Crop Water Requirements and Irrigation Scheduling

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Harare, 2002

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CWR	Crop Water Requirement
e	vapour pressure
E	Evaporation
EC	Electrical Conductivity
ET	Evapotranspiration
FC	Field Capacity
IR	Irrigation Requirement
IWMI	International Water Management Institute
K	Crop Coefficient
LAI	Leaf Area Index
Le	Leaching efficiency
LR	Leaching Requirement
N	Daylight Hours
P	Depletion
PWP	Permanent Wilting Point
R	Radiation
RH	Relative Humidity
RZD	Root Zone Depth
SM	Soil Moisture
T	Temperature
T	Transpiration
Y	Crop Yield

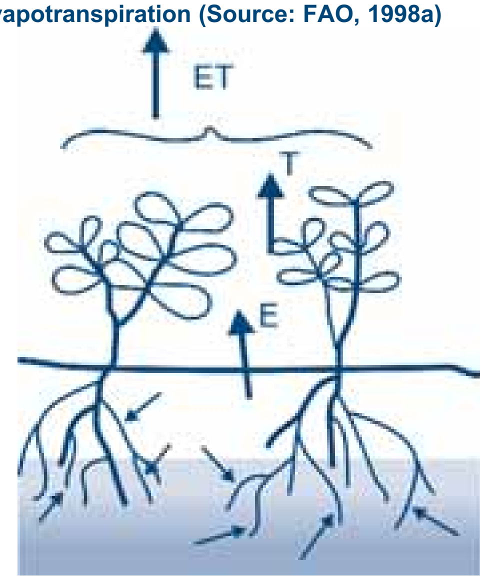
Chapter 1
Introduction

1.1. Evaporation, transpiration and evapotranspiration

In a cropped field water can be lost through two processes (Figure 1):

1. Water can be lost from the soil surface and wet vegetation through a process called *evaporation* (E), whereby liquid water is converted into water vapour and removed from the evaporating surface. Energy is required to change the state of the molecules of water from liquid to vapour. The process is affected by climatological factors such as solar radiation, air temperature, air humidity and wind speed. Where the evaporating surface is the soil surface, the degree of shading of the crop canopy and the amount of water available at the evaporating surface are the other factors that affect the evaporation process.
2. The second process of water loss is called *transpiration* (T), whereby liquid water contained in plant tissues vaporizes into the atmosphere through small openings in the plant leaf, called stomata. Transpiration, like direct evaporation, depends on the energy supply, vapour pressure gradient and wind. Hence solar radiation, air temperature, air humidity and wind terms should be considered when assessing transpiration. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate, as do waterlogging and soil salinity. Crop characteristics, environmental aspects and cultivation practices also have an influence on the transpiration.

Figure 1
Water loss through the process of evapotranspiration (Source: FAO, 1998a)



The combination of these two separate processes, whereby water is lost on one hand by evaporation from the soil surface and on the other hand by transpiration from a plant, is called *evapotranspiration* (ET). Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes.

When the crop is small evaporation is the main process, but once the crop is fully grown and completely covers the ground transpiration becomes the dominant process. It has been estimated that at crop sowing 100% of the total ET comes from evaporation, while at full crop cover evaporation accounts for about 10% of ET and transpiration for the remaining 90%.

1.2. Factors affecting crop evapotranspiration

The main factors affecting evapotranspiration are climatic parameters, crop characteristics, management practices and environmental aspects.

The main climatic factors affecting evapotranspiration are solar radiation, air temperature, air humidity and wind speed.

The crop type, variety and development stages affect evapotranspiration. Differences in crop resistance to transpiration, crop height, crop roughness, reflection, canopy cover and crop rooting characteristics result in different evapotranspiration levels in different types of crops under identical environmental conditions.

Factors such as soil salinity, poor land fertility, limited use of fertilizers and chemicals, lack of pest and disease control, poor soil management and limited water availability at the root zone may limit the crop development and reduce evapotranspiration. Other factors that affect evapotranspiration are groundcover and plant density. Cultivation practices and the type of irrigation system used can alter the microclimate, affect the crop characteristics or affect the wetting of the soil and crop surface. All these affect evapotranspiration.

1.3. Evapotranspiration concepts

1.3.1. Reference crop evapotranspiration

The evapotranspiration from a reference surface not short of water is called the reference crop evapotranspiration and is denoted by ET_o. The reference surface is a hypothetical grass reference crop with specific characteristics. The concept of ET_o was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development stage and management practices. As water is abundant at the evapotranspiring surface, soil factors do not affect evapotranspiration. Relating evapotranspiration to a specific surface provides a reference to which evapotranspiration from other surfaces can be related. It removes the need to define a separate evapotranspiration level for each crop and stage of growth.

The only factors affecting ET_o are climatic parameters. As a result, ET_o is a climatic parameter and can be computed from weather data. ET_o expresses the evaporative demand of the atmosphere at a specific location and time of the year and does not consider crop and soil factors. The calculation procedures for estimating ET_o are discussed in Chapter 2. The preparation of iso-ET_o maps is described in Chapter 3.

1.3.2. Crop evapotranspiration under standard conditions

The crop evapotranspiration under standard conditions, denoted as ET_c, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields under optimum soil water conditions and achieving full production under the given climatic conditions. The values of ET_c and CWR (Crop Water Requirements) are identical, whereby ET_c refers to the amount of water lost through evapotranspiration and CWR refers to the amount of water that is needed to compensate for the loss.

ET_c can be calculated from climatic data by directly integrating the effect of crop characteristics into ET_o. Using recognized methods, an estimation of ET_o is done. Experimentally determined ratios of ET_c/ET_o, called crop coefficients (K_c), are used to relate ET_c to ET_o as given in the following equation:

Equation 1

$$ET_c = ET_o \times K_c$$

Where:

ET_c = Crop evapotranspiration (mm/day)

ET_o = Reference crop evapotranspiration (mm/day)

K_c = Crop coefficient

Differences in leaf anatomy, stomata characteristics, aerodynamic properties and even albedo (solar radiation reflected by the surface) cause ET_c to differ from ET_o under the same climatic conditions. Due to variations in crop characteristics throughout its growing season, K_c for a given crop changes from sowing till harvest. The concept of K_c values will be discussed in detail in Chapter 4.

1.3.3. Crop evapotranspiration under non-standard conditions

The crop evapotranspiration under non-standard conditions, $ET_{c\ adj}$, is the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions. When cultivating crops in the field, the real crop evapotranspiration may be different from ET_c due to non-optimal conditions such as occurrence of pests and diseases, soil salinity, poor soil fertility and waterlogging.

$ET_{c\ adj}$ is calculated by using a water stress coefficient (K_s) and/or by adjusting K_c for all kinds of other stresses and environmental constraints on crop evapotranspiration. The calculation procedures for $ET_{c\ adj}$ will not be covered in this Module. For more details on this concept the reader is referred to the FAO (1998a).

The concepts of ET_o, ET_c and $ET_{c\ adj}$ are illustrated in Figure 2.

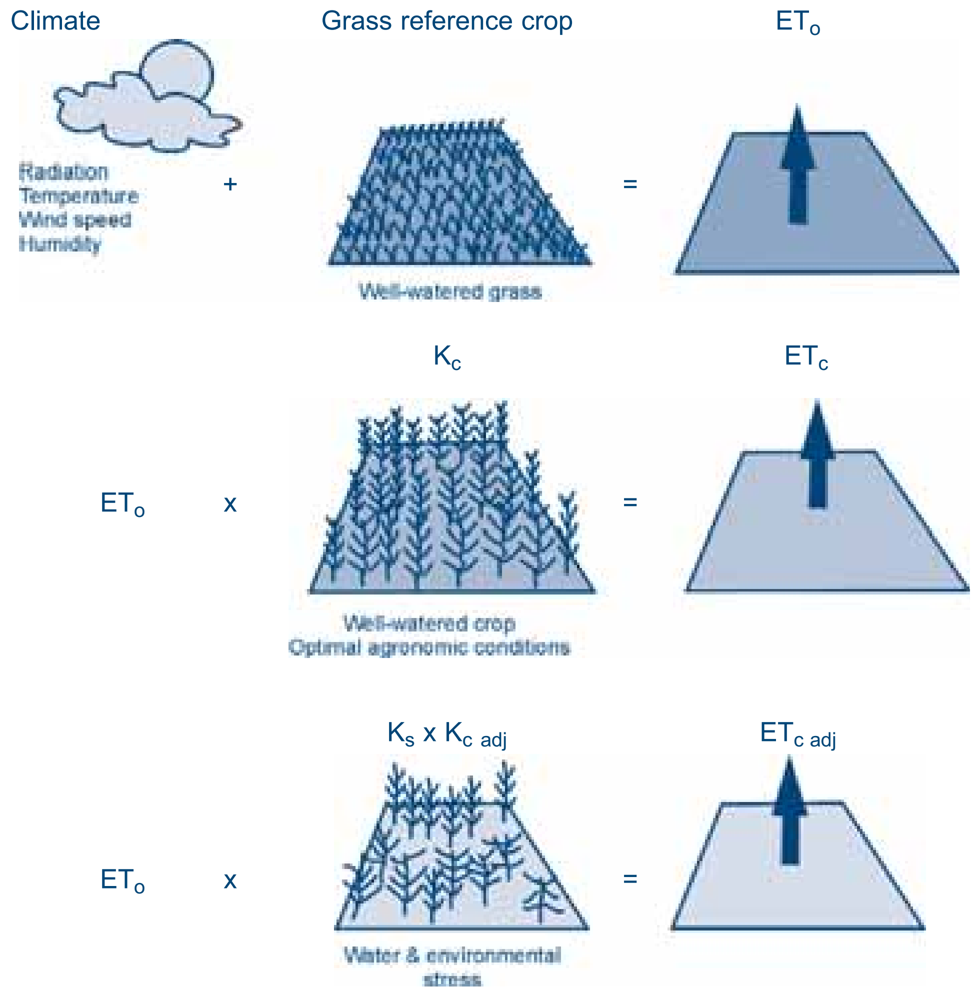
1.4. Crop water and irrigation requirements

Crop water requirements (CWR) encompass the total amount of water used in evapotranspiration. FAO (1984) defined crop water requirements as 'the depth of water needed to meet the water loss through evapotranspiration of a crop, being disease-free, growing in large fields under non restricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment'. CWR is equal to ET_c and will be dealt with in Chapter 4. The use of computer programmes for the estimation of ET_c or CWR is explained in Chapter 6.

Irrigation requirements (IR) refer to the water that must be supplied through the irrigation system to ensure that the crop receives its full crop water requirements. If irrigation is the sole source of water supply for the plant, the irrigation requirement will always be greater than the crop water requirement to allow for inefficiencies in the irrigation system. If the crop receives some of its water from other sources (rainfall, water stored in the ground, underground seepage, etc.), then the irrigation requirement can be considerably less than the crop water

Figure 2

Reference crop evapotranspiration (ET_o), crop evapotranspiration under standard conditions (ET_c) and crop evapotranspiration under non-standard conditions ($ET_{c\ adj}$) (Source: FAO, 1998a)



requirement. Chapter 5 describes the manual calculation for the irrigation requirements and Chapter 6 describes the estimation of the irrigation requirements through the use of computer programmes.

1.5. Irrigation scheduling

Once the crop water and irrigation requirements have been calculated, the next step is the preparation of field irrigation schedules. Three parameters have to be considered in preparing an irrigation schedule:

- The daily crop water requirements
- The soil, particularly its total available moisture or water-holding capacity
- The effective root zone depth

Plant response to irrigation is influenced by the physical condition, fertility and biological status of the soil. Soil condition, texture, structure, depth, organic matter, bulk density, salinity, sodicity, acidity, drainage, topography, fertility and chemical characteristics all affect the extent to which a plant root system penetrates into and uses available moisture and nutrients in the soil. Many of these factors influence the water movement in the soil, the water-holding capacity of the soil, and the ability of the plants to use the water. The irrigation system used should match all or most of these conditions.

The estimated values for available water-holding capacity and intake are shown as broad ranges in this Module. The values in local soil databases need to be continuously refined to fit the actual field conditions. In the field, the actual value may vary from site to site, season to season and even within the season. Within the season, it varies depending on the type of farm and tillage equipment, number of tillage operations, residue management, type of crop and water quality.

Soils to be irrigated must also have adequate surface and subsurface drainage, especially in the case of surface irrigation. Internal drainage within the crop root zone can either be natural or from an installed subsurface drainage system.

Chapter 7 describes the soil-water-plant relationship, while Chapter 8 deals with yield response to water. Finally, Chapter 9 describes different irrigation scheduling methods.

Chapter 2
Estimating reference crop evapotranspiration

The FAO Penman-Monteith method is now the sole recommended method for calculating ET_o and this method, its derivation and the required meteorological data are presented in this Chapter. Section 2.1 explains the need for a standardized method to calculate the reference evapotranspiration (ET_o). However, because of its practical value, the Pan Evaporation method is still in use in some parts of Southern Africa and will therefore be briefly presented in Section 2.2, before presenting, in more detail, the sole recommended Penman-Monteith method in Section 2.3.

2.1. The need for a standardized ET_o calculation method

ET_o can be calculated from meteorological data. Several empirical and semi-empirical methods have been developed over the last 50 years to estimate reference crop evapotranspiration from climatic variables. Some of the methods that have been developed are the Blaney-Criddle, Radiation, Modified Penman and Pan Evaporation methods. The different methods catered for users with different data availability and requiring different levels of accuracy. In all four methods the mean climatic data for a 10-day or a 30-day period are used. ET_o is expressed in mm/day, representing the mean daily value for the period under consideration. Details of these methods are given in FAO (1984).

The development of more accurate methods of assessing crop water use together with advances in science and research revealed the weaknesses in the above-mentioned four methodologies. The performances of the methods were analyzed for different locations and it became evident that the methods do not behave the same way in different locations around the world. Deviations from computed to observed values were often found to exceed the values indicated by researchers. For example, the Modified Penman method was frequently found to overestimate ET_o by up to 20% for low evaporative demands. The other three methods showed variable adherence to the reference crop evapotranspiration standard of grass. This revealed the need for formulating a standard and more consistent method for calculating ET_o.

In May 1990, FAO organized a consultation of experts, scientists and researchers to review the methodologies on the calculation of crop water requirements and to advise on the revision and updating of the procedures. As an outcome of this consultation, the FAO Penman-Monteith method is now recommended as the sole standard method for the definition and calculation of the reference crop evapotranspiration. It has been found to be a method with a strong likelihood of correctly predicting ET_o in a wide range of locations and climates. The method provides values that are more consistent with actual crop water use worldwide. In addition, the method has provisions for calculating ET_o in cases where some of the climatic data are missing. The use of older FAO or other reference evapotranspiration calculation methods is no longer advisable.

2.2. Pan Evaporation method

Despite the FAO Penman-Monteith being the sole recommended method for calculating ET_o, the Pan Evaporation method is still widely used in some parts of East and Southern Africa. This is mainly because the method is very practical and simple, which appeals to many farmers and practitioners. For this, a description of the method is given below.

2.2.1. Pan evaporation

The evaporation rate from pans filled with water can be easily determined. In the absence of rainfall, the amount of water evaporated during a given period corresponds to the decrease in water depth in the pan during the given period. Pans provide a measurement of the combined effect of radiation, wind, temperature and humidity on an open water surface. The pan responds in a similar manner to the same climatic factors affecting crop transpiration. However, several factors produce differences in the loss of water from a water surface and from a cropped surface.

Despite the difference between pan evaporation and reference crop evapotranspiration, the use of pans to predict ET_o for periods of 10 days or longer is still practiced. The measured evaporation from a pan (E_{pan}) is related to the reference crop evapotranspiration (ET_o) through an empirically derived pan coefficient (K_p) as given in the following equation from FAO (1998a):

Equation 2

$$ET_o = K_p \times E_{pan}$$

Where:

ET_o = Reference crop evapotranspiration (mm/day)

K_p = Pan coefficient

E_{pan} = Pan evaporation (mm/day)

2.2.2. The Class A pan

Various types of evaporation pans exist. The most common type is the Class A pan. Below follow the description and specifications as given in FAO (1998a).

The Class A evaporation pan is circular, 120.7 cm in diameter and 25 cm deep (Figure 3). It is made of galvanized iron (22 gauge) or Monel metal (0.8 mm). The pan is mounted on a wooden open frame platform, which is 15 cm above ground level. The soil is built up to within 5 cm of the bottom of the pan. The pan must be level. It is filled with water to 5 cm below the rim, and the water level should not be allowed to drop to more than 7.5 cm below the rim. The water should be regularly renewed, at least weekly, to eliminate extreme turbidity. The pan, if galvanized, is painted annually with aluminium paint. Screens over the pan are not a standard requirement and should preferably not be used. Pans should be protected by fences to prevent animals from drinking the water in the pan.

The area surrounding the pan should preferably be covered by grass, 20 by 20 m, open on all sides to permit free circulation of air. It is preferable that stations be located in the centre or on the leeward side of large cropped fields.

Pan readings are taken daily in the early morning, at the same time that precipitation is measured. Measurements are made in a stilling well that is situated in the pan near one edge. The stilling well is a metal cylinder of about 10 cm in diameter and some 20 cm deep, with a small hole at the bottom.

Pan coefficients are pan specific as the colour, size and position of the pan have influence on the measured results. In selecting the correct pan coefficient, consideration should be given to the pan type, the groundcover in the station where the pan is sited, its surroundings and the general wind and humidity conditions. The siting of the pan and the pan environment also influence the results. This is particularly true where the pan is placed in fallow rather than cropped fields. Two cases are normally considered: Case A, where the pan is sited on a short green (grass) cover and surrounded by fallow soil, and Case B, where the pan is sited on fallow soil and surrounded by a green crop (Figure 4).

As mentioned, the pan coefficient will differ depending on the type of pan and the size and state of the upwind buffer zone (the fetch in Figure 4). Table 1 provides the means of selecting appropriate K_p values applicable to the Class A pan for different groundcover, fetch and climatic conditions.

Figure 3
The Class A pan (Source: FAO, 1998a)

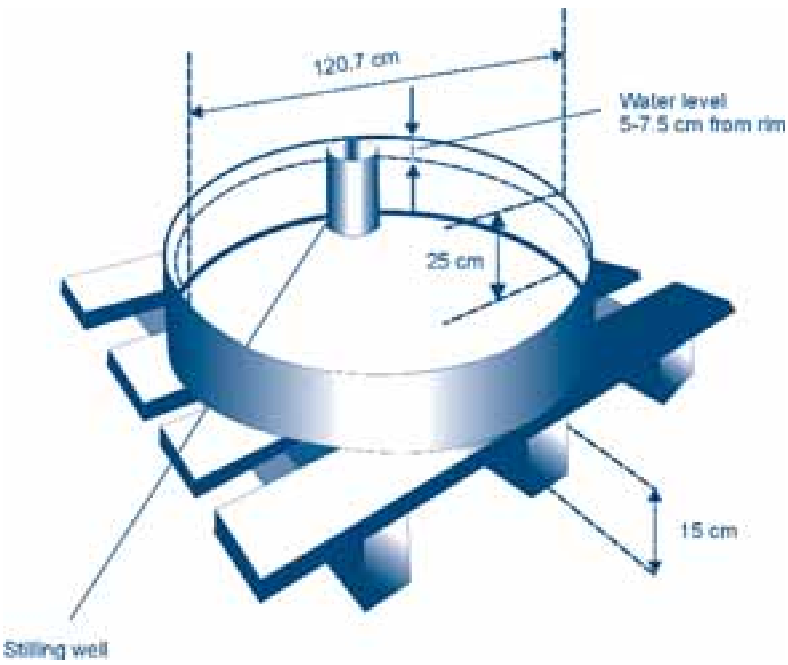


Figure 4

Two cases of evaporation pan siting and their environment (Source: FAO, 1998a)

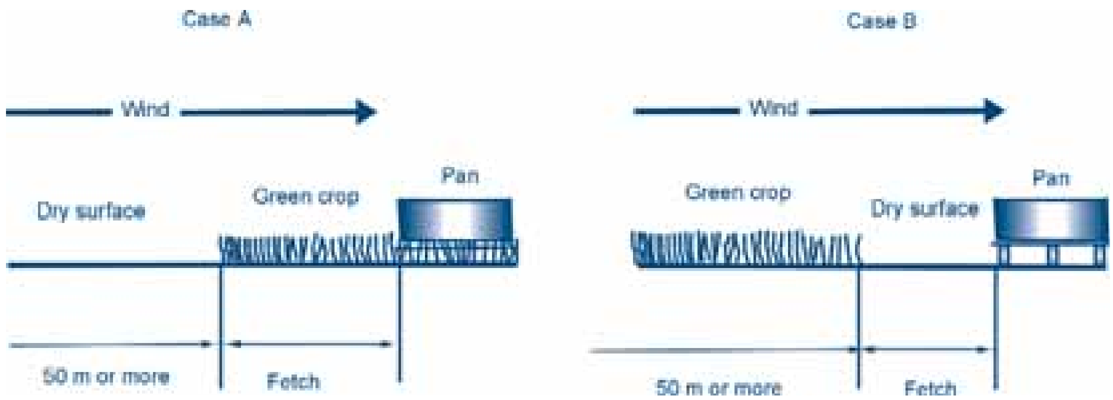


Table 1

Pan coefficients (K_p) for Class A pan for different pan siting and environment and different levels of mean relative humidity and wind speed (Source: FAO, 1984)

Class A pan	Case A: Pan placed in short green cropped area				Case B: Pan placed in dry fallow area			
Wind speed (m/sec)	Windward side distance of green crop (fetch) (m)	Mean relative humidity (%) low <40	medium 40-70	high >70	Windward side distance of dry fallow (fetch) (m)	Mean relative humidity (%) low < 40	medium 40-70	high >70
Light	1	0.55	0.65	0.75	1	0.70	0.80	0.85
< 2	10	0.65	0.75	0.85	10	0.60	0.70	0.80
	100	0.70	0.80	0.85	100	0.55	0.65	0.75
	1 000	0.75	0.85	0.85	1 000	0.50	0.60	0.70
Moderate	1	0.50	0.60	0.65	1	0.65	0.75	0.80
2-5	10	0.60	0.70	0.75	10	0.55	0.65	0.70
	100	0.65	0.75	0.80	100	0.50	0.60	0.65
	1 000	0.70	0.80	0.80	1 000	0.45	0.55	0.60
Strong	1	0.45	0.50	0.60	1	0.60	0.65	0.70
5-8	10	0.55	0.60	0.65	10	0.50	0.55	0.65
	100	0.60	0.65	0.70	100	0.45	0.50	0.60
	1 000	0.65	0.70	0.75	1 000	0.40	0.45	0.55
Very strong	1	0.40	0.45	0.50	1	0.50	0.60	0.65
> 8	10	0.45	0.55	0.60	10	0.45	0.50	0.55
	100	0.50	0.60	0.65	100	0.40	0.45	0.50
	1 000	0.55	0.60	0.65	1 000	0.35	0.40	0.45

2.2.3. Adjustments

Under some conditions not accounted for in Table 1, the given K_p values may need some adjustment. This is the case in areas with no agricultural development or in areas where the pans are surrounded by tall crops. Not maintaining the standard colour of the pan or installing screens can also affect the pan readings and hence will require some adjustment on the K_p value The following adjustments are recommended by FAO (1984):

- ❖ In areas with no agricultural development and extensive areas of bare soil (large fetch), the listed K_p values given for arid windy areas may need to be reduced by up to 20%. For areas with moderate levels of wind, temperature and relative humidity, the listed values may need to be reduced by 5-10%. No or little reduction in K_p is needed in humid, cool conditions.
- ❖ When the pan is surrounded by tall crops, such as maize, the listed K_p values need to be increased by up to 30% for dry, windy climates and 5-10% for calm, humid environments.
- ❖ The listed K_p values are for galvanized pans painted annually with aluminum paint. If the pan is painted black, an increase of E_{pan} up to 10% should be considered.

