity (R Hmin 7% and low wind (U 5 m/sec.)
Second figure : Under low humidity (R Hmin 20% strong wind (5 m/sec).
Source : FAO-33

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