Example 1

Given the following meteorological data for the months of January and October respectively for a location in Southern Africa:

January:	*October:*
E_{pan} = 148 mm	*E_{pan} = 236 mm*
Relative Humidity $(RH)_{mean}$ = 77%	*Relative Humidity $(RH)_{mean}$ = 54%*
Wind speed = 1.42 m/sec	*Wind speed = 2.01 m/sec*

The Class A pan used is screened and located in a green area surrounded by short irrigated field crops throughout the year, extending at least 100 m around the pan. What are the ET_o values for the two months?

Since screening reduces the evaporation by 10% the above E_{pan} figures will be increased by 10%.

Therefore:

E_{pan} = 148 x 1.10 = 162.8 mm for the month of January

E_{pan} = 236 x 1.10 = 259.6 mm for the month of October

The pan is installed on a green surface with short crops and thus Case A applies (Table 1).

Using Table 1, with a RH of >70%, a fetch of 100 m and a wind velocity of < 2 m/sec, the pan coefficient for the month of January will be: K_p = 0.85

Similarly, for the month of October where wind velocity is moderate (2.01 m/sec) and the RH is 54%: K_p = 0.80

Using Equation 2, the ET_o values will be:

ET_o = 162.8 x 0.85 = 138.4 mm for the month of January or 4.5 mm/day

ET_o = 259.6 x 0.80 = 207.7 mm for the month of October or 6.7 mm/day

- If pans are screened, a reduction of E_{pan} by up to 10% should be expected and the figures should thus be increased by 10%.
- The turbidity of the water in the pan usually does not affect E_{pan} by more than 5%.

The above adjustments indicate that the use of tables may not be enough to consider all local environmental factors influencing K_p and that local adjustment may be necessary.

2.2.4. Siting and maintenance of evaporation pans

It is important to site and maintain the evaporation pan correctly, in order to obtain reasonably accurate results. Attention should be paid to the following aspects:

- Siting is one of the most important aspects in the use of the evaporation pan. Ideally, the evaporation pan should be sited near the fields and downwind of the crops. For practical farming purposes, however, it is advised to site the pan in the vicinity of the homestead or farm buildings where there is easy access for maintenance and recording. The evaporation pan should be placed in a large, secure, wire enclosure to prevent animals from entering and drinking the water. It is absolutely essential that it is sited so that it is not sheltered from the sun and wind by tall grass, trees, buildings or other obstacles.
- The level at which the water is maintained in the pan is important. It should be maintained between 5 and 7.5 cm below the rim so that variations in air movement due to the part of the pan above the water level do not occur unnecessarily. When the water level drops below 7.5 cm from the rim of the pan, water should be added until the level is about 5 cm from the top. After heavy rainfall it may be it may be necessary to remove water to drop the level to the 5 cm mark.
- The mounting of the pan on a wooden open frame platform is necessary to allow free air movement beneath the pan. It is important, therefore, to keep the area under the pan free from weeds or grass at all times.
- The pan must be kept clean. Any frogs or insects that get into the pan must be removed, nor should grass, leaves or algae be allowed to accumulate in it, especially on the water surface. A dirty pan will have atypical thermal properties and possibly a lower evaporating surface area than a clean pan. The pan should be emptied, thoroughly cleaned and refilled with clean water at about four week intervals.
- The pan should be painted annually with aluminium paint. Care should be taken not to scratch the paint when cleaning. The frame for the screen should also be painted with aluminum paint.

The evaporation pan is widely used as a practical tool for irrigation scheduling, which is dealt with in Chapter 9.

2.3. FAO Penman-Monteith method

As explained in Section 2.1, the FAO Penman-Monteith method is now the sole recommended method for determining reference crop evapotranspiration (ET_o). This method overcomes the shortcomings of all other previous empirical and semi-empirical methods and provides ET_o values that are more consistent with actual crop water use data in all regions and climates.

The method has been developed by unambiguously defining the reference surface as 'a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec/m and an albedo of 0.23' (FAO, 1998a). The surface resistance describes the resistance of vapour flow through the transpiring crop and evaporating soil surface. The reference surface closely resembles an extensive surface of green grass that is of uniform height, actively growing, completely shading the ground and adequately watered. The requirement that the grass surface should be both extensive and uniform results from the assumption that all fluxes are one-dimensional upwards. The reference crop evapotranspiration (ET_o) provides a standard to which:

- ❖ Evapotranspiration at different periods of the year or in other regions can be compared
- ❖ Evapotranspiration of other crops can be related through the use of crop coefficients

2.3.1. Penman-Monteith Equation

The Penman-Monteith Equation is given by the following equation (FAO, 1998a):

Equation 3

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \dfrac{900}{T + 273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

Where:

ET_o	=	Reference evapotranspiration (mm/day)
R_n	=	Net radiation at the crop surface (MJ/m^2 per day)
G	=	Soil heat flux density (MJ/m^2 per day)
T	=	Mean daily air temperature at 2 m height (°C)
u_2	=	Wind speed at 2 m height (m/sec)
e_s	=	Saturation vapour pressure (kPa)
e_a	=	Actual vapour pressure (kPa)
$e_s - e_a$	=	Saturation vapour pressure deficit (kPa)
Δ	=	Slope of saturation vapour pressure curve at temperature T (kPa/°C)
γ	=	Psychrometric constant (kPa/°C)

The equation uses standard climatological records of solar radiation (sunshine), air temperature, humidity and wind speed for daily, weekly, ten-day or monthly calculations. The selection of the time step with which ET_o is calculated depends on the purpose of the calculation, the accuracy required and the time step of the climatic data available. Some of the data are measured directly in weather stations. Other parameters are related to commonly measured data and can be derived with the help of direct or empirical equations. To ensure the integrity of computations, weather measurements should be made at 2 m (or converted to that height) above an extensive surface of green grass shading the ground that is not short of water. It is important to verify the units in which the weather data are reported so that any common units can be converted to standard units.

Apart from the climatological records the equation requires the site location. Altitude above sea level (m) and latitude (degrees north or south) of the location should be specified. These data are needed to adjust some weather parameters for the local average value of atmospheric pressure (a function of the site elevation above mean sea level) and to compute extraterrestrial radiation (R_a) and, in some cases, daylight hours (N). In the calculation procedures for R_a and N the latitude is expressed in radians (= decimal degrees x $\pi/180$). A positive value is used for the Northern Hemisphere and a negative value for the Southern Hemisphere.

2.3.2. Sources of climatic data

The meteorological factors determining evapotranspiration are weather parameters, which provide energy for vaporization and remove water vapour from the evaporating surface. The principal weather parameters to consider are air temperature, air humidity, solar radiation and wind speed.

Meteorological data are recorded at various weather stations. Agrometeorological stations are sited in cropped areas where instruments are exposed to atmospheric conditions similar to those for the surrounding crops. In these stations air temperature and humidity, wind speed and sunshine duration are typically measured at 2 m above ground level on an extensive surface of grass or short crop. Data collected at stations other than agrometeorological stations require careful analysis of their validity before use.

In most countries in East and Southern Africa a national meteorological service commonly publishes meteorological bulletins, listing processed climatic data from the various stations. These services should be contacted for information on local climatic data, collected at various types of weather stations in the country, for use as input data in the FAO Penman-Monteith Equation.

Since 1984 FAO has created databases of mean monthly agroclimatic data for various climatic stations around the world, such as those given in FAO Irrigation and Drainage Papers No. 46 & 49 (FAO, 1992; FAO, 1993). The International Water Management Institute (IWMI) has also published electronic databases for parts of the world.

The databases can be consulted in order to verify the consistency of the actual database or to estimate missing climatic parameters. They should only be used for preliminary studies as they contain, in general, mean monthly data only and some stations have incomplete data. The information found from the databases should never replace actual long-term data.

2.3.3. Calculation procedures for ET_o using the FAO Penman-Monteith Equation

The use of the FAO Penman-Monteith Equation in calculating ET_o will be illustrated step by step in this section. Data from the Harare Kutsaga Research Station in Zimbabwe, which is located at an altitude of 1 479 m above sea level, 17°56' South Latitude and 31°05' East Longitude, will be used for this exercise (Table 2).

Psychrometric constant (γ)

For details on the psychrometric constant (γ) the reader is referred to FAO (1998a). Table 3 summarizes the values of γ as a function of altitude, using the following equation:

Equation 4

$$\gamma = \frac{c_p\, P}{\varepsilon\, \lambda} = 0.665 \times 10^{-3}\, P$$

Where:

c_p = Specific heat at constant pressure = 1.013×10^{-3} MJ/kg per °C

P = Atmospheric pressure (kPa)

ε = Ratio molecular weight of water vapour/dry air = 0.622

λ = Latent heat vaporization = 2.45 MJ/kg (at 20°C)

The altitude of Kutsaga Research Station is 1 479 m. Using Table 3, the value of γ is estimated, with the aid of interpolation, to be 0.056 kPa/°C.

Table 2

Meteorological data for Harare Kutsaga Research Station (Source: Department of Meteorological services, Zimbabwe, 1978)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max} (°C)	26.1	25.9	26.1	25.4	23.5	21.3	21.4	23.8	26.9	28.7	27.0	26.1
T_{min} (°C)	15.7	15.6	14.3	12.5	9.1	6.7	6.1	7.8	10.6	13.8	15.1	15.7
RH_{mean} (%)	76	77	72	67	62	60	55	50	45	48	63	73
Sunshine (hrs)	6.6	6.6	7.7	8.2	8.7	8.4	8.8	9.5	9.7	9.4	7.1	6.1
Wind speed (knots) *	6.1	6.0	6.4	6.3	6.1	6.4	6.9	7.7	8.7	9.1	7.5	6.7

**Measured at 14m above ground level*

Table 3

Psychrometric constant (γ) for different altitudes (z) (Source: FAO, 1998a)

z (m)	γ (kPa/°C)	z (m)	γ (kPa/°C)	z (m)	γ (kPa/°C)	z (m)	γ (kPa/°C)
0	0.067	1000	0.060	2000	0.053	3000	0.047
100	0.067	1100	0.059	2100	0.052	3100	0.046
200	0.066	1200	0.058	2200	0.052	3200	0.046
300	0.065	1300	0.058	2300	0.051	3300	0.045
400	0.064	1400	0.057	2400	0.051	3400	0.045
500	0.064	1500	0.056	2500	0.050	3500	0.044
600	0.063	1600	0.056	2600	0.049	3600	0.043
700	0.062	1700	0.055	2700	0.049	3700	0.043
800	0.061	1800	0.054	2800	0.048	3800	0.042
900	0.061	1900	0.054	2900	0.047	3900	0.042
1000	0.060	2000	0.053	3000	0.047	4000	0.041

Air temperature

The mean air temperature, which is also needed for the calculation of the slope of saturation pressure curve Δ (see below), is given by the following equation:

Equation 5

$$T_{mean} = \frac{T_{max} + T_{min}}{2}$$

Where:

T_{mean} = Mean daily temperature (°C)
T_{max} = Mean daily maximum temperature (°C)
T_{min} = Mean daily minimum temperature (°C)

Vapour pressure

Mean saturation vapour pressure (e_s)

As the saturation vapour pressure is related to the air temperature, it can be calculated from the air temperature. Table 4 provides the relationship between temperature (T) and saturation vapour pressure (e°). Details on this relationship can be found in FAO (1998a). From Table 4 the e° values corresponding to T_{max} and T_{min} are selected and averaged in order to obtain e_s, as given by the following equation:

Equation 6

$$e_s = \frac{e°(T_{max}) + e°(T_{min})}{2}$$

Where:

e_s = Mean saturation vapour pressure (kPa)
$e°(T_{max})$ = Saturation vapour pressure at the maximum air temperature (kPa)
$e°(T_{min})$ = Saturation vapour pressure at the minimum air temperature (kPa)

Equation 7

$$e°(T) = 0.6108 \exp\left[\frac{17.27\ T}{T + 237.3}\right]$$

Where:

T = Mean air temperature (°C)
exp[..] = 2.7183 (base of natural logarithm) raised to the power [..]

The values of $e°(T_{max})$ and $e°(T_{min})$ for Katsuga Research Station were derived through interpolation using Table 4 and are presented in Table 7, together with the e_s calculated using Equation 6.

Table 4
Saturation vapour pressure (e°) for different temperatures (T) (Source: FAO, 1998a)

T (°C)	e° (kPa)	T (°C)	e° (kPa)	T (°C)	e° (kPa)	T (°C)	e° (kPa)
1.0	0.657	13.0	1.498	25.0	3.168	37.0	6.275
1.5	0.681	13.5	1.547	25.5	3.263	37.5	6.448
2.0	0.706	14.0	1.599	26.0	3.361	38.0	6.625
2.5	0.731	14.5	1.651	26.5	3.462	38.5	6.806
3.0	0.758	15.0	1.705	27.0	3.565	39.0	6.991
3.5	0.785	15.5	1.761	27.5	3.671	39.5	7.181
4.0	0.813	16.0	1.818	28.0	3.780	40.0	7.376
4.5	0.842	16.5	1.877	28.5	3.891	40.5	7.574
5.0	0.872	17.0	1.938	29.0	4.006	41.0	7.778
5.5	0.903	17.5	2.000	29.5	4.123	41.5	7.986
6.0	0.935	18.0	2.064	30.0	4.243	42.0	8.199
6.5	0.968	18.5	2.130	30.5	4.366	42.5	8.417
7.0	1.002	19.0	2.197	31.0	4.493	43.0	8.640
7.5	1.037	19.5	2.267	31.5	4.622	43.5	8.867
8.0	1.073	20.0	2.338	32.0	4.755	44.0	9.101
8.5	1.110	20.5	2.412	32.5	4.891	44.5	9.339
9.0	1.148	21.0	2.487	33.0	5.030	45.0	9.582
9.5	1.187	21.5	2.564	33.5	5.173	45.5	9.832
10.0	1.228	22.0	2.644	34.0	5.319	46.0	10.086
10.5	1.270	22.5	2.726	34.5	5.469	46.5	10.347
11.0	1.313	23.0	2.809	35.0	5.623	47.0	10.613
11.5	1.357	23.5	2.896	35.5	5.780	47.5	10.885
12.0	1.403	24.0	2.984	36.0	5.491	48.0	11.163
12.5	1.449	24.5	3.075	36.5	6.106	48.5	11.447

Slope of saturation vapour pressure curve (Δ)

This is the slope of the relationship between saturation vapour pressure and temperature. For details, the reader is referred to FAO (1998a). Table 5 summarizes the values of the slope of saturation vapour pressure curve for different air temperatures calculated. The value of Δ is a function of the mean air temperature (see above) and is calculated using the following equation:

Equation 8

$$\Delta = \frac{4\,098 \left[0.6108 \exp\left(\frac{17.27\,T}{T + 237.3}\right)\right]}{(T + 237.3)^2}$$

Where:

$$0.6108 \exp\left[\frac{17.27\,T}{T + 237.3}\right] = e^{\circ} \text{ (Table 4)}$$

T = mean daily temperature (Equation 5)

For Katsuga Research Station, the values of T_{mean} can be calculated using Equation 5. These values are then used in Table 5 to estimate D, using interpolation. The results derived are summarized in Table 6.

Actual vapour pressure (e_a)

The calculation of the actual vapour pressure (e_a) is dependent on the meteorological data available. It can be derived from the dew point temperature data or from the relative humidity (RH) data. Since in most climatological stations relative humidity data are readily available, this is what is commonly used to determine e_a.

Table 5
Slope of saturation vapour pressure curve (Δ) for different air temperatures (T) (Source: FAO, 1998a)

T (°C)	Δ (kPa/°C)	T (°C)	Δ (kPa/°C)	T (°C)	Δ (kPa/°C)	T (°C)	Δ (kPa/°C)
1.0	0.047	13.0	0.098	25.0	0.189	37.0	0.342
1.5	0.049	13.5	0.101	25.5	0.194	37.5	0.350
2.0	0.050	14.0	0.104	26.0	0.199	38.0	0.358
2.5	0.052	14.5	0.107	26.5	0.204	38.5	0.367
3.0	0.054	15.0	0.110	27.0	0.209	39.0	0.375
3.5	0.055	15.5	0.113	27.5	0.215	39.5	0.384
4.0	0.057	16.0	0.116	28.0	0.220	40.0	0.393
4.5	0.059	16.5	0.119	28.5	0.226	40.5	0.402
5.0	0.061	17.0	0.123	29.0	0.231	41.0	0.412
5.5	0.063	17.5	0.126	29.5	0.237	41.5	0.421
6.0	0.065	18.0	0.130	30.0	0.243	42.0	0.431
6.5	0.067	18.5	0.133	30.5	0.249	42.5	0.441
7.0	0.069	19.0	0.137	31.0	0.256	43.0	0.451
7.5	0.071	19.5	0.141	31.5	0.262	43.5	0.461
8.0	0.073	20.0	0.145	32.0	0.269	44.0	0.471
8.5	0.075	20.5	0.149	32.5	0.275	44.5	0.482
9.0	0.078	21.0	0.153	33.0	0.282	45.0	0.493
9.5	0.080	21.5	0.157	33.5	0.289	45.5	0.504
10.0	0.082	22.0	0.161	34.0	0.296	46.0	0.515
10.5	0.085	22.5	0.165	34.5	0.303	46.5	0.526
11.0	0.087	23.0	0.170	35.0	0.311	47.0	0.538
11.5	0.090	23.5	0.174	35.5	0.318	47.5	0.550
12.0	0.092	24.0	0.179	36.0	0.326	48.0	0.562
12.5	0.095	24.5	0.184	36.5	0.334	48.5	0.574

Table 6
Values of T_{mean} and Δ for Kutsaga Research Station

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{mean}(°C)	20.9	20.8	20.2	19.0	16.3	14.0	13.8	15.8	18.8	21.3	21.1	20.9
Δ (kPa/°C)	0.152	0.151	0.146	0.137	0.118	0.104	0.102	0.115	0.136	0.155	0.154	0.152

If RH_{max} and RH_{min} values are available then the actual vapour pressure is calculated using the following equation:

Equation 9

$$e_a = \frac{\left[e^\circ(T_{min}) \times \frac{RH_{max}}{100}\right] + \left[e^\circ(T_{max}) \times \frac{RH_{min}}{100}\right]}{2}$$

Where:

e_a = Actual vapour pressure (kPa)

$e^\circ(T_{min})$ = Saturation vapour pressure at daily minimum temperature (kPa)

$e^\circ(T_{max})$ = Saturation vapour pressure at daily maximum temperature (kPa)

RH_{max} = Maximum relative humidity (%)

RH_{min} = Minimum relative humidity (%)

In the absence of RH_{max} and RH_{min} another equation can be used to estimate e_a:

Equation 10

$$e_a = \frac{RH_{mean}}{100} \times \left[\frac{e^\circ(T_{max}) + e^\circ(T_{min})}{2}\right] = \frac{RH_{mean}}{100} \times e_s$$

Where:

RH_{mean} = the mean relative humidity, defined as the average between RH_{max} and RH_{min}

Vapour pressure deficit (e_s - e_a)

The vapour pressure deficit is the difference between the mean saturation vapour pressure (e_s) and the actual vapour pressure (e_a) for a given time period.

At Kutsaga Research Station, we have meteorological data on T_{max}, T_{min} and RH_{mean}. Using Table 4 and Equation 6 to calculate e_s and Equation 10 to calculate e_a, the vapour pressure deficit (e_s - e_a) calculations for Kutsaga Research Station are presented in Table 7.

Radiation

Net Radiation (R_n)

One of the major inputs to the FAO Penman-Monteith Equation is the net radiation at the crop surface (R_n). The net radiation is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl}):

Equation 11

$$R_n = R_{ns} - R_{nl}$$

Where:

R_n = Net radiation (MJ/m² per day)

R_{ns} = Net incoming shortwave radiation(MJ/m² per day)

R_{nl} = Net outgoing longwave radiation (MJ/m² per day)

R_n is normally calculated from the measured shortwave radiation (R_s)

To explain the calculation of R_n, it is important to first explain some concepts and define certain parameters in the process of deriving the inputs of Equation 12 for the calculation of R_s.

Extraterrestrial radiation (R_a)

Extraterrestrial radiation (R_a) is the solar radiation received at the top of the earth's atmosphere on a horizontal surface. The local intensity of the radiation is determined by the angle between the direction of the sun's rays and the normal (perpendicular) to the surface of the atmosphere. This angle will change during the day and will be different at different latitudes and in different seasons. The angle is zero, if the sun is directly overhead. As seasons change, the position of the sun, the length of the day and, hence, R_a change. R_a for each day of the year and for different

Table 7
Monthly vapour pressure deficit values for Kutsaga Research Station

	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max}	(°C)	26.1	25.9	26.1	25.4	23.5	21.3	21.4	23.8	26.9	28.7	27.0	26.1
T_{min}	(°C)	15.7	15.6	14.3	12.5	9.1	6.7	6.1	7.8	10.6	13.8	15.1	15.7
RH_{mean}	(%)	76	77	72	67	62	60	55	50	45	48	63	73
$e^\circ(T_{max})$	(kPa)	3.381	3.341	3.381	3.244	2.896	2.533	2.549	2.949	3.544	3.937	3.565	3.381
$e^\circ(T_{min})$	(kPa)	1.784	1.772	1.630	1.449	1.156	0.982	0.942	1.059	1.279	1.578	1.716	1.784
e_s	(kPa)	2.582	2.556	2.506	2.346	2.026	1.758	1.746	2.004	2.412	2.758	2.641	2.582
e_a	(kPa)	1.962	1.968	1.804	1.572	1.256	1.055	0.960	1.002	1.085	1.324	1.664	1.885
(e_s-e_a)	(kPa)	0.620	0.588	0.702	0.774	0.770	0.703	0.786	1.002	1.327	1.434	0.977	0.697

latitudes can be estimated by calculation using equations. The relevant equations and calculation procedures are presented in detail in FAO (1998a). Some values of R_a for different latitudes are summarized in Table 8 for the Northern Hemisphere and Table 9 for the Southern Hemisphere. These values represent R_a on the 15th day of each month and provide a good estimate (error < 1%) of R_a averaged over all days within the month.

Table 8

Daily extraterrestrial radiation (R_a) for different latitudes in the Northern Hemisphere for the 15th day of the month[a] (Source: FAO, 1998a)

Latitude	Northern Hemisphere: Values in MJ/m² per day[b]											
Degree	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
70	0.0	2.6	10.4	23.0	35.2	42.5	39.4	28.0	14.9	4.9	0.1	0.0
68	0.1	3.7	11.7	23.9	35.3	42.0	38.9	28.6	16.1	6.0	0.7	0.0
66	0.6	4.8	12.9	24.8	35.6	41.4	38.8	29.3	17.3	7.2	1.5	0.1
64	1.4	5.9	14.1	25.8	35.9	41.2	38.8	30.0	18.4	8.5	2.4	0.6
62	2.3	7.1	15.4	26.6	36.3	41.2	39.0	30.6	19.5	9.7	3.4	1.3
60	3.3	8.3	16.6	27.5	36.6	41.2	39.2	31.3	20.6	10.9	4.4	2.2
58	4.3	9.6	17.7	28.4	37.0	41.3	39.4	32.0	21.7	12.1	5.5	3.1
56	5.4	10.8	18.9	29.2	37.4	41.4	39.6	32.6	22.7	13.3	6.7	4.2
54	6.5	12.0	20.0	30.0	37.8	41.5	39.8	33.2	23.7	14.5	7.8	5.2
52	7.7	13.2	21.1	30.8	38.2	41.6	40.1	33.8	24.7	15.7	9.0	6.4
50	8.9	14.4	22.2	31.5	38.5	41.7	40.2	34.4	25.7	16.9	10.2	7.5
48	10.1	15.7	23.3	32.2	38.8	41.8	40.4	34.9	26.6	18.1	11.4	8.7
46	11.3	16.9	24.3	32.9	39.1	41.9	40.6	35.4	27.5	19.2	12.6	9.9
44	12.5	18.0	25.3	33.5	39.3	41.9	40.7	35.9	28.4	20.3	13.9	11.1
42	13.8	19.2	26.3	34.1	39.5	41.9	40.8	36.3	29.2	21.4	15.1	12.4
40	15.0	20.4	27.2	34.7	39.7	41.9	40.8	36.7	30.0	22.5	16.3	13.6
38	16.2	21.5	28.1	35.2	39.9	41.8	40.8	37.0	30.7	23.6	17.5	14.8
36	17.5	22.6	29.0	35.7	40.0	41.7	40.8	37.4	31.5	24.6	18.7	16.1
34	18.7	23.7	29.9	36.1	40.0	41.6	40.8	37.6	32.1	25.6	19.9	17.3
32	19.9	24.8	30.7	36.5	40.0	41.4	40.7	37.9	32.8	26.6	21.1	18.5
30	21.1	25.8	31.4	36.8	40.0	41.2	40.6	38.0	33.4	27.6	22.2	19.8
28	22.3	26.8	32.2	37.1	40.0	40.9	40.4	38.2	33.9	28.5	23.3	21.0
26	23.4	27.8	32.8	37.4	39.9	40.6	40.2	38.3	34.5	29.3	24.5	22.2
24	24.6	28.8	33.5	37.6	39.7	40.3	39.9	38.3	34.9	30.2	25.5	23.3
22	25.7	29.7	34.1	37.8	39.5	40.0	39.6	38.4	35.4	31.0	26.6	24.5
20	26.8	30.6	34.7	37.9	39.3	39.5	39.3	38.3	35.8	31.8	27.7	25.6
18	27.9	31.5	35.2	38.0	39.0	39.1	38.9	38.2	36.1	32.5	28.7	26.8
16	28.9	32.3	35.7	38.1	38.7	38.6	38.5	38.1	36.4	33.2	29.6	27.9
14	29.9	33.1	36.1	38.1	38.4	38.1	38.1	38.0	36.7	33.9	30.6	28.9
12	30.9	33.8	36.5	38.0	38.0	37.6	37.6	37.8	36.9	34.5	31.5	30.0
10	31.9	34.5	36.9	37.9	37.6	37.0	37.1	37.5	37.1	35.1	32.4	31.0
8	32.8	35.2	37.2	37.8	37.1	36.3	36.5	37.2	37.2	35.6	33.3	32.0
6	33.7	35.8	37.4	37.6	36.6	35.7	35.9	36.9	37.3	36.1	34.1	32.9
4	34.6	36.4	37.6	37.4	36.0	35.0	35.3	36.5	37.3	36.6	34.9	33.9
2	35.4	37.0	37.8	37.1	35.4	34.2	34.6	36.1	37.3	37.0	35.6	34.8
0	36.2	37.5	37.9	36.8	34.8	33.4	33.9	35.7	37.2	37.4	36.3	35.6

a Values for R_a on the 15th day of the month provide a good estimate (error < 1%) of R_a averaged over all days within the month. Only for high latitudes, greater than 55° (N or S), during winter months may deviations be more than 1%.

b Values can be converted to equivalent values in mm/day by dividing by λ = 2.45 (see Table 3).

Table 9

Daily extraterrestrial radiation (R_a) for different latitudes in the Southern Hemisphere for the 15th day of the month[a] (Source: FAO, 1998a)

Latitude	Southern Hemisphere: Values in MJ/m² per day[b]											
Degree	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
70	41.4	28.6	15.8	4.9	0.2	0.0	0.0	2.2	10.7	23.5	37.3	45.3
68	41.0	29.3	16.9	6.0	0.8	0.0	0.0	3.2	11.9	24.4	37.4	44.7
66	40.9	30.0	18.1	7.2	1.5	0.1	0.5	4.2	31.1	25.4	37.6	44.1
64	41.0	30.8	19.3	8.4	2.4	0.6	1.2	5.3	14.4	26.3	38.0	43.9
62	41.2	31.5	20.4	9.6	3.4	1.2	2.0	6.4	15.5	27.2	38.3	43.9
60	41.5	32.3	21.5	10.8	4.4	2.0	2.9	7.6	16.7	28.1	38.7	43.9
58	41.7	33.0	22.6	12.0	5.5	2.9	3.9	8.7	17.9	28.9	39.1	44.0
56	42.0	33.7	23.6	13.2	6.6	3.9	4.9	9.9	19.0	29.8	39.5	44.1
54	42.2	34.3	24.6	14.4	7.7	4.9	6.0	11.1	20.1	30.6	39.9	44.3
52	42.5	35.0	25.6	15.6	8.8	6.0	7.1	12.2	21.2	31.4	40.2	44.4
50	42.7	35.6	26.6	16.7	10.0	7.1	8.2	13.4	22.2	32.1	40.6	44.5
48	42.9	36.2	27.5	17.9	11.1	8.2	9.3	14.6	23.3	32.8	40.9	44.5
46	43.0	36.7	28.4	19.0	12.3	9.3	10.4	15.7	24.3	33.5	41.1	44.6
44	43.2	37.2	29.3	20.1	13.5	10.5	11.6	16.8	25.2	34.1	41.4	44.6
42	43.3	37.7	30.1	21.2	14.6	11.6	12.8	18.0	26.2	34.7	41.6	44.6
40	43.4	38.1	30.9	22.3	15.8	12.8	13.9	19.1	27.1	35.3	41.8	44.6
38	43.4	38.5	31.7	23.3	16.9	13.9	15.1	20.2	28.0	35.8	41.9	44.5
36	43.4	38.9	32.4	24.3	18.1	15.1	16.2	21.2	28.8	36.3	42.0	44.4
34	43.4	39.2	33.0	25.3	19.2	16.2	17.4	22.3	29.6	36.7	42.0	44.3
32	43.3	39.4	33.7	26.3	20.3	17.4	18.5	23.3	30.4	37.1	42.0	44.1
30	43.1	39.6	34.3	27.2	21.4	18.5	19.6	24.3	31.1	37.5	42.0	43.9
28	43.0	39.8	34.8	28.1	22.5	19.7	20.7	25.3	31.8	37.8	41.9	43.6
26	42.8	39.9	35.3	29.0	23.5	20.8	21.8	26.3	32.5	38.0	41.8	43.3
24	42.5	40.0	35.8	29.8	24.6	21.9	22.9	27.2	33.1	38.3	41.7	43.0
22	42.2	40.1	36.2	30.6	25.6	23.0	24.0	28.1	33.7	38.4	41.4	42.6
20	41.9	40.0	36.6	31.3	26.6	24.1	25.0	28.9	34.2	38.6	41.2	42.1
18	41.5	40.0	37.0	32.1	27.6	25.1	26.0	29.8	34.7	38.7	40.9	41.7
16	41.1	39.9	37.2	32.8	28.5	26.2	27.0	30.6	35.2	38.7	40.6	41.2
14	40.6	39.7	37.5	33.4	29.4	27.2	279	31.3	35.6	38.7	40.2	40.6
12	40.1	39.6	37.7	34.0	30.2	28.1	289	32.1	36.0	38.6	39.8	40.0
10	39.5	39.3	37.8	34.6	31.1	29.1	29.8	32.8	36.3	38.5	39.3	39.4
8	38.9	39.0	37.9	35.1	31.9	30.0	30.7	33.4	36.6	38.4	38.8	38.7
6	38.3	38.7	38.0	35.6	32.7	30.9	31.5	34.0	36.8	38.2	38.2	38.0
4	37.6	38.3	38.0	36.0	33.4	31.8	32.3	34.6	37.0	38.0	37.6	37.2
2	36.9	37.9	38.0	36.4	34.1	32.6	33.1	35.2	37.1	37.7	37.0	36.4
0	36.2	37.5	37.9	36.8	34.8	33.4	33.9	35.7	37.2	37.4	36.3	35.6

a *Values for R_a on the 15th day of the month provide a good estimate (error < 1%) of R_a averaged over all days within the month. Only for high latitudes, greater than 55° (N or S), during winter months may deviations be more than 1%.*

b *Values can be converted to equivalent values in mm/day by dividing by λ = 2.45 (see Table 3).*

Solar or shortwave radiation (R_s)

Part of the extraterrestrial radiation (R_a) is scattered, reflected or absorbed in the process of entering the atmosphere. The amount of radiation that reaches the earth's surface is called solar radiation (R_s). It depends on R_a and the transmission through the atmosphere, which is largely dependent on cloud cover.

R_s can be measured in weather stations with pyranometers, radiometers or solarimeters. In some stations values of solar radiation are part of the climatological data available. If it is not measured it can be calculated through the use of an equation which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

Equation 12

$$R_s = \left[0.25 + 0.5\frac{n}{N}\right] R_a$$

Where:

R_s = Solar or shortwave radiation (MJ/m^2 per day)

n = Actual sunshine hours (hour)

N = Maximum possible duration of sunshine hours or daylight hours (hour)

n/N = Relative sunshine duration

R_a = Extraterrestrial radiation (MJ/m^2 per day)

The maximum duration of sunshine (N) can be calculated using equations. However, to simplify the calculation procedures, values of N for different latitudes can be read from Table 10 for the Northern Hemisphere and Table 11 for the Southern Hemisphere.

The actual duration of sunshine (n) is recorded with a sunshine recorder and is part of the climatological data provided by weather stations. The n/N ratio can also be obtained from data on cloud cover, if data on sunshine hours are not available, using the general conversions in Table 12.

Table 10

Mean daylight hours (N) for different latitudes in the Northern Hemisphere for the 15th day of the month[a] (Source: FAO, 1998a)

Latitude	Northern Hemisphere											
Degree	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
70	0.0	6.6	11.0	15.6	21.3	24.0	24.0	17.6	12.8	8.3	2.3	0.0
68	2.1	7.3	11.1	15.3	19.7	24.0	22.3	17.0	12.7	8.7	4.1	0.0
66	3.9	7.8	11.2	14.9	18.7	22.0	20.3	16.4	12.7	9.0	5.2	1.9
64	5.0	8.2	11.2	14.7	17.9	2.0	19.2	16.0	12.6	9.3	6.0	3.7
62	5.7	8.5	11.3	14.4	17.3	19.2	18.4	15.7	12.6	9.5	6.6	4.8
60	6.4	8.8	11.4	14.2	16.8	18.4	17.7	15.3	12.5	9.7	7.1	5.6
58	6.9	9.1	11.4	14.1	16.4	17.8	17.2	15.1	12.5	9.9	7.5	6.2
56	7.3	9.3	11.5	13.9	16.0	17.3	16.8	14.8	12.4	10.1	7.9	6.7
54	7.7	9.5	11.5	13.8	15.7	16.8	16.4	14.6	12.4	10.2	8.2	7.1
52	8.0	9.7	11.5	13.6	15.4	16.5	16.0	14.4	12.4	10.3	8.5	7.5
50	8.3	9.8	11.6	13.5	15.2	16.1	15.7	14.3	12.3	10.4	8.7	7.9
48	8.6	10.0	11.6	13.4	15.0	15.8	15.5	14.1	12.3	10.6	9.0	8.2
46	8.8	10.1	11.6	13.3	14.8	15.5	15.2	14.0	12.3	10.7	9.2	8.5
44	9.1	10.3	11.6	13.2	14.6	15.3	15.0	13.8	12.3	10.7	9.4	8.7
42	9.3	10.4	11.7	13.2	14.4	15.0	14.8	13.7	12.3	10.8	9.6	9.0
40	9.5	10.5	11.7	13.1	14.2	14.8	14.6	13.6	12.2	10.9	9.7	9.2
38	9.6	10.6	11.7	13.0	14.1	14.6	14.4	13.5	12.2	11.0	9.9	9.4
36	9.8	10.7	11.7	12.9	13.9	14.4	14.2	13.4	12.2	11.1	10.1	9.6
34	10.0	10.8	11.8	12.9	13.8	14.3	14.1	13.3	12.2	11.1	10.2	9.7
32	10.1	10.9	11.8	12.8	13.6	14.1	13.9	13.2	12.2	11.2	10.3	9.9
30	10.3	11.0	11.8	12.7	13.5	13.9	13.8	13.1	12.2	11.3	10.5	10.1
28	10.4	11.0	11.8	12.7	13.4	13.8	13.6	13.0	12.2	11.3	10.6	10.2
26	10.5	11.1	11.8	12.6	13.3	13.6	13.5	12.9	12.1	11.4	10.7	10.4
24	10.7	11.2	11.8	12.6	13.2	13.5	13.3	12.8	12.1	11.4	10.8	10.5
22	10.8	11.3	11.9	12.5	13.1	13.3	13.2	12.8	12.1	11.5	10.9	10.7
20	10.9	11.3	11.9	12.5	12.9	13.2	13.1	12.7	12.1	11.5	11.0	10.8
18	11.0	11.4	11.9	12.4	12.8	13.1	13.0	12.6	12.1	11.6	11.1	10.9
16	11.1	11.5	11.9	12.4	12.7	12.9	12.9	12.5	12.1	11.6	11.2	11.1
14	11.3	11.6	11.9	12.3	12.6	12.8	12.8	12.5	12.1	11.7	11.3	11.2
12	11.4	11.6	11.9	12.3	12.6	12.7	12.6	12.4	12.1	11.7	11.4	11.3
10	11.5	11.7	11.9	12.2	12.5	12.6	12.5	12.3	12.1	11.8	11.5	11.4
8	11.6	11.7	11.9	12.2	12.4	12.5	12.4	12.3	12.0	11.8	11.6	11.5
6	11.7	11.8	12.0	12.1	12.3	12.3	12.3	12.2	12.0	11.9	11.7	11.7
4	11.8	11.9	12.0	12.1	12.2	12.2	12.2	12.1	12.0	11.9	11.8	11.8
2	11.9	11.9	12.0	12.0	12.1	12.1	12.1	12.1	12.0	12.0	11.9	11.9
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

a Values for N on the 15th day of the month provide a good estimate (error < 1%) of N averaged over all days within the month. Only for high latitudes, greater than 55° (N or S), during winter months may deviations be more than 1%.

Table 11

Mean daylight hours (N) for different latitudes in theSouthern Hemisphere for the 15th day of the month a (Source: FAO, 1998a)

Latitude	Southern Hemisphere											
Degree	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
70	24.0	17.4	13.0	8.4	2.7	0.0	0.0	6.4	11.2	15.7	21.7	24.0
68	21.9	16.7	12.9	8.7	4.3	0.0	1.7	7.0	11.3	15.3	19.9	24.0
66	20.1	16.2	12.8	9.1	5.3	2.0	3.7	7.6	11.3	15.0	18.8	22.1
64	19.0	15.8	12.8	9.3	6.1	3.7	4.8	8.0	11.4	14.7	18.0	20.3
62	18.3	15.5	12.7	9.6	6.7	4.8	5.6	8.3	11.4	14.5	17.4	19.2
60	17.6	15.2	12.6	9.8	7.2	5.6	6.3	8.7	11.5	14.3	16.9	18.4
58	17.1	14.9	12.6	9.9	7.6	6.2	6.8	8.9	11.5	14.1	16.5	17.8
56	16.7	14.7	12.5	10.1	8.0	6.7	7.2	9.2	11.6	13.9	16.1	17.3
54	16.3	14.5	12.5	10.2	8.3	7.2	7.6	9.4	11.6	13.8	15.8	16.9
52	16.0	14.3	12.5	10.4	8.6	7.5	8.0	9.6	11.6	13.7	15.5	16.5
50	15.7	14.2	12.4	10.5	8.8	7.9	8.3	9.7	11.7	13.6	15.3	16.1
48	15.4	14.0	12.4	10.6	9.0	8.2	8.5	9.9	11.7	13.4	15.0	15.8
46	15.2	13.9	12.4	10.7	9.2	8.5	8.8	10.0	11.7	13.3	14.8	15.5
44	14.9	13.7	12.4	10.8	9.4	8.7	9.0	10.2	11.7	13.3	14.6	15.3
42	14.7	13.6	12.3	10.8	9.6	9.0	9.2	10.3	11.7	13.2	14.4	15.0
40	14.5	13.5	12.3	10.9	9.8	9.2	9.4	10.4	11.8	13.1	14.3	14.8
38	14.4	13.4	12.3	11.0	9.9	9.4	9.6	10.5	11.8	13.0	14.1	14.6
36	14.2	13.3	12.3	11.1	10.1	9.6	9.8	10.6	11.8	12.9	13.9	14.4
34	14.0	13.2	12.2	11.1	10.2	9.7	9.9	10.7	11.8	12.9	13.8	14.3
32	13.9	13.1	12.2	11.2	10.4	9.9	10.1	10.8	11.8	12.8	13.7	14.1
30	13.7	13.0	12.2	11.3	10.5	10.1	10.2	10.9	11.8	12.7	13.5	13.9
28	13.6	13.0	12.2	11.3	10.6	10.2	10.4	11.0	11.8	12.7	13.4	13.8
26	13.5	12.9	12.2	11.4	10.7	10.4	10.5	11.1	11.9	12.6	13.3	13.6
24	13.3	12.8	12.2	11.4	10.8	10.5	10.7	11.2	11.9	12.6	13.2	13.5
22	13.2	12.7	12.1	11.5	10.9	10.7	10.8	11.2	11.9	12.5	13.1	13.3
20	13.1	12.7	12.1	11.5	11.1	10.8	10.9	11.3	11.9	12.5	13.0	13.2
18	13.0	12.6	12.1	11.6	11.2	10.9	11.0	11.4	11.9	12.4	12.9	13.1
16	12.9	12.5	12.1	11.6	11.3	11.1	11.1	11.5	11.9	12.4	12.8	12.9
14	12.7	12.4	12.1	11.7	11.4	11.2	11.2	11.5	11.9	12.3	12.7	12.8
12	12.6	12.4	12.1	11.7	11.4	11.3	11.4	11.6	11.9	12.3	12.6	12.7
10	12.5	12.3	12.1	11.8	11.5	11.4	11.5	11.7	11.9	12.2	12.5	12.6
8	12.4	12.3	12.1	11.8	11.6	11.5	11.6	11.7	12.0	12.2	12.4	12.5
6	12.3	12.2	12.0	11.9	11.7	11.7	11.7	11.8	12.0	12.1	12.3	12.3
4	12.2	12.1	12.0	11.9	11.8	11.8	11.8	11.9	12.0	12.1	12.2	12.2
2	12.1	12.1	12.0	12.0	11.9	11.9	11.9	11.9	12.0	12.0	12.1	12.1
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

a *Values for N on the 15th day of the month provide a good estimate (error < 1%) of N averaged over all days within the month. Only for high latitudes, greater than 55° (N or S), during winter months may deviations be more than 1%.*

Table 12

Conversion factors for cloudiness into equivalent values of n/N [source: FAO, 1984)

Cloudiness (oktas)	0	1	2	3	4	5	6	7	8
n/N ratio	0.95	0.85	0.75	0.65	0.55	0.45	0.30	0.15	0

Net solar or shortwave radiation (R_{ns})

The net solar or shortwave radiation, resulting from the balance between incoming and reflected solar radiation, is given by:

Equation 13

$$R_{ns} = (1 - 0.23)\, R_s$$

Where:

R_{ns} = Net solar or shortwave radiation (MJ/m^2 per day)

R_s = Incoming solar or shortwave radiation (MJ/m^2 per day)

Clear sky radiation (R_{so})

The calculation of clear sky radiation (R_{so}), when n = N, is required to compute net longwave radiation. R_{so} is given by the following simplified expression:

Equation 14

$$R_{so} = \left[0.75 + \frac{2\,z}{100\,000}\right] \times R_a$$

Where:

R_{so} = Clear sky solar radiation (MJ/m^2 per day)

z = Station elevation above sea level (m)

Net longwave radiation (R_{nl})

The rate of longwave radiation emission is proportional to the absolute temperature (Kelvin) of the surface raised to the fourth power. R_{nl} is calculated using the following expression:

Equation 15

$$R_{nl} = \left[\frac{\sigma(T_{max,\,K})^4 + \sigma(T_{min,\,K})^4}{2}\right] \times (0.34 - 0.14\sqrt{e_a}) \times \left[1\ 35\frac{R_s}{R_{so}} - 0.35\right]$$

Where:

R_{nl} = Net outgoing longwave radiation MJ/m^2 per day)

σ = Stefan-Boltmann constant (4.903 x 10^{-9} MJ/K^4 per m^2 per day)

$T_{max,\,K}$ = Maximum absolute temperature during the 24-hour period (K)

$T_{min,\,K}$ = Minimum absolute temperature during the 24-hour period (K)

K = °C + 273.16

e_a = Actual vapour pressure (kPa)

R_s/R_{so} = Relative shortwave radiation (limited ≤ 1)

R_s = Measured or calculated (Equation 12) solar radiation (MJ/m^2 per day)

R_{so} = Calculated (Equation 14) clear sky radiation (MJ/m^2 per day)

Table 13

$\sigma(T_K)^4$ values at different temperatures (Source: FAO, 1998a)

With σ = 4.903 x 10^{-9} MJ/K^4/m^2/day and $T_K = T_C + 273.16$					
T_C (°C)	$\sigma(T_K)^4$ MJ/m^2 per day	T_C (°C)	$\sigma(T_K)^4$ MJ/m^2 per day	T_C (°C)	$\sigma(T_K)^4$ MJ/m^2 per day
1.0	27.70	17.0	34.75	33.0	43.08
1.5	27.90	17.5	34.99	33.5	43.36
2.0	28.11	18.0	35.24	34.0	43.64
2.5	28.31	18.5	35.48	34.5	43.93
3.0	28.52	19.0	35.72	35.0	44.21
3.5	28.72	19.5	35.97	35.5	44.50
4.0	28.93	20.0	36.21	36.0	44.79
4.5	29.14	20.5	36.46	36.5	45.08
5.0	29.35	21.0	36.71	37.0	45.37
5.5	29.56	21.5	36.96	37.5	45.67
6.0	29.78	22.0	37.21	38.0	45.96
6.5	29.99	22.5	37.47	38.5	46.26
7.0	30.21	23.0	37.72	39.0	46.56
7.5	30.42	23.5	37.98	39.5	46.85
8.0	30.64	24.0	38.23	40.0	47.15
8.5	30.86	24.5	38.49	40.5	47.46
9.0	31.08	25.0	38.75	41.0	47.76
9.5	31.30	25.5	39.01	41.5	48.06
10.0	31.52	26.0	39.27	42.0	48.37
10.5	31.74	26.5	39.53	42.5	48.68
11.0	31.97	27.0	39.80	43.0	48.99
11.5	32.19	27.5	40.06	43.5	49.30
12.0	32.42	28.0	40.33	44.0	49.61
12.5	32.65	28.5	40.60	44.5	49.92
13.0	32.88	29.0	40.87	45.0	50.24
13.5	33.11	29.5	41.14	45.5	50.56
14.0	33.34	30.0	41.41	46.0	50.87
14.5	33.57	30.5	41.69	46.5	51.19
15.0	33.81	31.0	41.96	47.0	51.51
15.5	34.04	31.5	42.24	47.5	51.84
16.0	34.28	32.0	42.52	48.0	52.16
16.5	34.52	32.5	42.80	48.5	52.49

Table 14
Monthly net radiation for Kutsaga Research Station

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max} (°C) (from Table 2)	26.1	25.9	26.1	25.4	23.5	21.3	21.4	23.8	26.9	28.7	27.0	26.1
T_{min} (°C) (from Table 2)	15.7	15.6	14.3	12.5	9.1	6.7	6.1	7.8	10.6	13.8	15.1	15.7
n (hrs) (from Table 2)	6.6	6.6	7.7	8.2	8.7	8.4	8.8	9.5	9.7	9.4	7.1	6.1
N (hrs) (from Table 11, latitude is 17°56' South)	13.0	12.6	12.1	11.5	11.2	10.9	11.0	11.4	11.9	12.4	12.9	13.1
n/N ratio	0.51	0.52	0.64	0.71	0.78	0.77	0.8	0.83	0.82	0.76	0.55	0.47
R_a (MJ/m² per day) (from Table 9, latitude is 17°56' South)	41.5	40.0	37.0	32.1	27.6	25.1	26.0	29.8	34.7	38.7	40.9	41.7
$R_s = \left[0.25 + 0.5 \frac{n}{N}\right] R_a$ (MJ/m² per day) (Equation 12)	20.958	20.400	21.090	19.421	17.600	15.939	16.900	19.817	22.902	24.381	21.472	20.224
$R_{ns} = (1 - 0.23) R_s$ (MJ/m² per day) (Equation 13)	16.138	15.708	16.239	14.954	13.552	12.273	13.013	15.259	17.635	18.773	16.533	15.572
$R_{so} = \left[0.75 + \frac{2z}{100\,000}\right] R_a$ (MJ/m² per day) (Equation 14)	32.352	31.183	28.844	25.025	21.516	19.567	20.269	23.231	27.051	30.170	31.885	32.508
e_a (kPa) (from Table 7)	1.962	1.968	1.804	1.572	1.256	1.055	0.960	1.002	1.085	1.324	1.664	1.885
$\sigma(T_{max,K})^4$ (MJ/m² per day) (from Table 13)	39.32	39.22	39.32	38.96	37.98	36.86	36.91	38.13	39.75	40.71	39.80	39.32
$\sigma(T_{min,K})^4$ (MJ/m² per day) (from Table 13)	34.14	34.09	33.48	32.65	31.12	30.08	29.82	30.55	31.79	33.25	33.86	31.14
$R_{nl} = \left[\frac{\sigma(T_{max,K})^4 + \sigma(T_{min,K})^4}{2}\right](0.34 - 0.14\sqrt{e_a})\left[1.35 \frac{R_s}{R_{so}} - 0.35\right]$ ``` (MJ/m² per day) (Equation 15)	2.772	2.806	3.525	4.109	4.772	4.923	5.248	5.503	5.508	4.902	3.282	2.551
$R_n = R_{ns} - R_{nl}$ (MJ/m² per day) (Equation 11)	**13.366**	**12.902**	**12.714**	**10.845**	**8.780**	**7.350**	**7.765**	**9.576**	**12.127**	**13.871**	**13.251**	**13.021**

An average of the maximum air temperature to the fourth power and minimum air temperature to the fourth power is commonly used in Equation 15 for daily time steps. The term $(0.34 - 0.14\sqrt{e_a})$ expresses the correction for air humidity and will be smaller if the humidity increases. The effect of cloudiness is expressed by $(1.35R_s/R_{so} - 0.35)$. The term becomes smaller if the cloudiness increases and hence R_s decreases. The smaller the correction factors, the smaller the net outgoing flux of longwave radiation.

Values of σT_K^4 for different temperatures can be alternatively be read from Table 13 and used as input in Equation 15. After determining R_{ns} and R_{nl} as explained above, R_n can be easily calculated from Equation 11.

Going back to Kutsaga Research Station and using Equations 11, 12, 13, 14 and 15 and Tables 2, 7, 9, 11 and 13, the values of R_n on a month by month basis are calculated and the results presented in Table 14.

Soil heat flux (G)

The soil heat flux (G) is another input required in the FAO Penman-Monteith Equation. G is the energy that is utilized in heating the soil and it is a component of the energy balance equation and should be considered when making estimates of evapotranspiration. The size of the soil heat flux beneath the grass reference surface for one-day and ten-day periods is relatively small and it may be ignored for all practical purposes. Hence, in ET_o calculations using the FAO Penman-Monteith Equation G is considered to be zero.

Wind speed (u_2)

For input into the FAO Penman-Monteith Equation, the wind speed measured at 2 m height above the surface is required. To adjust wind speed data obtained from instruments placed at elevations other than the standard height of 2 m the following equation is used:

Equation 16

$$u_2 = u_z \times \frac{4.87}{\ln(67.8\,z - 5.42)}$$

Where:

u_2 = Wind speed at 2 m above ground surface (m/sec)

u_z = Measured wind speed at z m above ground surface (m/sec)

z = Height of measurement above ground surface (m)

The corresponding multipliers or conversion factors [= 4.87/ln(67.8z - 5.42)], which can be used to adjust wind speed, are given in Table 15.

Table 15

Conversion factors (multipliers) to convert wind speed measured at given height (over grass) to wind speed measured at standard height of 2 m above ground surface (Source: FAO, 1998a)

Height z (m)	Conversion factor	Height z (m)	Conversion factor	Height z (m)	Conversion factor	Height z (m)	Conversion factor
–	–	2.2	0.980	4.2	0.865	6.0	0.812
–	–	2.2	0.980	4.2	0.865	6.0	0.812
–	–	2.4	0.963	4.4	0.857	6.5	0.802
–	–	2.6	0.947	4.6	0.851	7.0	0.792
–	–	2.8	0.933	4.8	0.844	7.5	0.783
1.0	1.178	3.0	0.921	5.0	0.838	8.0	0.775
1.2	1.125	3.2	0.910	5.2	0.833	8.5	0.767
1.4	1.084	3.4	0.899	5.4	0.827	9.0	0.760
1.6	1.051	3.6	0.889	5.6	0.822	9.5	0.754
1.8	1.023	3.8	0.881	5.8	0.817	10.0	0.748
2.0	1.000	4.0	0.872	6.0	0.812	10.5	0.742

Table 16

Monthly wind speed at Kutsaga Research Station, adjusted to 2 m height above ground level

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
u_{14} (knots)[a]	6.1	6.0	6.4	6.3	6.1	6.4	6.9	7.7	8.7	9.1	7.5	6.7
u_{14} (m/sec)[a]	3.135	3.084	3.290	3.240	3.135	3.292	3.547	3.958	4.472	4.677	3.855	3.444
u_2 (m/sec)[b]	2.229	2.193	2.339	2.304	2.229	2.339	2.522	2.814	3.179	3.325	2.741	2.448
u_2 (km/day)[b]	193	189	202	199	193	202	218	243	275	287	239	212

a = measured speed at 14 m height above ground level.

b = converted to speed at 2 m height above ground level.

At Kutsaga Research Station the wind speed is measured at 14 m above ground level and is expressed in knots. Adjusting the wind speed to 2 m elevation above ground level, through the use of Equation 16, and converting the speed to m/sec (1 knot = 1.852 km/hr = 0.514 m/sec) will give the results as shown in Table 16.

Calculation of ET_o

After all the parameters of the FAO Penman-Monteith Equation have been determined, it is now possible to calculate ET_o. For Kutsaga Research Station these calculated values are presented in Table 17. From this table it can be seen that the peak ET_o of Kutsaga Research Station is 6.2 mm/day, if calculated manually using the FAO Penman-Monteith Equation. The peak occurs in the month of October.

The manual calculation of ET_o is a long and tedious procedure, and the risk of making arithmetical errors is fairly high. Computer software has been developed to speed up the calculations and make them less tedious to perform. One such software is the FAO CROPWAT computer programme for estimating ET_o and crop water requirements. The details on the use of CROPWAT will be covered in Chapter 6. At this stage it is only important to compare the monthly ET_o values obtained through manual calculations with those obtained through the use of CROPWAT.

Using the climatic data from Table 2 for Kutsaga Research Station, ET_o was estimated with CROPWAT Version 7.0. The results from CROPWAT 7.0 are included in the last row of Table 17. It appears that the results from the CROPWAT 7.0 and the manual calculation are very close. The values of ET_o calculated with CROPWAT are slightly higher, but the maximum difference in values between the two methods is shown to be 0.4 mm/day.

To simplify the calculations of ET_o, FAO (1998a) provides a calculation sheet, as shown in Table 18, which can be used with the relevant equations and meteorological tables, when developing a spreadsheet or computer programme to calculate ET_o. The equations and tables have already been introduced earlier on in this chapter.

2.3.4. Estimating ET_o with missing climatic data

If some of the required weather data for input into the FAO Penman-Monteith Equation are missing or cannot be calculated, it is strongly recommended that the reader estimates the missing climatic data with the procedures outlined in FAO (1998a) and uses the FAO Penman-Monteith Equation for the calculation of ET_o. These procedures will not be covered in this Module, instead the reader is referred to the above-mentioned reference. The use of other calculation procedures requiring only limited meteorological parameters is not recommended.

Although the Penman-Monteith method for calculating the ET_o is the sole recommended method, the Pan Evaporation method can be used under certain circumstances, as explained in Section 2.2.

Table 17

Mean monthly reference crop evapotranspiration (ET_o) values (in mm/day) for Kutsaga Research Station

Data for Kutsaga Research Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T = Monthly mean temperature (°C) (from Table 6)	20.9	20.8	20.2	19.0	16.3	14.0	13.8	15.8	18.8	21.3	21.1	20.9
Δ = Slope vapour pressure curve (kPa/°C) (from Table 5)	0.152	0.151	0.146	0.137	0.118	0.104	0.102	0.115	0.136	0.155	0.154	0.152
γ = Psychrometric constant (from Table 3)	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056
u_2 = Wind speed at 2 m height (m/sec) (from Table 16)	2.229	2.193	2.339	2.304	2.229	2.339	2.522	2.814	3.179	3.325	2.741	2.448
e_s-e_a = Vapour pressure deficit (kPa) (from Table 7)	0.620	0.588	0.702	0.774	0.770	0.703	0.786	1.002	1.327	1.434	0.977	0.697
G = Soil heat flux (MJ/m^2 per day) (assumed to be zero)	0	0	0	0	0	0	0	0	0	0	0	0
R_n = Net Radiation (MJ/m^2 per day) (from Table 14)	13.366	12.902	12.714	10.845	8.780	7.350	7.765	9.756	12.127	13.871	13.251	13.021
Reference crop evapotranspiration (ET_O)												
$\left[\frac{\Delta}{[\Delta + \gamma(1 + 0.34 u_2)]}\right]$	0.609	0.605	0.592	0.578	0.545	0.508	0.495	0.512	0.539	0.565	0.587	0.597
$\left[\frac{\gamma}{[\Delta + \gamma(1 + 0.34 u_2)]}\right]$	0.224	0.225	0.227	0.236	0.259	0.274	0.272	0.249	0.222	0.204	0.214	0.220
$\left[\frac{900}{(T_{mean} + 273)}\right] \times u_2$	6.716	6.828	7.180	7.101	6.934	7.335	7.914	8.769	9.805	10.168	8.338	7.496
$(e_s - e_a)$	0.620	0.588	0.702	0.774	0.770	0.703	0.786	1.002	1.327	1.434	0.977	0.697
$[0.408(R_n - G)]$	5.453	5.264	5.187	4.425	3.582	2.999	3.168	3.980	4.948	5.659	5.406	5.313
$\left[\frac{\Delta}{[\Delta + \gamma(1 + 0.34 u_2)]}\right] \times [0.408\, \Delta \{R_n - G)]$	3.319	3.187	3.072	2.559	1.953	1.525	1.569	2.038	2.665	3.198	3.176	3.172
$\left[\frac{\gamma}{[\Delta + \gamma(1 + 0.34 u_2)]}\right] \times \left[\frac{900}{(T_{mean} + 273)}\right] \times u_2 \times (e_s - e_a)$	0.934	0.901	1.145	1.299	1.381	1.412	1.691	2.191	2.885	2.977	1.750	1.149
$ET_o = \frac{0.408\, \Delta \{R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2\}}$ (mm/day)	4.3	4.1	4.2	3.9	3.3	2.9	3.2	4.2	5.5	6.2	4.9	4.3
ET_o calculated with CROPWAT 7.0 (mm/day)	4.4	4.3	4.4	4.1	3.6	3.2	3.5	4.6	5.9	6.5	5.2	4.6

Table 18

Calculation sheet for ET_o (FAO Penman-Monteith method) using Tables 3, 4, 5, 8, 9, 10, 11, 13 (Source: FAO, 1998a)

Parameters						
T_{max}		°C				
T_{min}		°C	$T_{mean} = (T_{max} + T_{min})/2$			°C
T_{mean}		°C	Δ	(Table 5)		kPa/°C
Altitude		m	γ	(Table 3)		kPa/°C
u_2		m/sec	$(1 + 0.34u_2)$			
			$\Delta / [\Delta + \gamma (1 + 0.34u_2)]$			
			$\gamma / [\Delta + \gamma (1 + 0.34u_2)]$			
			$[900 / (T_{mean} + 273)]\, u_2$			
Vapour pressure deficit						
T_{max}		°C	$e° (T_{max})$	(Table 4)		kPa
T_{min}		°C	$e° (T_{min})$	(Table 4)		kPa
Saturation vapour pressure $e_s = [e° (T_{max}) + e° (T_{min})] / 2$						kPa
e_a from dew point temperature:						
T_{dew}		°C	$e_a = e° (T_{dew})$	(Table 4)		kPa
or e_a derived from maximum and minimum relative humidity:						
RH_{max}		%	$e° (T_{min}) \times RH_{max}/100$			kPa
RH_{min}		%	$e° (T_{max}) \times RH_{min}/100$			kPa
			e_a (average)			kPa
or e_a derived from maximum relative humidity (recommended if there are errors in RH_{min}):						
RH_{max}		%	$e_a = e° (T_{min}) \times RH_{max}/100$			kPa
or e_a derived from mean relative humidity (less recommended due to non-linearities):						
RH_{mean}		%	$e_a = e_s \times RH_{mean}/100$			kPa
Vapour pressure deficit			**$(e_s - e_a)$**			kPa
Radiation						
Latitude		°				
Day			R_a	(Table 8 or 9)		MJ/m² per day
Month			N	(Table 10 or 11)		hours
n		hours	n/N			
If no R_s data available:			$R_s = (0.25 + 0.5\, n/N) \times R_a$			MJ/m² per day
			$R_{so} = [0.75 + 2 (\text{Altitude})]/100\,000$			MJ/m² per day
			R_s/R_{so}			
			$R_{ns} = 0.77\, R_s$			MJ/m² per day
T_{max}		°C	$\sigma(T_{max,K})^4$	(Table 13)		MJ/m² per day
T_{min}		°C	$\sigma(T_{min,K})^4$	(Table 13)		MJ/m² per day
			$[\sigma(T_{max,K})^4 + \sigma(T_{min,K})^4]/2$			MJ/m² per day
e_a		kPa	$(0.34 - 0.14\sqrt{e_a})$			
R_s/R_{so}			$1.35 R_s/R_{so} - 0.35)$			
$R_{nl} = [\sigma(T_{max,K})^4 + \sigma(T_{min,K})^4]/2 \times (0.34 - 0.14\sqrt{e_a}) \times 1.35\, R_s/R_{so} - 0.35)$						MJ/m² per day
			$R_n = R_{ns} - R_{nl}$			MJ/m² per day
T_{month}		°C	G_{day} (assume)		0	MJ/m² per day
T_{month}^{-1}		°C	$G_{month} = 0.14 (T_{month} - T_{month-1})$			MJ/m² per day
			$R_n - G$			
			$0.408 (R_n - G)$			mm/day
Reference crop evapotranspiration (ET_o)						
			$\left[\frac{\Delta}{\Delta + \gamma (1 + 0.34u_2)}\right] \times [0.408 (R_n - G)]$			mm/day
			$\left[\frac{\gamma}{\Delta + \gamma (1 + 0.34u_2)}\right] \times \left[\frac{900}{T + 273}\right] \times u_2 (e_s - e_a)$			mm/day
			$ET_o = \frac{0.408\, \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}$			mm/day

Chapter 3
Reference crop evapotranspiration (iso-ET_o) maps

As shown in Chapter 2, the manual calculation of the reference crop evapotranspiration ET_o using the FAO Penman-Monteith Equation is long and complicated. This problem has been partly solved by the introduction of computer programmes like CROPWAT for the calculation of ET_o and crop water requirements. However, the availability of computer hardware and software is still limited in some remote parts of East and Southern Africa. In addition, computer literacy still may be a constraint. In most of such situations, field staff and extension workers normally require quick methods which can be used to estimate ET_o and crop water requirements with reasonable accuracy.

Mean monthly reference crop evapotranspiration or iso-ET_o maps for a given region or country can find such use. Using the CROPWAT software with the FAO Penman-Monteith Equation (see Chapter 6), it is possible to calculate ET_o values for all the meteorological stations in a country or region with sufficient data. Most of these stations are well distributed throughout a given country making it possible to prepare reference crop evapotranspiration maps for a country.

3.1. Development of iso-ET_o maps

In order to illustrate the use of iso-ET_o maps, such maps were developed for four selected countries in East and Southern Africa: Ethiopia, Kenya, South Africa and Zimbabwe. For each of the mentioned countries, CROPWAT and CLIMWAT were used to calculate ET_o values for those meteorological stations contained in CLIMWAT. The monthly ET_o values, together with the coordinates of each station and using interpolation, were used to plot the iso-ET_o maps for each country. For illustrative purposes only one map per country for the month of peak ET_o has been drawn, as shown in Figures 5, 7, 9 and 11. Other iso-ET_o maps for the rest of the months for each country can be developed in the same manner. For readability, in this Module separate maps showing the meteorological stations have been prepared (Figures 6, 8, 10 and 12). Ideally, the stations and the iso-lines should be combined in one map.

3.2. Use and application of iso-ET_o maps

The usual approach in estimating ET_o in a proposed irrigation service area, regardless of what method is adopted, is to identify a meteorological station nearest the project site and utilize its data. In those cases where the project site is located between two or more stations, the problem of choosing which station to use often confronts the planner. A greater problem, however, exists if the nearest meteorological station is located at quite a distance from the project site. In such a situation the common, but very rough, solution is to utilize the data of the 'nearest' station.

The developed iso-ET_o maps simplify the estimation of ET_o of a given project area. These maps eliminate the problem of which station to choose and in addition, since they are based on the FAO Penman-Monteith method, they are fairly accurate when compared to earlier methods, which are no longer recommended.

In using the iso-ET_o maps, it is necessary to locate the project area on the map. This is done by determining the coordinates (longitude and latitude) of the area. The next step is to read or interpolate between two lines the mean monthly ET_o. The obtained mean monthly ET_o can be used to estimate crop water requirements. In the estimation of ET_c, crop coefficients (K_c) for each crop to be grown in the project area will have to be estimated. The methodologies of estimating K_c values will be covered in Chapter 4. It must be noted that it is preferable to use local data on K_c, if they are available. In the absence of local data, K_c values in Table 21 can be used for preliminary planning. The ET_o value will have to be multiplied by the K_c for the crop and growth stage under consideration (Equation 1).

Figure 5
Reference evapotranspiration map for Ethiopia for the month of April

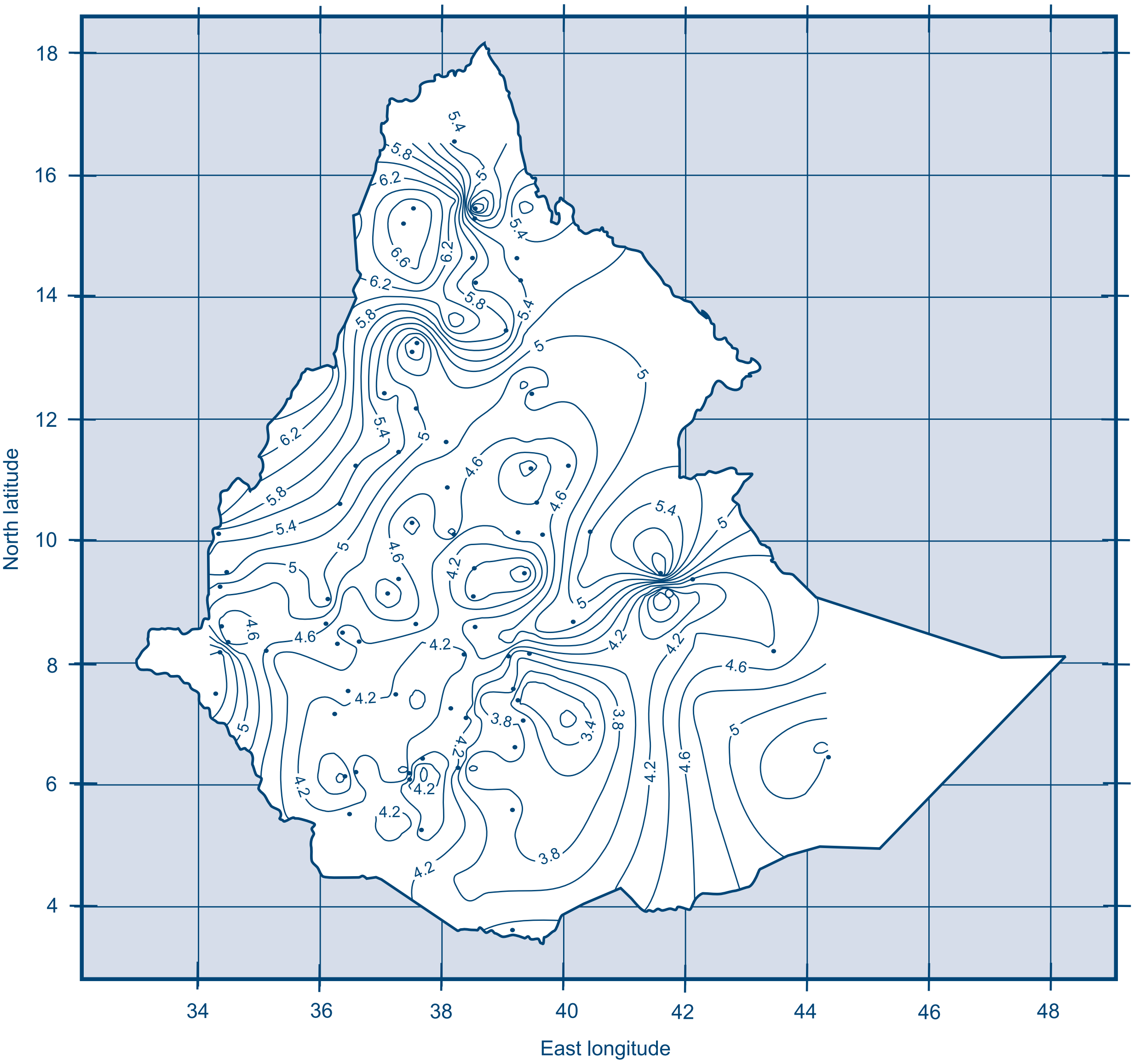


Figure 6
Location of meteorological stations in Ethiopia

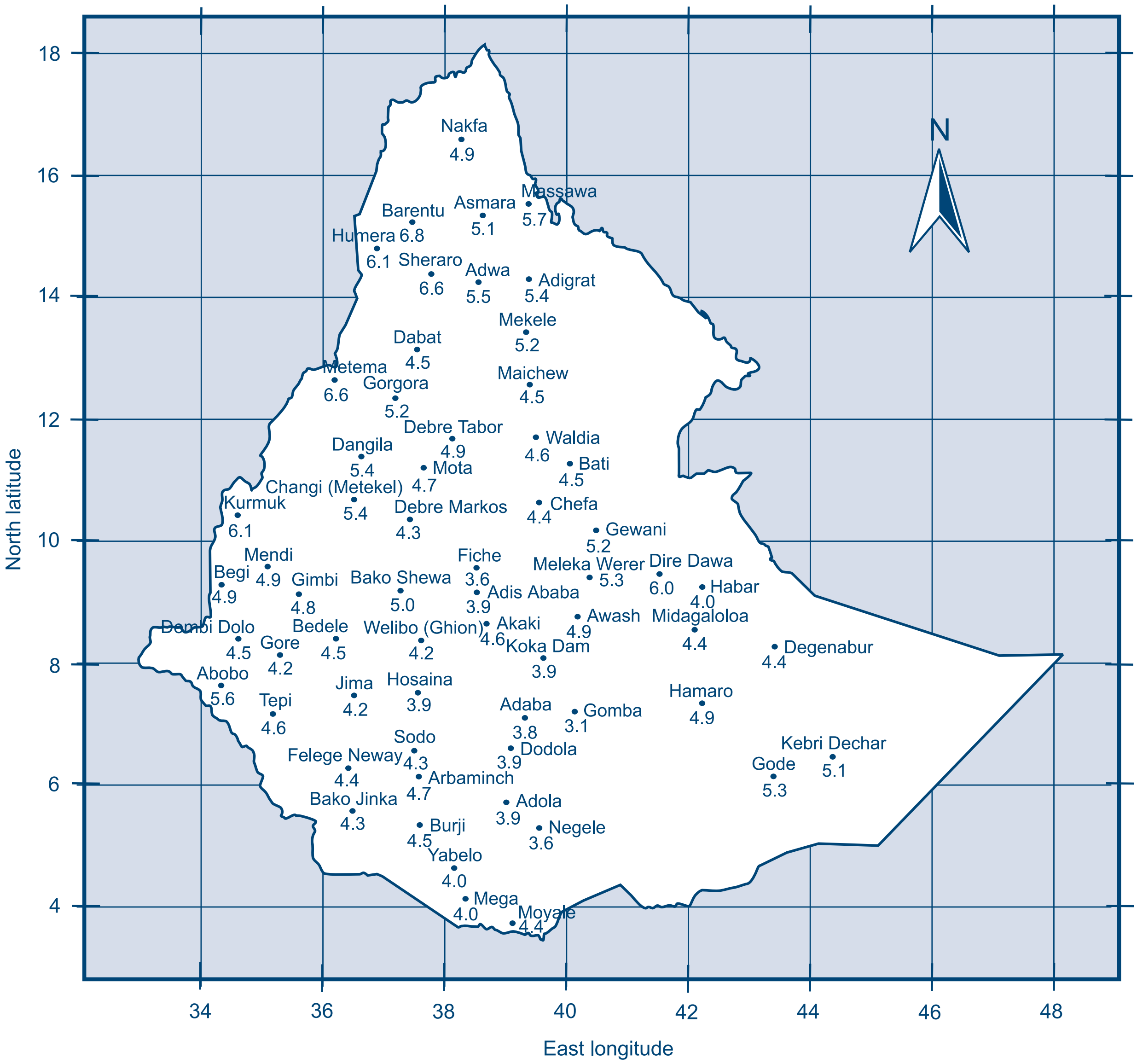


Figure 7
Reference evapotranspiration map for Kenya for the month of February

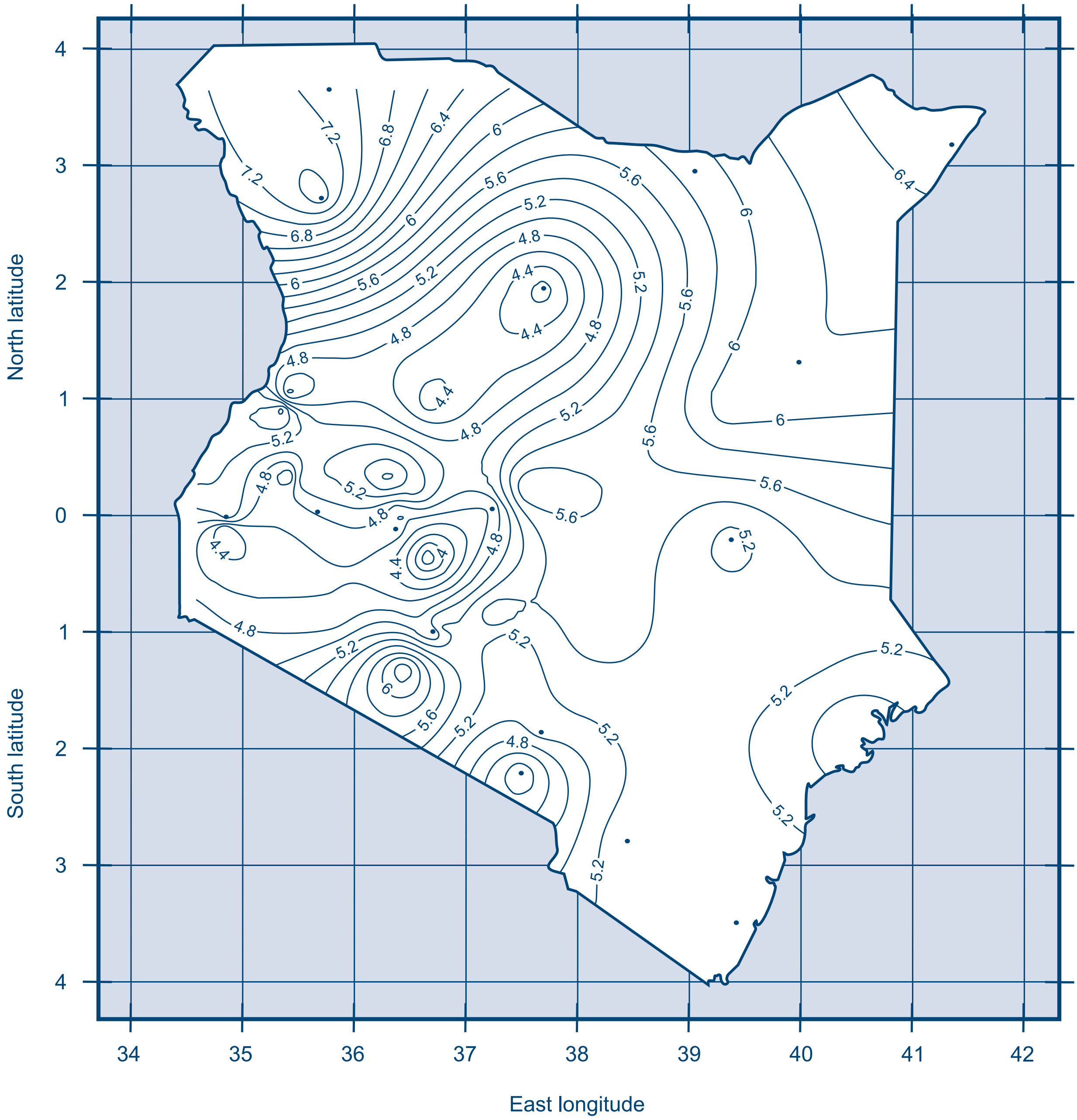


Figure 8
Location of meteorological stations in Kenya

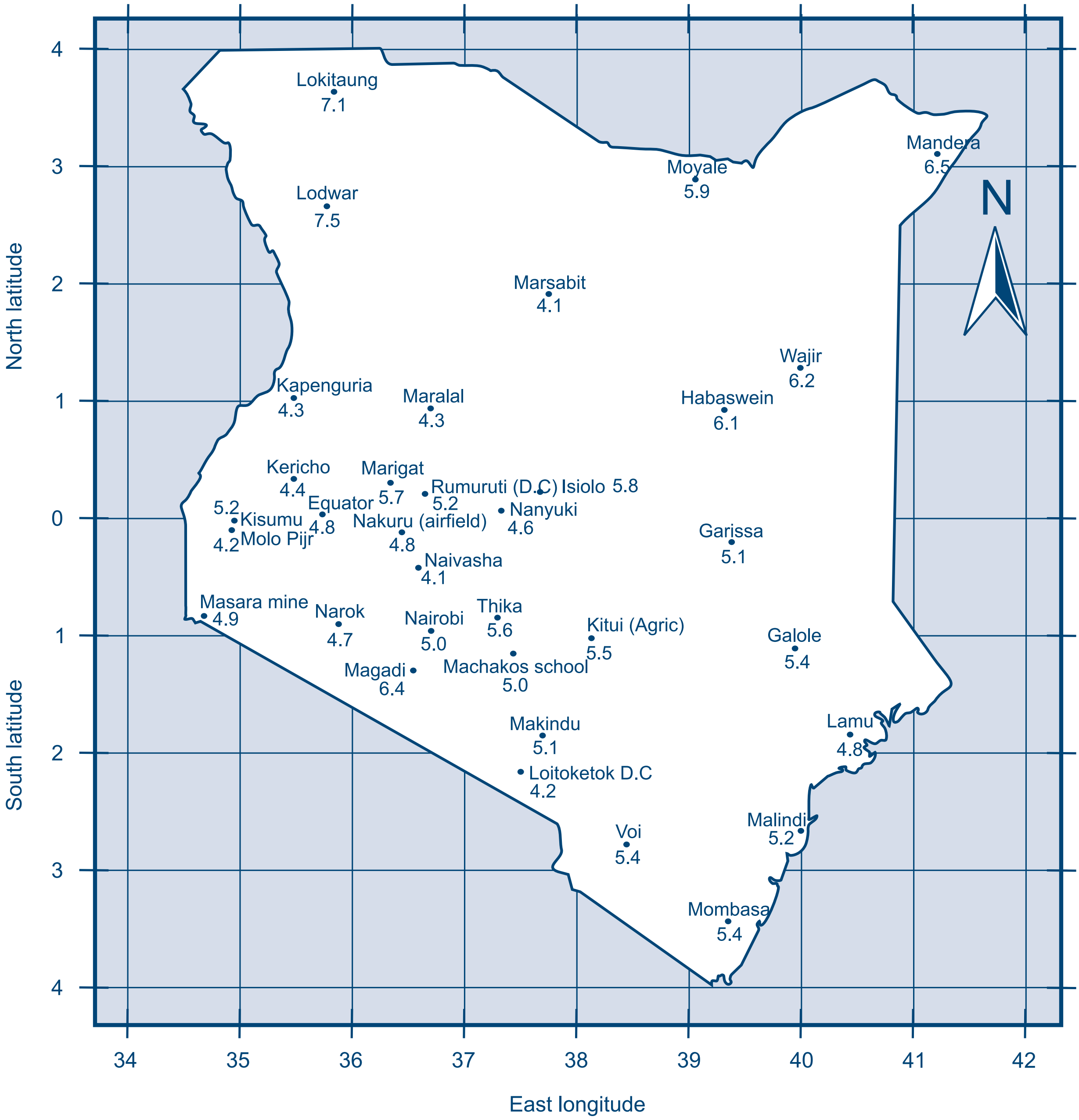


Figure 9
Reference evapotranspiration map for South Africa for the month of January

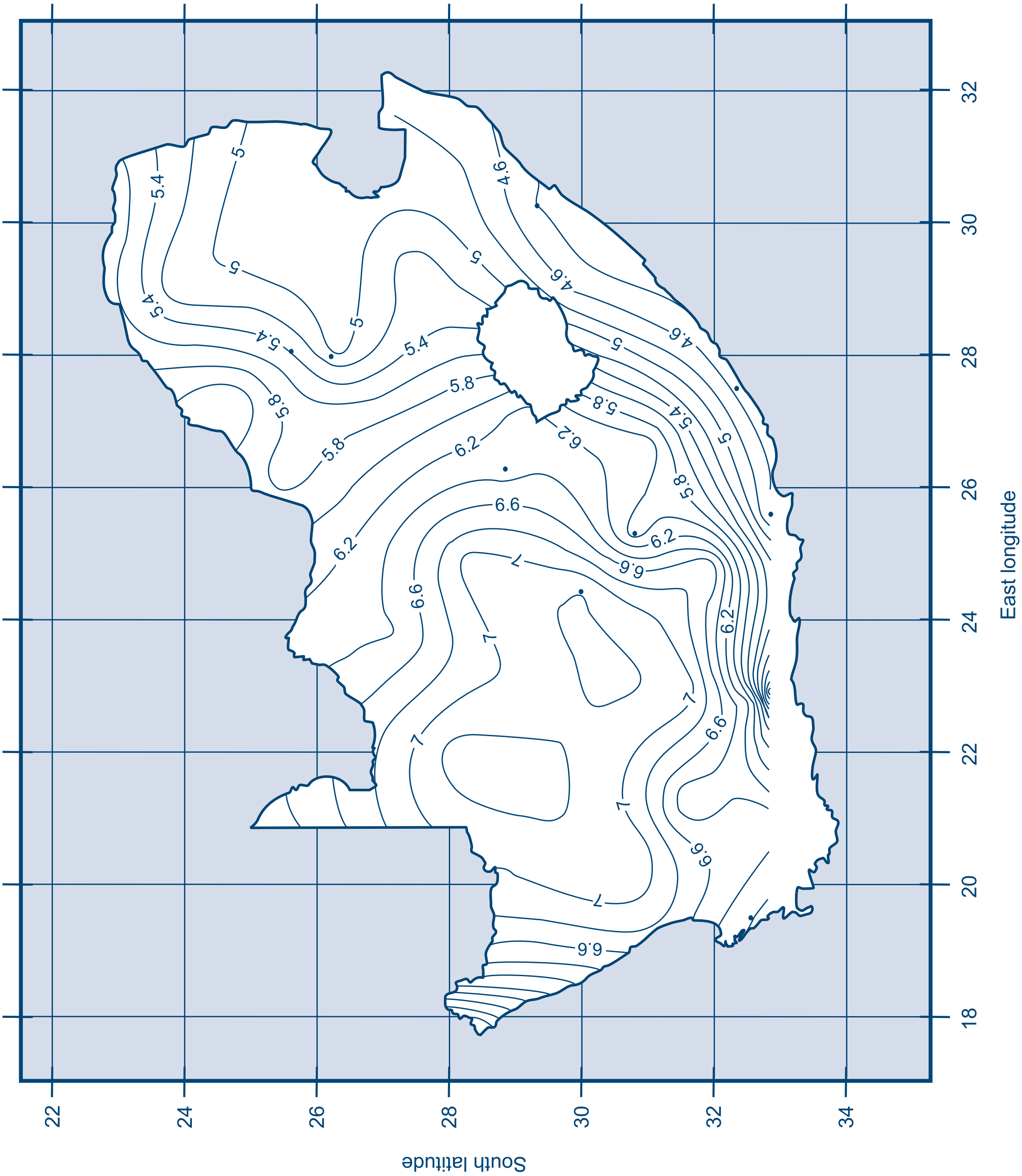


Figure 10

Location of meteorological stations in South Africa

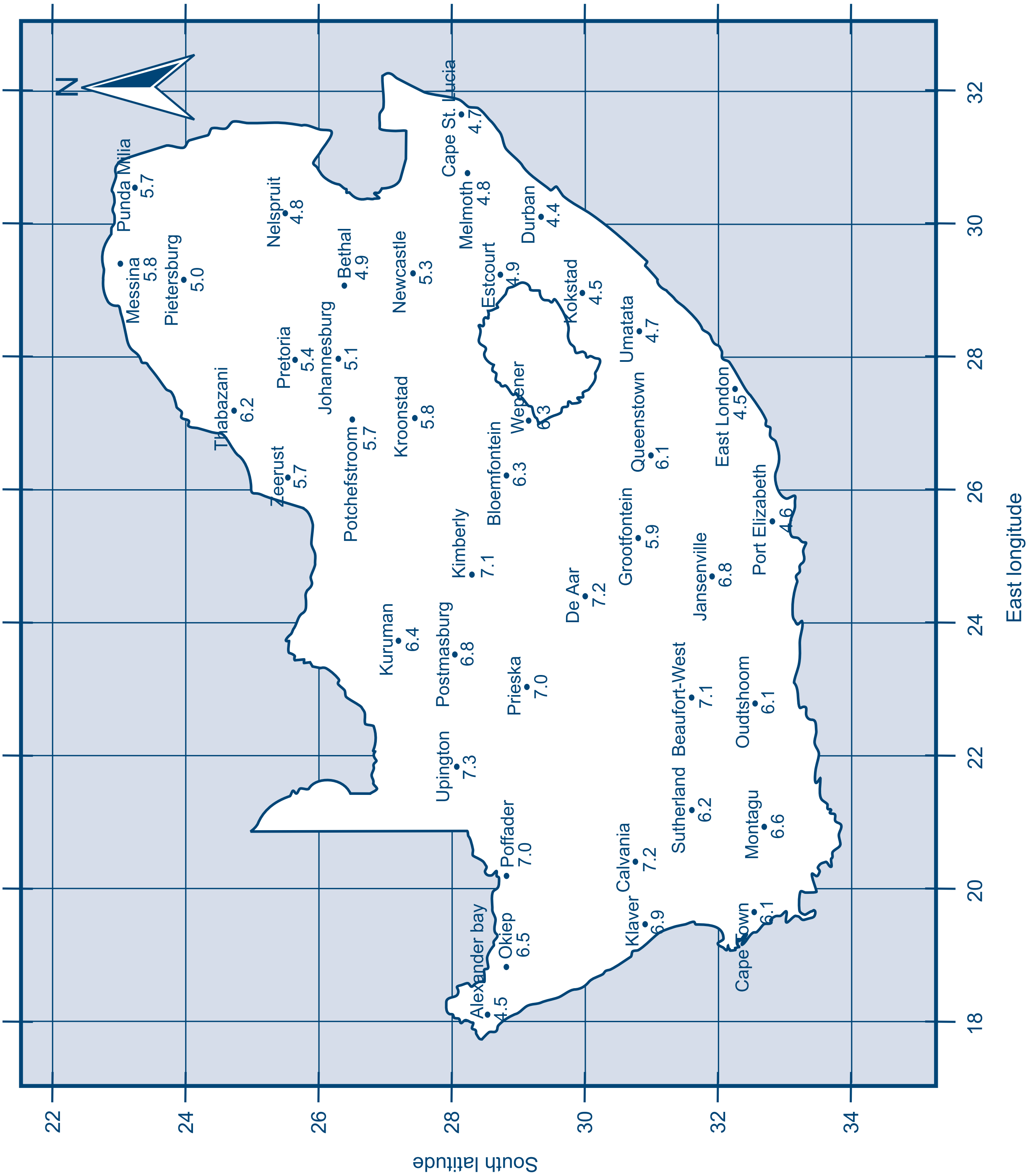


Figure 11
Reference evapotranspiration map for Zimbabwe for the month of October

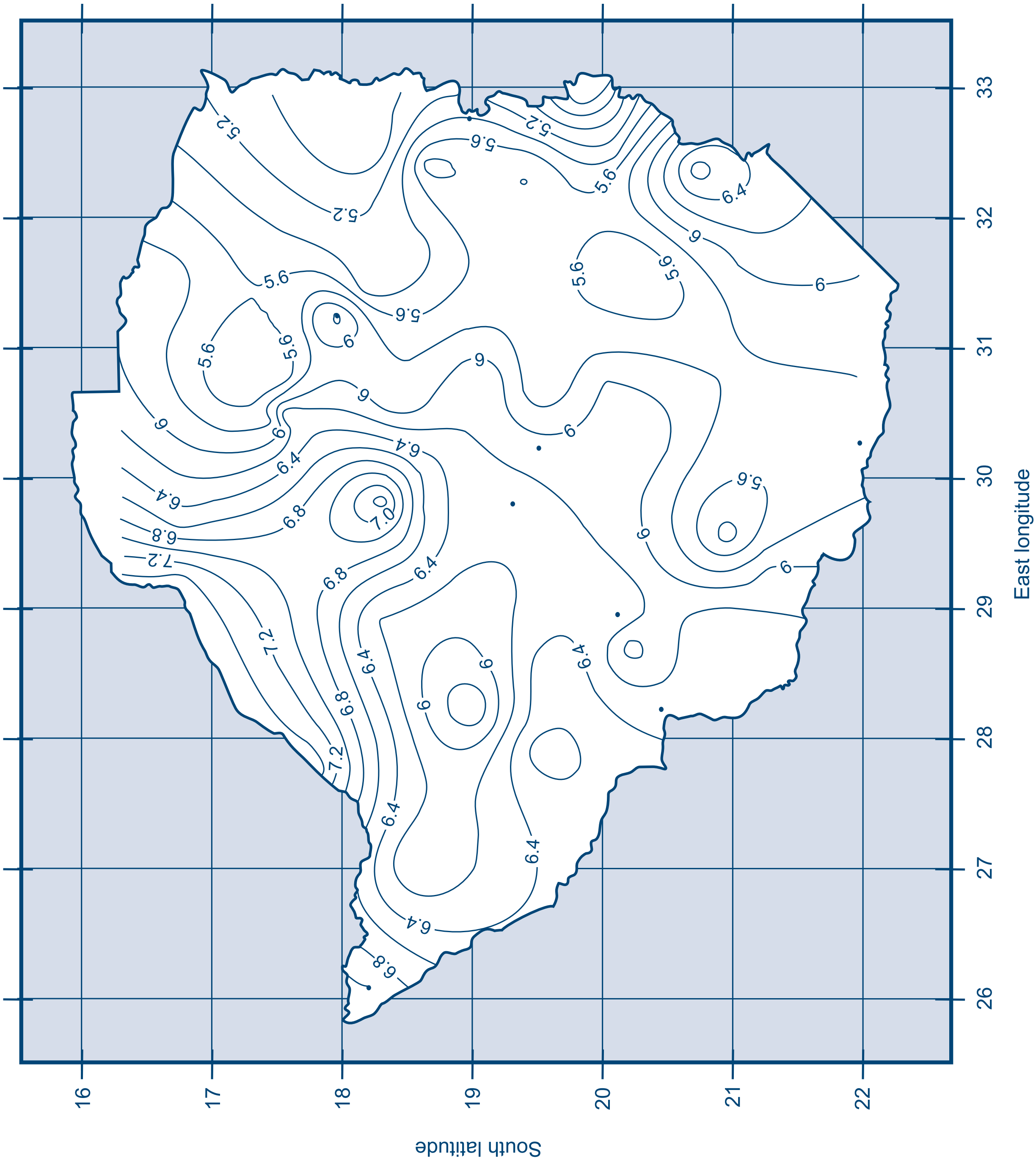
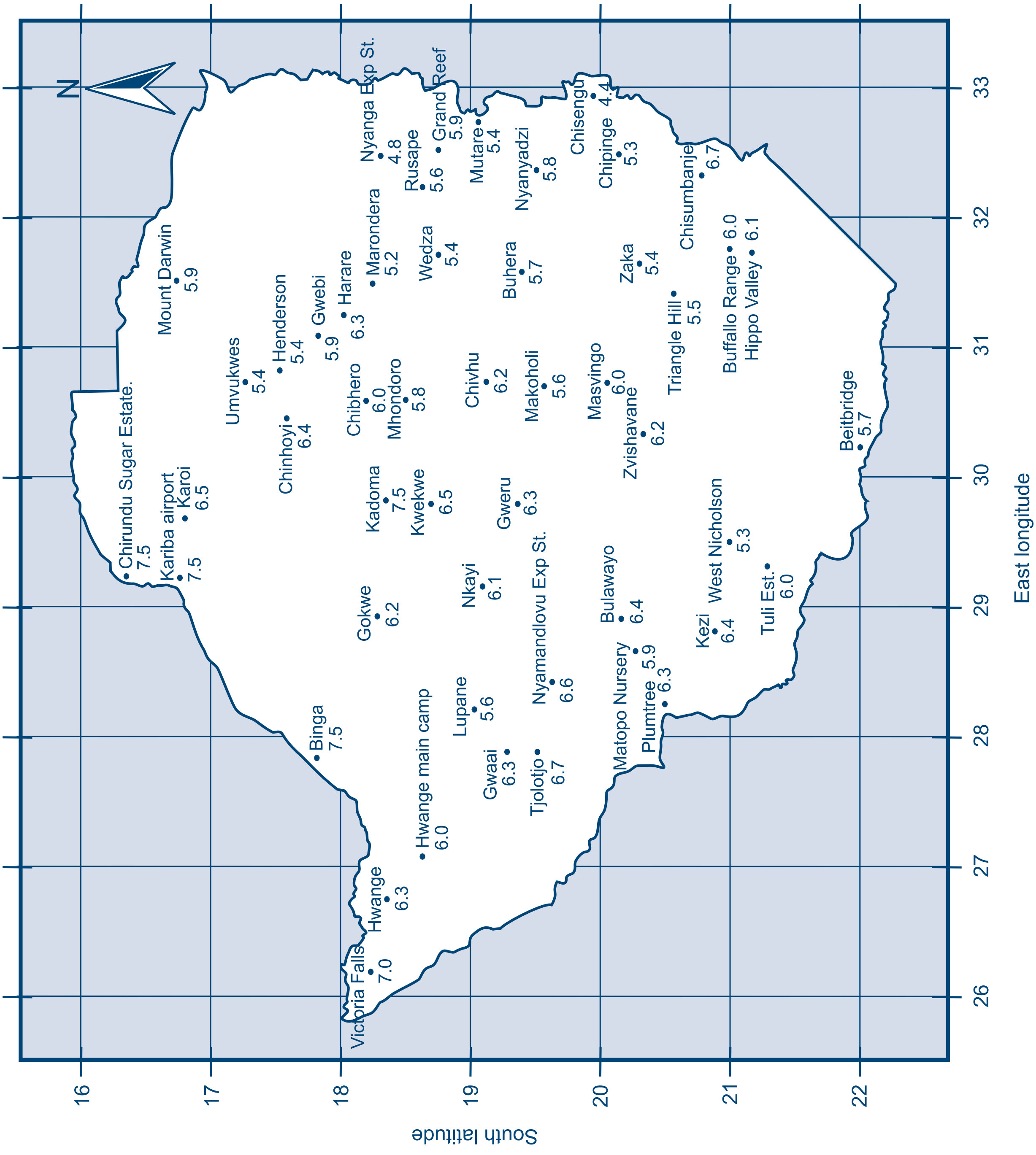


Figure 12
Location of meteorological stations in Zimbabwe



Chapter 4

Estimating crop evapotranspiration or crop water requirements under standard conditions

As explained in Chapter 1, crop evapotranspiration can be calculated under standard conditions (ET_c) or under non-standard conditions ($ET_{c\ adj}$). Standard conditions refer to crops grown in large fields under non-limiting agronomic and soil water conditions. Non-standard conditions refer to management and environmental conditions that deviate from the standard conditions. Such non-standard conditions can be low soil fertility, salt toxicity, waterlogging, pests, diseases and the presence of a hard or impenetrable soil horizon in the root zone. These environmental conditions are described by introducing stress coefficients when calculating crop evapotranspiration under non-standard conditions.

This Chapter will be limited to the calculation of ET_c. The calculation of $ET_{c\ adj}$ is not covered in this Module, but details for this calculation can be found in FAO (1998a).

4.1. Crop coefficient approach for calculating ET_c

In this calculation procedure ET_c is calculated by multiplying ET_o by a crop coefficient K_c, as was given in Equation 1:

$$ET_c = ET_o \times K_c$$

Where

ET_c	=	Crop evapotranspiration (mm/day)
ET_o	=	Reference crop evapotranspiration (mm/day)
K_c	=	Crop coefficient

The effects of weather conditions are captured in the ET_o estimate. Therefore, as ET_o represents a factor of climatic demand, K_c varies mainly with the specific crop characteristics. This allows the transfer of standard values for K_c between locations and climates. This has been the main reason for the worldwide acceptance of the crop coefficient approach and usefulness of K_c factors developed in past studies.

From Equation 1 it can be seen that K_c is basically the ratio of ET_c to ET_o and it expresses the difference in evapotranspiration between the cropped area and the reference grass surface. The difference can be combined into one single coefficient or can be split into two factors describing separately the differences in evaporation and transpiration between both surfaces. This gives rise to the single and dual crop coefficient approaches for calculating crop evapotranspiration.

4.1.1. Single crop coefficient approach

The effects of crop transpiration and soil evaporation are combined into a single K_c coefficient. This coefficient combines differences in soil evaporation and crop transpiration rate between the crop and the grass reference surface.

As the single K_c averages soil evaporation and crop transpiration, the approach is used to calculate ET_c for weekly or longer time periods. The time-averaged single K_c is used for planning purposes and irrigation system design where averaged effects of soil wetting are acceptable and relevant. The single coefficient approach will be used in this Module.

4.1.2. Dual crop coefficient approach

In the dual crop coefficient approach, the effects of crop transpiration and soil evaporation are determined separately. Two coefficients are used: the basal crop coefficient (K_{cb}) to describe plant transpiration and the soil water evaporation coefficient (K_e) to describe evaporation from the soil surface. The single K_c coefficient is replaced by:

Equation 17

$$K_c = K_{cb} + K_e$$

Where:

K_{cb}	=	Basal crop coefficient
K_e	=	Soil water coefficient

Substituting Equation 17 into Equation 1 the dual coefficient approach for calculating ET_c can be given as:

Equation 18

$$ET_c = (K_{cb} + K_e) \times ET_o$$

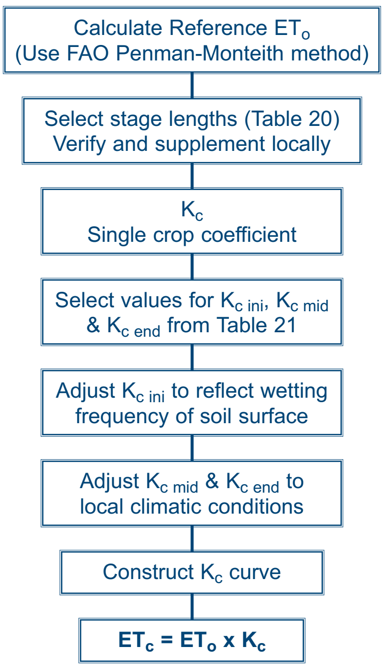
The dual crop coefficient approach is more complicated and requires more numerical calculations than the single crop coefficient approach. It is best for real-time irrigation scheduling, soil water balance computations and for research studies where effects of day to day variations in soil water fluxes are important. This is the case with high frequency irrigation systems like micro-irrigation and lateral move systems such as center pivots.

4.1.3. Selection of the approach to be used

The selection of which approach to use, the single coefficient or the dual coefficient approach, depends on the purpose of the calculation, the accuracy required, the climatic data available and the time step to which the calculations are being carried. Table 19 below gives the general selection criteria. Figure 13 presents the general calculation procedures for the single crop coefficient approach under standard conditions. The dual crop coefficient approach will not be covered in detail in this module but can be found in FAO (1998a).

Figure 13

General procedures for calculating ET_c under standard conditions (Source: FAO, 1998a)



4.2. Factors determining the crop coefficient

Many factors affect K_c, namely crop type, changing crop characteristics over the growing season (stages of growth) and, to a limited extent, the prevailing weather conditions. As evaporation is part of crop evapotranspiration, conditions affecting soil evaporation will also affect K_c.

4.2.1. Crop type

The large variation in K_c values between major groups of crops is due to the resistance to transpiration of different crops, such as closed stomata during the day (pineapple) and waxy leaves (citrus). Also, differences in crop height, crop roughness, reflection and groundcover produce different K_c values. Typical K_c values for different types of full grown crops are illustrated in Figure 14.

4.2.2. Climate

General climatic conditions, especially wind and humidity, affect crop coefficients. Variations in wind change the aerodynamic resistance of the crops and their crop coefficients, especially for those crops that are substantially taller than the grass reference crop. Crop aerodynamic properties also change with climate, in particular relative humidity. K_c for many crops increases as wind speed increases and as relative humidity decreases. More arid climates and conditions of greater wind speed will have higher values for K_c. More humid climates and conditions of lower wind speed will have lower values for K_c. The relative impact of climate on K_c for full grown crops is shown in Figure 15.

Table 19

General selection criteria for the single and dual crop coefficient approaches (Source: FAO, 1998a)

	Single crop coefficient (K_c)	Dual crop coefficient (K_{cb}+ K_e)
Purpose of calculation	• Irrigation planning and design • Irrigation management • Basic irrigation scheduling • Real-time irrigation scheduling for non-frequent water applications (surface and sprinkler irrigation)	• Research • Real time irrigation scheduling • Irrigation scheduling for high frequency water application (micro irrigation and automated sprinkler irrigation) • Supplementary irrigation • Detailed soil and hydrologic water balance studies
Time step	• Daily, ten-day, monthly (data and calculation)	• Daily (data and calculation)
Solution method	• Graphical • Pocket calculator • Computer	• Computer

Figure 14
Typical K_c values for different types of full grown crops (Source: FAO, 1998a)

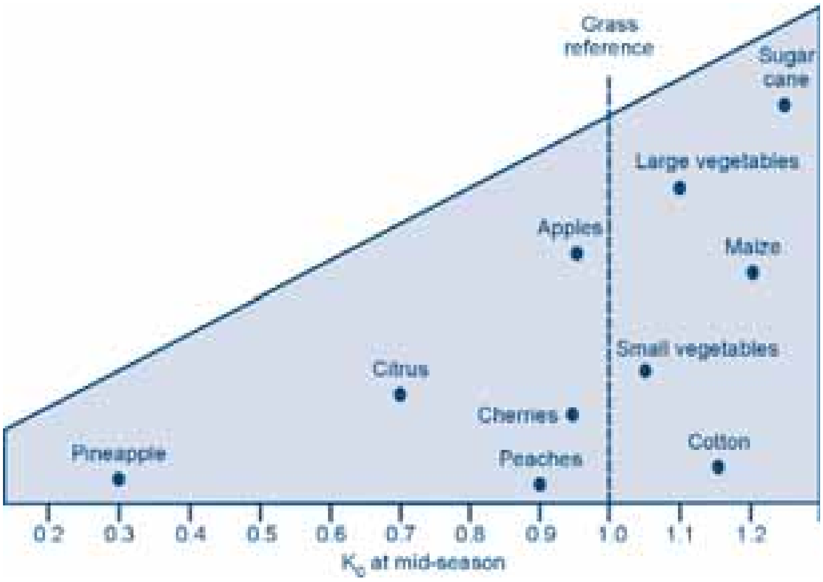
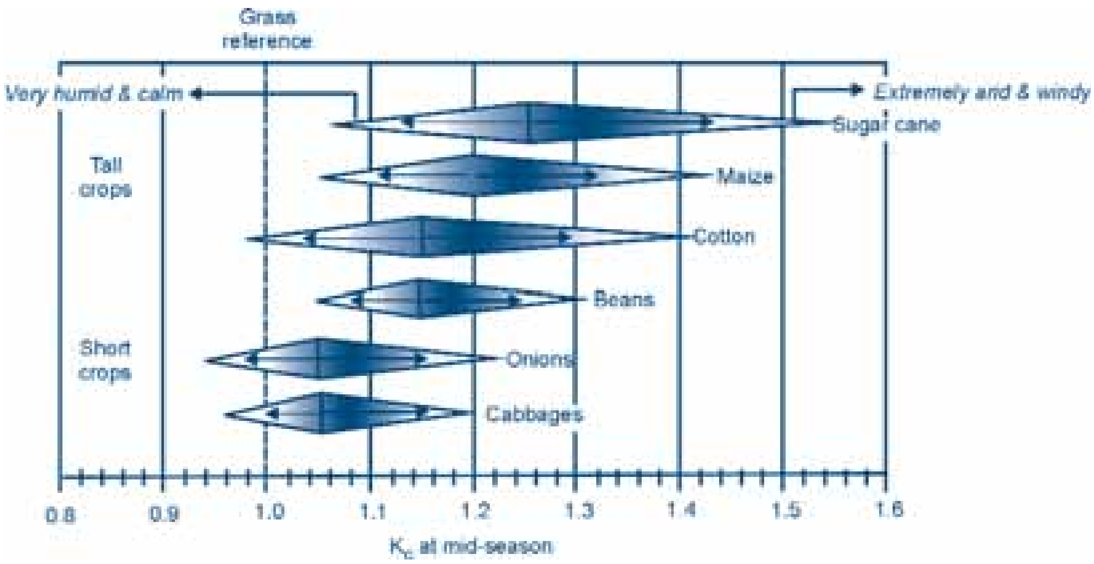


Figure 15
Extreme ranges expected in K_c for full grown crops as climate and weather change (Source: FAO, 1998a)



4.2.3. Soil evaporation

Crop evapotranspiration is a combination of transpiration by the crop and evaporation from the soil surface. Differences in soil evaporation and crop transpiration between field crops and the reference surface are integrated within the crop coefficient. The K_c for full cover crops reflects differences in transpiration, as the contribution of soil evaporation is relatively small. After rainfall or irrigation, the contribution of soil evaporation is significant, especially if the crop is small and has small groundcover. For such low cover conditions K_c is largely determined by how frequent the soil is wetted.

4.2.4. Crop growth stages

The K_c for a given crop changes over the growing period as the groundcover, crop height and leaf area changes. Four growth stages are recognized for the selection of K_c: initial stage, crop development stage, mid-season stage and the late season stage.

Figure 16 illustrates the different sequence and proportion of the growth stages for different types of crops, while Figure 17 shows the variation in K_c for different crops as influenced by weather factors and crop development.

Figure 16
Crop growth stages for different types of crops (Source: FAO, 1998a)

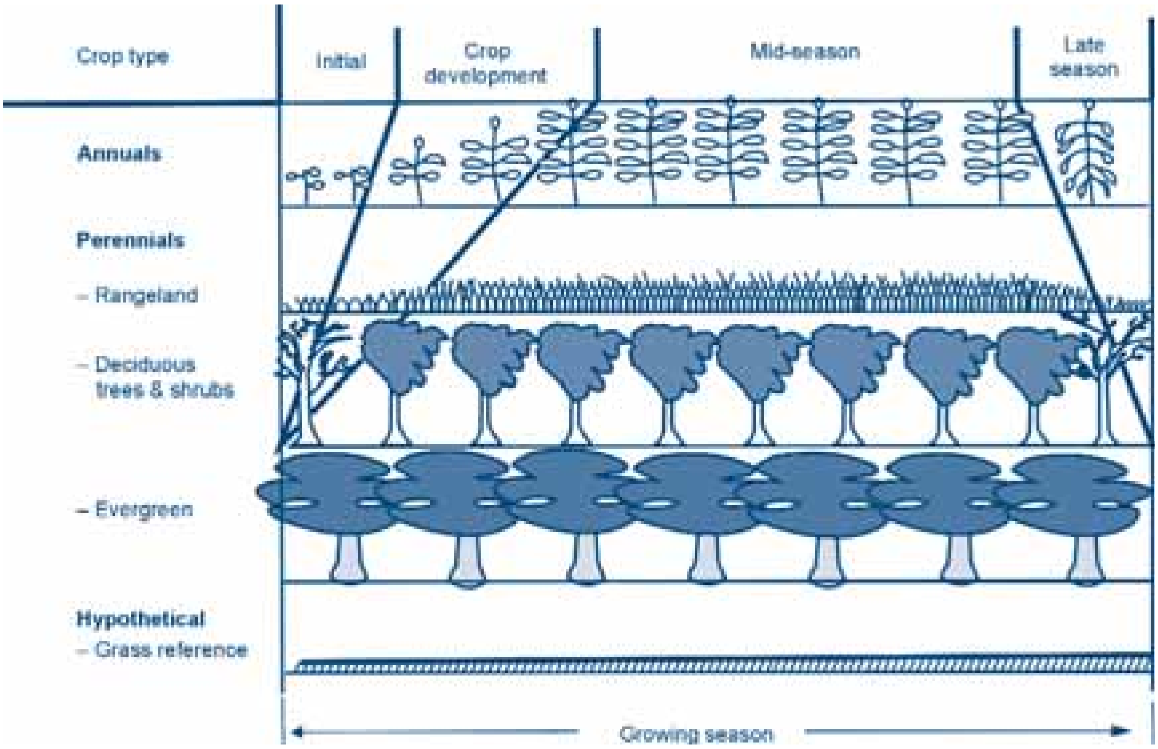
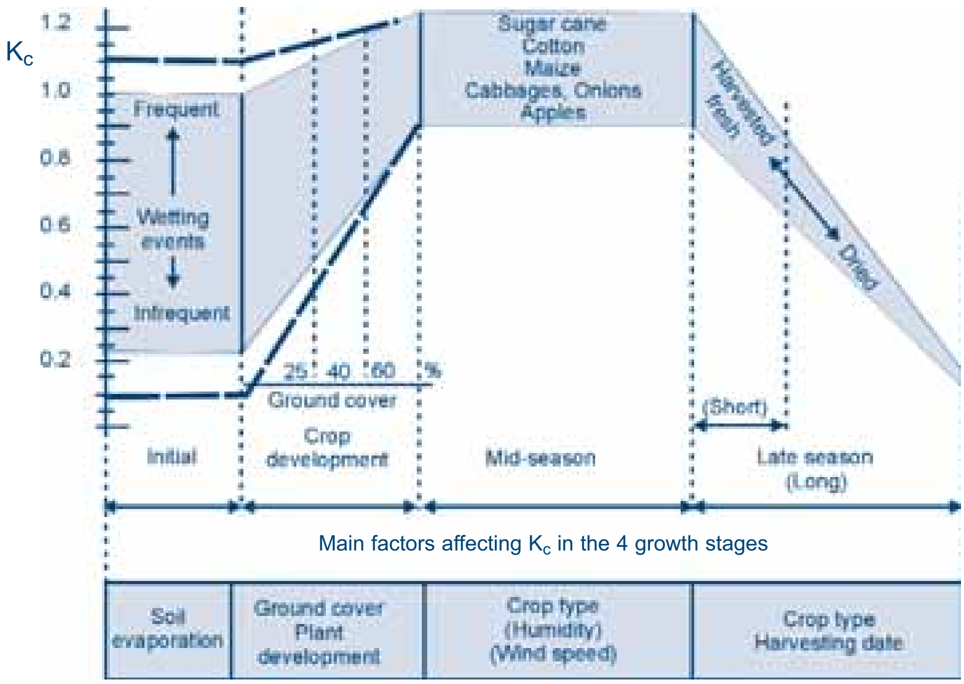


Figure 17
Typical ranges expected in K_c for the four growth stages (Source: FAO, 1998a)



Initial stage

The initial stage refers to the germination and early growth stage when the soil surface is not or is hardly covered by the crop (groundcover < 10%). The K_c during this initial stage ($K_{c\ ini}$) is large when the soil is wet from irrigation and rainfall and is low when the soil surface is dry.

Crop development stage

The crop development stage is the stage from the end of the initial stage to attainment of effective full groundcover (groundcover 70-80%). As the crop develops and shades more and more of the ground, soil evaporation becomes more restricted and transpiration becomes the dominant process. During the crop development stage, the K_c values correspond to amounts of groundcover and plant development and thus varies. If the soil is dry, $K_{c\ dev} = 0.5$ corresponds to about 20-40% groundcover. A $K_{c\ dev} = 0.7$ often corresponds to about 40-60% groundcover.

Mid-season stage

The mid-season stage is the stage from attainment of effective full groundcover to the start of maturity, as indicated for example by discolouring of leaves (as in beans) or falling of leaves (as in cotton). The mid-season stage is the longest stage for perennial crops and for many annual crops, but it may be relatively short for vegetables that are harvested fresh for their green vegetation. At this stage, K_c reaches its maximum value. The value of $K_{c\ mid}$ is relatively constant for most growing and cultural conditions.

Late season stage

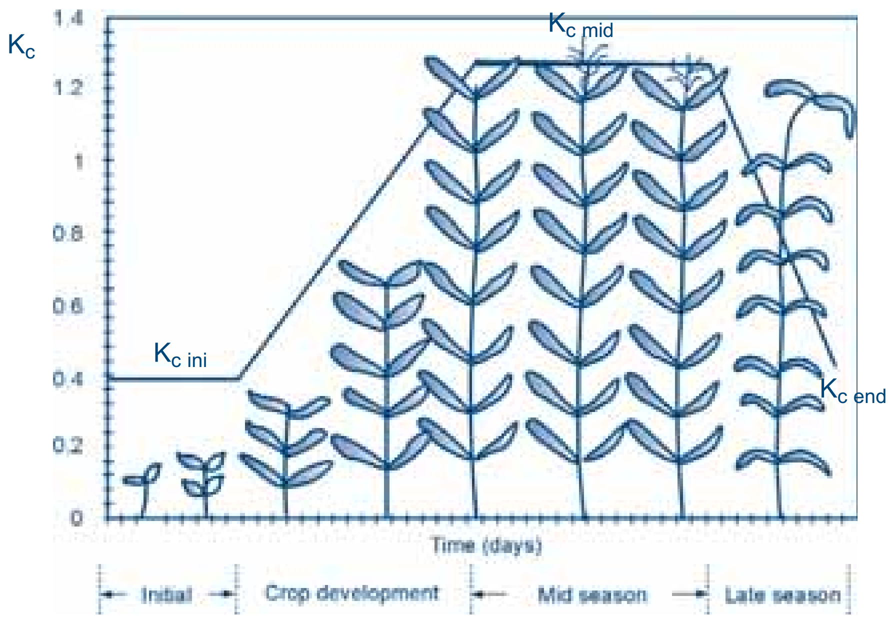
The late season stage runs from the start of maturity to harvest or full senescence. The calculation of K_c and ET_o is presumed to end when the crop is harvested, dries out naturally, reaches full senescence, or experiences leaf drop.

The K_c value at the end of the late season stage ($K_{c\ end}$) reflects crop and water management practices (Figure 18). The $K_{c\ end}$ value is high if the crop is frequently irrigated until harvested fresh. If the crop is allowed to senescence and to dry out in the field before harvest, the $K_{c\ end}$ value will be small.

4.3. Crop coefficient curves

Based on the determination of the length of crop growth stages and the corresponding crop coefficients, a crop coefficient curve can be constructed. The curve represents the changes in crop coefficient over the length of the growing season. The shape of the curve represents the changes in the vegetation and groundcover during plant development and maturation that affect the ratio of ET_c to ET_o. From the curve, the K_c factor and hence ET_c can be derived for any period within the growing season. The generalized crop coefficient curve for the single crop coefficient approach is shown in Figure 18.

Figure 18
Generalized crop coefficient curve for the single crop coefficient approach (Source: FAO, 1998a)



The calculation of ET_c consists of the following general steps:

- Identification of the crop growth stages, determination of their lengths and selection of the corresponding K_c values
- Adjustment of the selected K_c values for frequency of wetting or climatic conditions during each stage
- Construction of the crop coefficient curve (allowing one to determine K_c values for any period during the growing period)
- Calculation of ET_c as the product of ET_o and K_c

4.4. Length of growth stages

FAO (1998a) gives general lengths for the four distinct growth stages and total growing period for various types of climates and locations. This information has been supplemented from other sources and is given in Table 20. It is important to note that this information is only indicative and will need to be verified and supplemented with local information. Local information can be obtained from field observations, by interviewing farmers, local extension officers and local researchers.

Table 20

Length of crop development stages[1] for various planting periods and climatic regions (days) (Source: FAO, 1998a)

Crop	Initial (L_{ini})	Develop (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total days	Planting Date	Region
a. Small vegetables							
Broccoli	35	45	40	15	135	Sept	California Desert, USA
Cabbages	40	60	50	15	165	Sept	California Desert, USA
Carrots	20	30	50/30	20	100/120	Oct/Jan	Arid climate
	30	40	60	20	150	Feb/Mar	Mediterranean
	30	50	90	30	200	Oct	California Desert, USA
Cauliflowers	35	50	40	15	140	Sept	California Desert, USA
Celery	25	40	95	20	180	Oct	(Semi) Arid
	25	40	45	15	125	April	Mediterranean
	30	55	105	20	210	Jan	(Semi) Arid
Crucifers[2]	20	30	20	10	80	April	Mediterranean
	25	35	25	10	95	February	Mediterranean
	30	35	90	40	195	Oct/Nov	Mediterranean
Lettuce	20	30	15	10	75	April	Mediterranean
	30	40	25	10	105	Nov/Jan	Mediterranean
	25	35	30	10	100	Oct/Nov	Arid region
	35	50	45	10	140	Feb	Mediterranean
Onions (dry)	15	25	70	40	150	April	Mediterranean
	20	35	110	45	210	Oct; Jan	Arid region; California
Onions (green)	25	30	10	5	70	April/May	Mediterranean
	20	45	20	10	95	Oct	Arid region
	30	55	55	40	180	March	California, USA
Onions (seed)	20	45	165	45	275	Sept	California Desert, USA
Spinach	20	20	15/25	5	60/70	Apr; Sep/Oct	Mediterranean
	20	30	40	10	100	Nov	Arid region
Radish	5	10	15	5	35	Mar/Apr	Mediterranean; Europe
	10	10	15	5	40	Winter	Arid region
b. Vegetables – Solanum Family (*Solanaceae*)							
Eggplants	30	40	40	20	130	October	Arid region
	30	45	40	25	140	May/June	Mediterranean
Sweet peppers (bell)	25/30	35	40	20	120/125	April/June	Europe; Mediterranean
	30	40	110	30	210	October	Arid region
Tomatoes	30	40	40	25	135	January	Arid region
	35	40	50	30	155	April/May	California, USA
	25	40	60	30	155	Jan	California Desert, USA
	35	45	70	30	180	Oct/Nov	Arid region
	30	40	45	30	145	April/May	Mediterranean

c. Vegetables – Cucumber Family (*Cucurbitaceae*)							
Cantaloupes	30	45	35	10	120	Jan	California, USA
	10	60	25	25	120	Aug	California, USA
Cucumbers	20	30	40	15	105	June/Aug	Arid region
	25	35	50	20	130	Nov; Feb	Arid region
Pumpkin, Winter squash	20	30	30	20	100	Mar; Aug	Mediterranean
	25	35	35	25	120	June/Aug	Europe
Squash, Zucchini	25	35	25	15	100	April; Dec	Mediterranean & Arid
	20	30	25	15	90	May/June	Mediterranean; Europe
Sweet melons	25	35	40	20	120	May	Mediterranean
	30	30	50	30	140	March	California, USA
	15	40	65	15	135	Aug	California Desert, USA
	30	45	65	20	160	Dec/Jan	Arid region
Water melons	20	30	30	30	110	April	Italy
	10	20	20	30	80	Mar/Aug	Near East (desert)
d. Roots and tubers							
Beets, table	15	25	20	10.00	70	Apr/May	Mediterranean
	25	30	25	10	90	Feb/Mar	Mediterranean & Arid
Cassava: – year 1	20	40	90	60	210	Rainy season	Tropical regions
– year 2	150	40	110	60	360		
Potatoes	25	30	30/45	30	115/130	Jan/Nov	(Semi) Arid Climate
	25	30	45	30	130	May	Continental Climate
	30	35	50	30	145	April	Europe
	45	30	70	20	165	Apr/May	Idaho, USA
	30	35	50	25	140	Dec/Jan	California Desert, USA
Sweet Potatoes	20	30	60	40	150	April	Mediterranean
	15	30	50	30	125	Rainy season	Tropical regions
Sugar beet	30	45	90	15	180	March	California, USA
	25	30	90	10	155	June	California, USA
	25	65	100	65	255	Sept	California Desert, USA
	50	40	50	40	180	April	Idaho, USA
	25	35	50	50	160	May	Mediterranean
	45	75	80	30	230	Nov	Mediterranean
	35	60	70	40	205	Nov	Arid region
e. Legumes (*Leguminosae*)							
Beans (green)	20	30	30	10	90	Feb/Mar	California; Mediterranean
	15	25	25	10	75		
Beans (dry)	20	30	40	20	110	May/June	Continental Climate
	15	25	35	20	95	June	Pakistan; California
	25	25	30	20	100	June	Idaho, USA
Faba beans, Broad	15	25	35	15	90	May	Europe
beans	20	30	35	15	100	Mar/Apr	Mediterranean
– dry	90	45	40	60	235	Nov	Europe
– green	90	45	40	0	175	Nov	Europe
Green gram cowpeas	20	30	30	20	110	March	Mediterranean
Groundnuts	25	35	45	25	130	Dry	West Africa
	35	35	35	35	140	season	High Latitudes
	35	45	35	25	140	May/June	Mediterranean
Lentils	20	30	60	40	150	April	Europe
	25	35	70	40	170	Oct/Nov	Arid region
Peas	15	25	35	15	90	May	Europe
	20	30	35	15	100	Mar/Apr	Mediterranean
	35	25	30	20	110	April	Idaho, USA
Soya beans	15	15	40	15	85	Dec	Tropics
	20	30/35	60	25	135/140	May	Central USA
	20	25	75	30	150	June	Japan

f. Perennial vegetables (with winter dormancy and initially bare or mulched soil)							
Artichokes	40	40	250	30	360	Apr (1st year)	California
	20	25	250	30	325	May (2nd year)	(cut in May)
Asparagus	50	30	100	50	230	Feb	Warm winter
	90	30	200	45	365	Feb	Mediterranean
g. Fibre crops							
Cotton	30	50	60	55	195	Mar-May	Egypt; Pakistan; California
	45	90	45	45	225	Mar	California Desert, USA
	30	50	60	55	195	Sept	Yemen
	30	50	55	45	180	April	Texas
Flax	25	35	50	40	150	April	Europe
	30	40	100	50	220	Oct	Arizona
h. Oil crops							
Castor beans	25	40	65	50	180	March	(Semi) Arid climate
	20	40	50	25	135	Nov.	Indonesia
Safflower	20	35	45	25	125	April	California, USA
	25	35	55	30	145	Mar	High latitudes
	35	55	60	40	190	Oct/Nov	Arid region
Sesame	20	30	40	20	100	June	China
Sunflower	25	35	45	25	130	April/May	Mediterranean; California
i. Cereals							
Barley/oats/wheat	15	25	50	30	120	Nov	Central India
	20	25	60	30	135	March/Apr	35-45 °L
	15	30	65	40	150	July	East Africa
	40	30	40	20	130	Apr	
	40	60	60	40	200	Nov	
	20	50	60	30	160	Dec	California Desert, USA
Winter wheat	20[3]	60[3]	70	30	180	Dec	California, USA
	30	140	40	30	240	Nov	Mediterranean
	160	75	75	25	335	Oct	Idaho, USA
Grains (small)	20	30	60	40	150	Apr	Mediterranean
	25	35	65	40	165	Oct/Nov	Pakistan, Arid region
Maize (grain)	30	50	60	40	180	April	East Africa (alt.)
	25	40	45	30	140	Dec/Jan	Arid climate
	20	35	40	30	125	June	Nigeria (humid)
	20	35	40	30	125	October	India (dry, cool)
	30	40	50	30	150	April	Spain (spr,. sum.); California
	30	40	50	50	170	April	Idaho, USA
Maize (sweet)	20	20	30	10	80	March	Philippines
	20	25	25	10	80	May/June	Mediterranean
	20	30	50/30	10	110/90	Oct/Dec	Arid climate
	30	30	30	10[4]	110	April	Idaho, USA
	30	40	70	10	140	Jan	California Desert, USA
Millet	15	25	40	25	105	June	Pakistan
	20	30	55	35	140	April	Central USA
Sorghum	20	35	40	30	130	May/June	USA; Pakistan; Mediterran
	20	35	45	30	140	March/April	Arid region
Rice	30	30	60	30	150	Dec; May	Tropics; Mediterranean
	30	30	80	40	180	May	Tropics
j. Forages							
Alfalfa, total season[5]	10	30	varies	varies	varies		last -4°C in spring until first -4°C in fall
Alfalfa[5], 1st cutting cycle	10	20	20	10	60	Jan	California, USA
	10	30	25	10	75	Apr (last -4°C)	Idaho, USA
Alfalfa[5], other cutting cycles	5	10	10	5	30	March	California, USA
	5	20	10	10	45	Jun	Idaho, USA

Bermuda for seed	10	25	35	35	105	March	California Desert, USA
Bermuda for hay (several cuttings)	10	15	75	35	135	-	California Desert, USA
Grass pasture[5]	10	20	–	–	–		7 days before last -4°C in spring until 7 days after first -4°C in fall
Sudan, 1st cutting cycle	25	25	15	10	75	Apr	California Desert, USA
Sudan, other cutting cycles	3	15	12	7	37	Jun	California Desert, USA
k. Sugar cane							
Sugarcane, virgin	35 50 75	60 70 105	190 220 330	120 140 210	405 480 720		Low latitudes Tropics Hawaii, USA
Sugarcane, ratoon	25 30 35	70 50 105	135 180 210	50 60 70	280 320 420		Low latitudes Tropics Hawaii, USA
l. Tropical fruits and trees							
Bananas, 1st year Bananas, 2nd year	120 120	90 60	120 180	60 5	390 365	Mar Feb	Mediterranean Mediterranean
Pineapples	60	120	600	10	790		Hawaii, USA
m. Grapes and berries							
Grapes	20 20 20 30	40 50 50 60	120 75 90 40	60 60 20 80	240 205 180 210	April March May April	Low latitudes California, USA High latitudes Mid latitudes (wine)
Hops	25	40	80	10	155	April	Idaho, USA
n. Fruit trees							
Citrus	60	90	120	95	365	Jan	Mediterranean
Deciduous orchards	20 20 30	70 70 50	90 120 130	30 60 30	210 270 240	March March March	High latitudes Low latitudes California, USA
Olives	30	90	60	90	270[6]	April	Mediterranean
Pistachios	20	60	30	40	150	Feb	Mediterranean
Walnuts	20	10	130	30	190	April	Utah, USA
o. Wetlands – temperate climate							
Wetlands (Cattails, Bulrush)	10 180	30 60	80 90	20 35	140 365	May November	Utah, USA; killing frost Florida, USA
Wetlands (short vegetat.)	180	60	90	35	365	November	frost-free climate

1 *Lengths of crop development stages provided in this table are indicative of general conditions, but may vary substantially from region to region, with climate and cropping conditions, and with crop variety. The user is strongly encouraged to obtain appropriate local information.*

2 *Cruficers include cabbage, cauliflower, broccoli, and Brussel sprouts. The wide range in lengths of seasons is due to varietal and species differences.*

3 *These periods for winter wheat will lengthen in frozen climates according to days having zero growth potential and wheat dormancy. Under general conditions and in the absence of local data, fall planting of winter wheat can be presumed to occur in northern temperate climates when the 10-day running average of mean daily air temperature decreases to 17°C or December 1, whichever comes first. Planting of spring wheat can be presumed to occur when the 10-day running average of mean daily air temperature increases to 5°C. Spring planting of maize grain can be presumed to occur when the 10-day running average of mean daily air temperature increases to 13°C.*

4 *The late season for sweet maize will be about 35 days, if the grain is allowed to mature and dry.*

5 *In climates having killing frosts, growing seasons can be estimated for alfalfa and grass as:* alfalfa*: last -4°C in spring until first -4°C in fall;* grass*: 7 days before last -4°C in spring and 7 days after -4°C in fall.*

6 *Olive trees gain new leaves in March. See footnote 24 of Table 21 for additional information, where the K_c continues outside the 'growing period'.*

4.5. Crop coefficients

The trends in K_c values during the growing period are represented in the crop coefficient curve. Only three values of K_c are required to describe and construct the crop coefficient curve: those during the initial stage ($K_{c\ ini}$), the mid-season stage ($K_{c\ mid}$) and at the end of the late season stage ($K_{c\ end}$).

Table 21 lists typical values for $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ for various agricultural crops. The coefficients are organized by group type similar to the way it was done for the length of growth stages in Table 20. There is close similarity in coefficients among crops of the same crop group, since the plant height, leaf area, ground coverage and water management are normally similar.

Table 21

Single (time-averaged) crop coefficients and mean maximum plant heights for non-stressed, well-managed crops in sub humid climates ($RH_{min} \approx 45\%$, $u_2 \approx 2$ m/sec) for use with the FAO Penman-Monteith ET_o (Source: FAO, 1998a)

Crop		$K_{c\ ini}$ [1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (h) (m)
a. Small vegetables		**0.7**	**1.05**	**0.95**	
Broccoli			1.05	0.95	0.3
Brussels sprouts			1.05	0.95	0.4
Cabbages			1.05	0.95	0.4
Carrots			1.05	0.95	0.3
Cauliflowers			1.05	0.95	0.4
Celery			1.05	1.00	0.6
Garlic			1.00	0.70	0.3
Lettuce			1.00	0.95	0.3
Onions	– dry		1.05	0.75	0.4
	– green		1.00	1.00	0.3
	– seed		1.05	0.80	0.5
Spinach			1.00	0.95	0.3
Radishes			0.90	0.85	0.3
b. Vegetables - Solanum Family (*Solanaceae*)		**0.6**	**1.15**	**0.80**	
Eggplants			1.05	0.90	0.8
Sweet Peppers (bell)			1.05[2]	0.90	0.7
Tomatoes			1.15[2]	0.70-0.90	0.6
c. Vegetables - Cucumber Family (*Cucurbitaceae*)		**0.5**	**1.00**	**0.80**	
Cantaloupes		0.5	0.85	0.60	0.3
Cucumbers	– Fresh Market	0.6	1.00	0.75	0.3
	– Machine harvest	0.5	1.00[2]	0.90	0.3
Pumpkin, Winter Squash			1.00	0.80	0.4
Squash, Zucchini			0.95	0.75	0.3
Sweet Melons			1.05	0.75	0.4
Watermelon		0.4	1.00	0.75	0.4
d. Roots and tubers		**0.5**	**1.10**	**0.95**	
Beets, table			1.05	0.95	0.4
Cassava	– year 1	0.3	0.80[3]	0.30	1
	– year 2	0.3	1.10	0.50	1.5
Parsnips		0.5	1.05	0.95	0.4
Potatoes			1.15	0.75[4]	0.6
Sweet Potatoes			1.15	0.65	0.4
Turnips (and Rutabaga)			1.10	0.95	0.6
Sugar beet		0.35	1.20	0.70[5]	0.5
e. Legumes (*Leguminosae*)		**0.4**	**1.15**	**0.55**	
Beans, green		0.5	1.05[2]	0.90	0.4
Beans, dry, and Pulses		0.4	1.15[2]	0.35	0.4
Chick peas			1.00	0.35	0.4
Faba beans (broad beans)	– fresh	0.5	1.15[2]	1.10	0.8
	– dry/seed	0.5	1.15[2]	0.30	0.8
Garbanzo		0.4	1.15	0.35	0.8

Crop		$K_{c\ ini}$ [1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (h) (m)
Green gram and cowpeas			1.05	0.60- 0.35[6]	0.4
Groundnuts (peanuts)			1.15	0.60	0.4
Lentil			1.10	0.30	0.5
Peas	– fresh	0.5	1.15[2]	1.10	0.5
	– dry/seed		1.15	0.30	0.5
Soya beans			1.15	0.50	0.5-1
f. Perennial vegetables (with winter dormancy and initially bare or mulched soil)			**0.5**	**1.00**	**0.80**
Artichokes		0.5	1.00	0.95	0.07
Asparagus		0.5	0.95[7]	0.30	0.2-0.8
Mint		0.60	1.15	1.10	0.6-0.8
Strawberries		0.40	0.85	0.75	0.2
g. Fibre crops		**0.35**			
Cotton			1.15-01.20	0.70- 0.50	1.2-1.5
Flax			1.10	0.25	1.2
Sisal[8]			0.4- 0.7	0.4- 0.7	1.5
h. Oil crops		**0.35**	**1.15**	**0.35**	
Castor beans (ricinus)			1.15	0.55	0.3
Rapeseed, Canola			1.0-1.15[9]	0.35	0.6
Safflower			1.0-1.15[9]	0.25	0.8
Sesame			1.10	0.35	1
Sunflower			1.0-1.15[9]	0.40	2
i. Cereals		**0.3**	**1.15**	**0.4**	
Barley			1.15	0.25	1
Oats			1.15	0.25	1
Spring wheat			1.15	0.25- 0.4[10]	1
Winter wheat	– with frozen soils	0.4	1.15	0.25- 0.4[10]	1
	– with non-frozen soils	0.7	1.15	0.25- 0.4[10]	
Maize	– field grain (field corn)		1.20	0.60; 0.35[11]	2
Maize	– sweet (sweet corn)		1.15	1.05[12]	1.5
Millet			1.00	0.30	1.5
Sorghum	– grain		1.00- 1.10	0.55	1-2
	– sweet		1.20	1.05	2-4
Rice		1.05	1.20	0.90- 0.60	1
j. Forages					
Alfalfa hay	– average cutting effects	0.40	0.95[13]	0.90	0.7
	– individual cutting period	0.4[14]	1.20[14]	1.15[14]	0.7
	– for seed	0.40	0.50	0.50	0.7
Bermuda for hay	– average cutting effects	0.55	1.00	0.85	0.35
	– spring crop for seed	0.35	0.90	0.65	0.4
Clover hay, Berseem	– average cutting effects	0.40	0.90[13]	0.85	0.6
	– individual cutting period	0.40[14]	1.15[14]	1.10[14]	0.6
Rye grass hay	– average cutting effects	0.95	1.05	1.00	.3
Sudan grass hay (annual)	– average cutting effects	0.50	0.90[14]	0.85	1.2
	– individual cutting period	0.50[14]	1.15[14]	1.10[14]	1.2
Grazing pasture	– rotated grazing	0.40	0.85-1.05	0.85	0.15-0.30
	– extensive grazing	0.30	0.75	0.75	0.10
Turf grass	– cool season[15]	0.90	0.95	0.95	0.10
	– warm season[15]	0.80	0.85	0.85	0.10
k. Sugar cane		**0.40**	**1.25**	**0.75**	**3**
l. Tropical fruits and trees					
Bananas	– 1st year	0.50	1.10	1.00	3
	– 2nd year	1.00	1.20	1.10	4
Cacao		1.00	1.05	1.05	3
Coffee	– bare ground cover	0.90	0.95	0.95	2-3
	– with weeds	1.05	1.10	1.10	2-3

Crop		$K_{c\ ini}$ [1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (h) (m)
Date palms		0.90	0.95	0.95	8
Palm trees		0.95	1.00	1.00	8
Pineapples[16]	– bare soil	0.50	0.30	0.30	0.6-1.2
	– with grass cover	0.50	0.50	0.50	0.6-1.2
Rubber trees		0.95	1.00	1.00	10
Tea	– non-shaded	0.95	1.00	1.00	1.5
	– shaded[17]	1.10	1.15	1.15	2
m. Grapes and berries					
Berries (bushes)		0.30	1.05	0.50	1.5
Grapes	– table or raisin	0.30	0.85	0.45	2
	– wine	0.30	0.70	0.45	1.5-2
Hops		0.3	1.05	0.85	5
n. Fruit trees					
Almonds, no ground cover		0.40	0.90	0.65[18]	5
Apples, cherries, pears[19]					
	– no ground cover, killing frost	0.45	0.95	0.70[18]	4
	– no ground cover, no frosts	0.60	0.95	0.75[18]	4
	– active ground cover, killing frost	0.50	1.20	0.95[18]	4
	– active ground cover, no frosts	0.80	1.20	0.85[18]	4
Apricots, peaches, stone fruit[19,20]					
	– no ground cover, killing frost	0.45	0.90	0.65[18]	3
	– no ground cover, no frosts	0.55	0.90	0.65[18]	3
	– active ground cover, killing frost	0.50	1.15	0.90[18]	3
	– active ground cover, no frosts	0.80	1.15	0.85[18]	3
Avocado, no ground cover		0.60	0.85	0.75	3
Citrus, no ground cover[21]					
	– 70% canopy	0.70	0.65	0.70	4
	– 50% canopy	0.65	0.60	0.65	3
	– 20% canopy	0.50	0.45	0.55	2
Citrus, with active ground cover or weeds[22]					
	– 70% canopy	0.75	0.70	0.75	4
	– 50% canopy	0.80	0.80	0.80	3
	– 20% canopy	0.85	0.85	0.85	2
Conifer trees[23]		1.00	1.00	1.00	10
Kiwi		0.40	1.05	1.05	3
Olives (40 to 60% ground coverage by canopy)[24]		0.65	0.70	0.70	3 5
Pistachios, no ground cover		0.40	1.10	0.45	3 5
Walnut orchard[19]		0.50	1.10	0.65[18]	4 5
o. Wetlands – temperate climate					
Cattails, Bulrushes, killing frost		0.30	1.20	0.30	2
Cattails, Bulrushes, no frost		0.60	1.20	0.60	2
	– short vegetation, no frost	1.05	1.10	1.10	0.30
	– reed swamp, standing water	1.00	1.20	1.00	1-3
	– reed swamp, moist soil	0.90	1.20	0.70	1-3
p. Special					
Open water, < 2 m depth, or in sub-humid climates or tropics			1.05	1.05	
Open Water, > 5 m depth, clear of turbidity, temperate climate			0.65[25]	1.25[25]	

1 *These are general values for $K_{c\ ini}$ under typical irrigation management and soil wetting. For frequent wettings such as with high frequency sprinkler irrigation or daily rainfall, these values may increase substantially and may approach 1.0 to 1.2. $K_{c\ ini}$. Is a function of wetting interval and potential evaporation rate during the initial and development periods and is more accurately estimated using Figures 11 and 12.*

2 *Beans, peas, legumes, tomatoes, peppers and cucumbers are sometimes grown on stalks reaching 1.5-2 m in height. In such cases increased K_c values need to be taken. For green beans, peppers and cucumbers 1.15 can be taken and for tomatoes, dry beans and peas 1.20. Under these conditions h should be increased also.*

3 *The mid season values for cassava assume non-stressed conditions during or following the rainy season. The $K_{c\ end}$ values account for dormancy during the dry season.*

4 The $K_{c\ end}$ value for potatoes is about 0.4 for long season potatoes with vine kill.

5 This $K_{c\ end}$ value is for no irrigation during the last month of the growing season. The $K_{c\ end}$ value for sugar beets is higher up to 1.0, when irrigation or significant rain occurs during the last month.

6 The first $K_{c\ end}$ is for harvested fresh. The second value is for harvested dry.

7 The K_c for asparagus usually remains at $K_{c\ ini}$ during harvest of the spears, due to sparse groundcover. The $K_{c\ mid}$ value is for following re-growth of plant vegetation following termination of harvest of spears.

8 K_c for sisal depends on the planting density and water management (for example intentional moisture stress).

9 The lower values are for rainfed crops having less dense plant populations.

10 The higher value is for hard harvested crops.

11 The first $K_{c\ end}$ value for harvest at high grain moisture. The second $K_{c\ end}$ value is for harvest after complete field drying of the grain (to about 18% moisture, wet basis).

12 If harvested fresh for human consumption. Use $K_{c\ end}$ for field maize if the sweet maize is allowed to mature and dry in the field.

13 This $K_{c\ mid}$ coefficient for hay crops is an overall average $K_{c\ mid}$ coefficient that averages K_c for both before and following cuttings. It is applied to the period following the first development period until the beginning of the last late season period of the growing season.

14 These K_c coefficients for hay crops represent immediately following cutting, at full cover, and immediately before cutting, respectively. The growing season is described as a series of individual cutting periods.

15 Cool season grass varieties include dense stands of bluegrass, ryegrass and fescue. Warm season varieties include Bermuda grass and St. Augustine grass. The 0.95 values for cool season grass represent a 0.06-0.08 m mowing height under general turf conditions. Where careful water management is practiced and rapid growth is not required K_c's for turf can be reduced by 0.10.

16 The pineapple plant has very low transpiration because it closes its stomata during the day and opens them during the night. Therefore, the majority of ET_c from pineapple is evaporation the soil. The $K_{c\ mid} < K_{c\ ini}$ since $K_{c\ mid}$ occurs during full groundcover so that soil evaporation is less. Values given assume that 50% of the ground surface is covered by black plastic mulch and that irrigation is by sprinkler. For drip irrigation beneath the plastic mulch, K_c's given can be reduced by 0.10.

17 Includes the water requirements of the shade trees.

18 These $K_{c\ late}$ values represent K_c prior to leaf drop. After leaf drop, $K_{c\ end} \approx 0.20$ for bare dry soil or dead groundcover and $K_{c\ end} \approx 0.50$ to 0.80 for actively growing groundcover.

19 Refer to equations in FAO (1998a) and footnotes 21 and 22 for estimating K_c for immature stands.

20 Stone fruit category refers to peaches, apricots, pears, plums and pecans.

21 These Kc values can be calculated using the equations in FAO (1998a) for $K_{c\ min} = 0.15$ and $K_{c\ full} = 0.75$, 0.70 and 0.75 for the initial, mid season and end of season periods, and $f_{c\ eff} = f_c$ where f_c = fraction of groundcover covered by tree canopy (for example, the sun is presumed to be directly overhead). The values listed correspond with those in FAO (1992) and with more recent measurements. The mid-season value is lower than the initial and ending values due to the effects to stomatal closure during periods of peak ET. For humid and sub-humid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ can be increased by 0.1 - 0.2.

22 These K_c values can be calculated as $K_c = f_c K_{c\ ngc} + (1 - f_c) K_{c\ cover}$ where $K_{c\ ngc}$ is the K_c of citrus with no active groundcover (calculated as in footnote 21). $K_{c\ cover}$ is the K_c for the active groundcover (0.95), and f_C is defined as in footnote 21. The values listed correspond with those in FAO (1992) and with more recent measurements. Alternatively K_c for citrus can be calculated using the equations and procedures given in FAO (1998a). For humid and sub humid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ can be increased by 0.1-0.2.

For non-active or only moderately active groundcover (active indicates green and growing groundcover with Leaf Area Index (LAI) > 2- 3), K_c should be weighted between K_c for no groundcover and K_c for active groundcover, with the weighting based on 'greenness' and approximate leaf area of the groundcover.

23 Confers exhibit substantial stomatal control due to reduced aerodynamic resistance. The K_c can easily reduce below the values presented, which present well-watered conditions for large forests.

24 These coefficients represent 40 to 60% groundcover. Refer to FAO (1998a) and footnotes 21 and 22 for estimating K_c for immature stands. In Spain the following K_c 's have been found for olive orchards with 60% groundcover: 0.50, 0.50, 0.65, 0.60, 055. 050, 045, 0.45, 0.55, 0.60, 065, 0.50 for months of January to December. These coefficients can be invoked by using $K_{c\ ini} = 0.65$, $K_{c\ mid} = 0.45$ and $K_{c\ end} = 0.65$ with stage lengths = 30, 90, 60, and 90days respectively for initial, development, mid-season and late season periods, and using K_c during the winter ('off season') in December to February = 0.50.

25 The K_cs are for deep water in temperate latitudes where large temperature changes in the water body occur during the year, and initial and peak period evaporation is low as radiation energy is absorbed into the deep-water body. During fall and winter periods ($K_{c\ end}$), heat is released from the water body that increases the evaporation above that for grass. Therefore $K_{c\ mid}$ corresponds to the period when the water body is gaining thermal energy and K_c end when releasing thermal energy. These K_cs should be used with caution.

4.5.1. Determination of $K_{c\ ini}$

The coefficients in Table 21 combine the effects of both transpiration and evaporation over time. The effects of the integration over time represent an average wetting frequency for a standard crop under typical growing conditions in an irrigated setting. The values of K_c in the initial and development stages are subject to effects of large variations in wetting frequencies and therefore refinements to $K_{c\ ini}$ should always be made. The $K_{c\ ini}$ values given in Table 21 are only approximations and should only be used for estimating ET_c during preliminary or planning stages. More accurate estimates of $K_{c\ ini}$ can be obtained by considering the time interval between wetting events, the evaporation power of the atmosphere (ET_o) and the magnitude of the wetting event. Figures 19 and 20 can be used to provide estimates of $K_{c\ ini}$ as a function of the average interval between wetting events, the evaporative power and the magnitude of wetting event.

Figure 19

Average $K_{c\ ini}$ as related to the level of ET_o and the interval between irrigations and/or significant rain during the initial growth stage when wetting events are light to medium (3–10 mm per event) for all soil types (Source: FAO, 1998a)

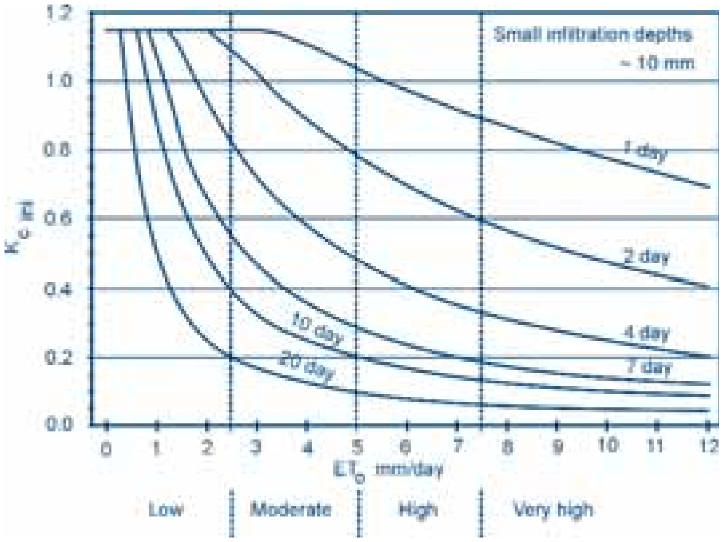
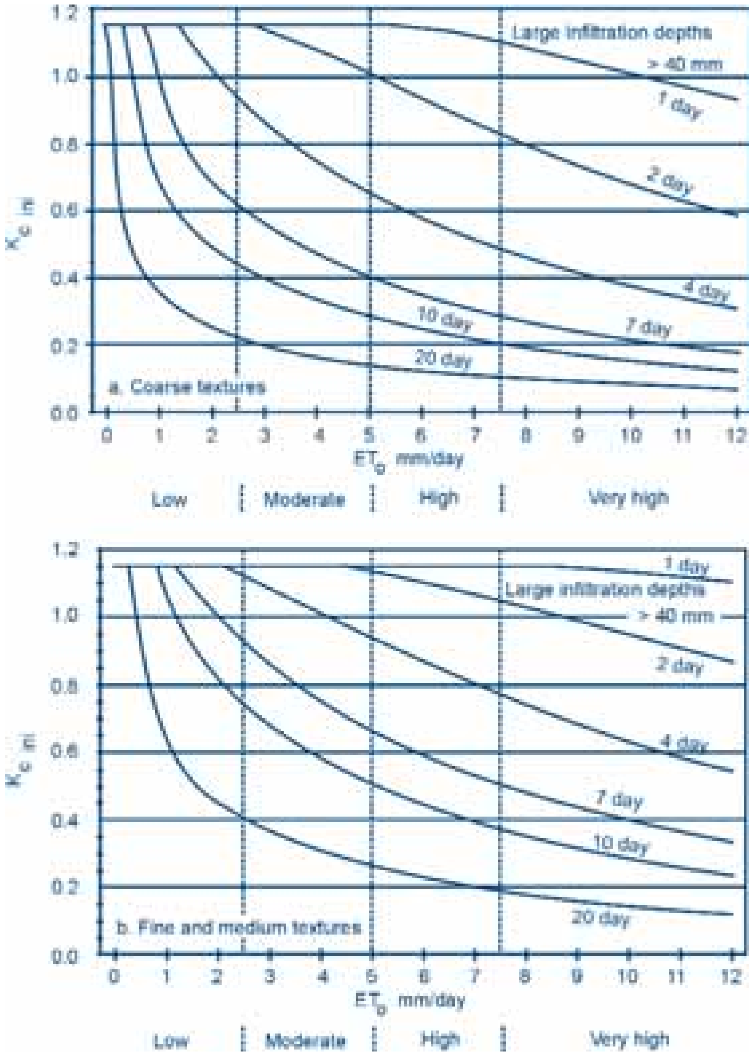


Figure 20

Average $K_{c\ ini}$ as related to the level of ET_o and the interval between irrigations greater than or equal to 40 mm per wetting event, during the initial growth stage for a) coarse textured soils; b) medium and fine textured soils (Source: FAO, 1998a)



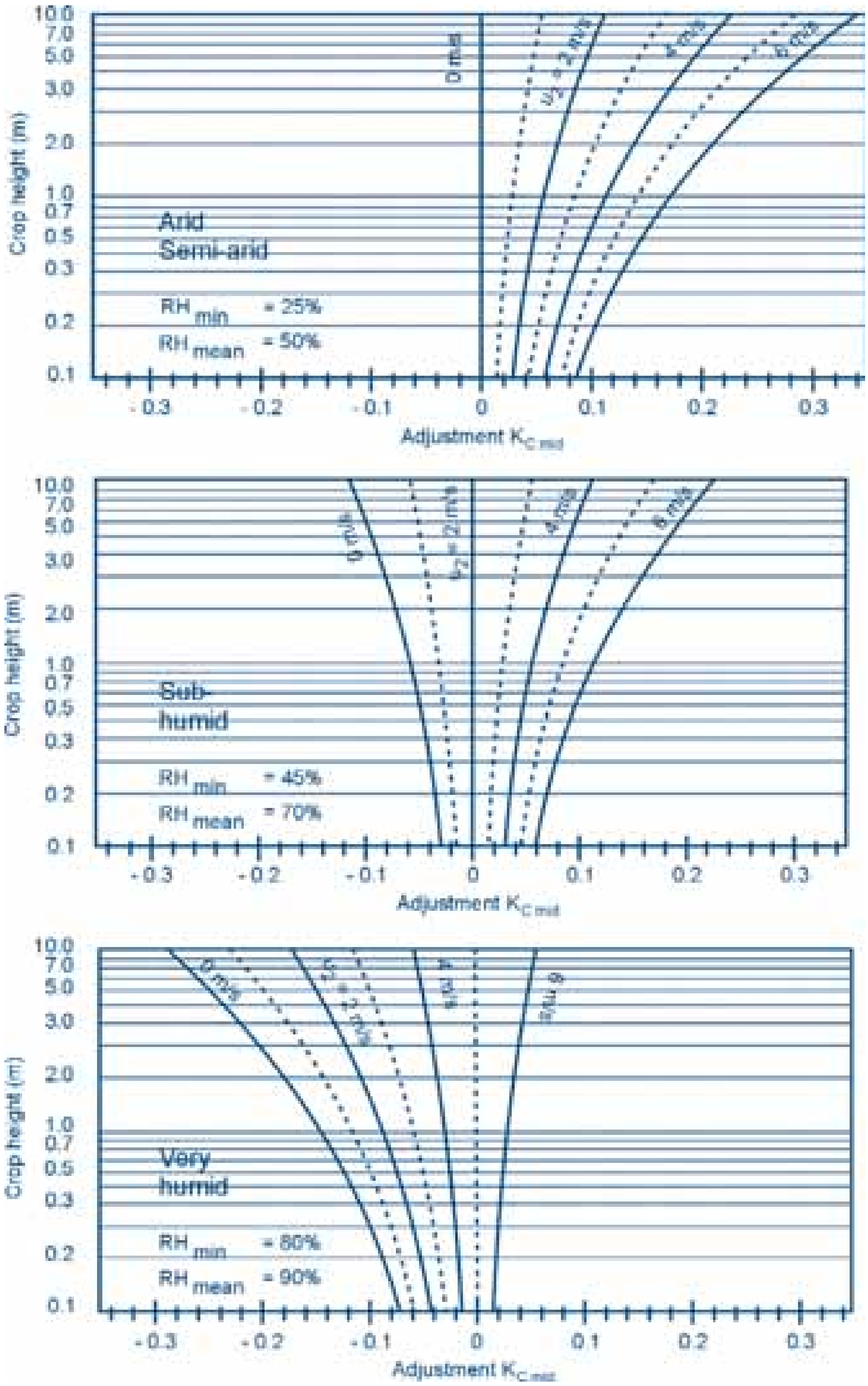
4.5.2. Determination of $K_{c\ mid}$ and $K_{c\ end}$

The values of $K_{c\ mid}$ and $K_{c\ end}$ in Table 21 represent those for sub-humid climates with an average day time minimum relative humidity (RH_{min}) of about 45% and with calm to moderate wind speeds averaging 2 m/sec. For different climatic conditions it will be necessary to modify the values.

Figure 21 is used to estimate the adjustments to be added on the $K_{c\ mid}$ values given in Table 21 for various climates, mean daily wind speeds and various crop heights.

Figure 21

Adjustment (additive) to the $K_{c\ mid}$ values from Table 21 for different crop heights and mean daily wind speeds (u_2) for different humidity conditions (Source: FAO, 1998a)



As far as $K_{c\ end}$ is concerned, more arid climates and conditions of greater wind speed will have higher values for $K_{c\ end}$, while more humid climates and conditions of lower wind speed will have lower values for $K_{c\ end}$. In these cases, where RH and u_2 differ from 45% and 2 m/sec respectively, the following equation can be used:

Equation 19

$$K_{c\ end} = K_{c\ end\ (Table)} + [0.04\ (u_2 - 2) - 0.004(RH_{min} - 45)] \times \left[\frac{h}{3}\right]^{0.3}$$

Where:

$K_{c\ end\ (Table)}$	=	Value for $K_{c\ end}$ taken from Table 21
u_2	=	Mean value for daily wind speed at 2 m height over grass during late season growth stage (m/sec) for 1 m/sec ≤ u_2 ≤ 6 m/sec
RH_{min}	=	Mean value for daily minimum relative humidity during the late season stage (%) for 20% ≤ RH_{min} ≤ 80%
h	=	Mean plant height during the late season stage (m) for 0.1 m ≤ h ≤ 10 m

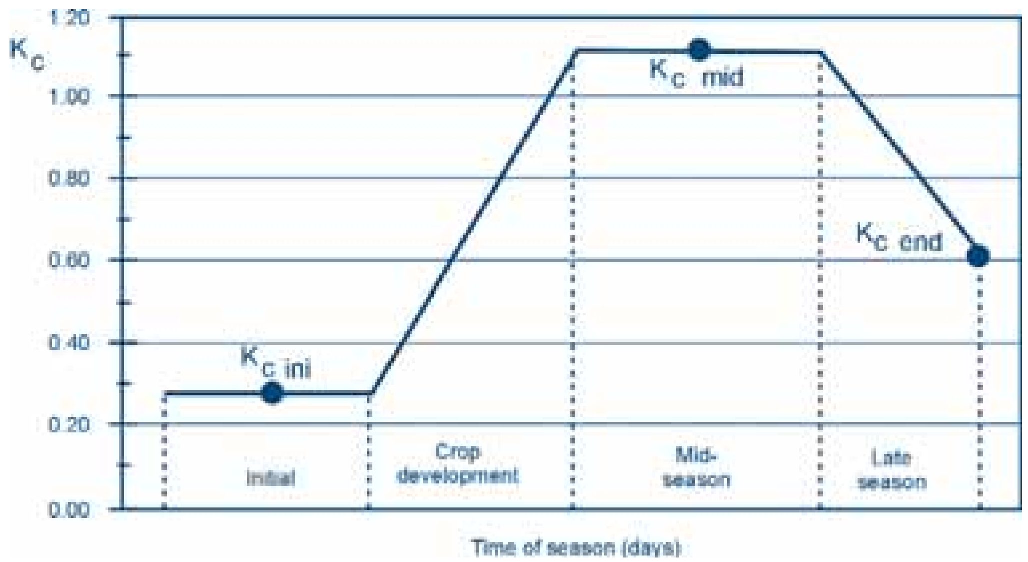
Equation 19 only needs to be applied when the tabulated values for $K_{c\ end}$ exceed 0.45. No adjustment is made when $K_{c\ end\ (Table)}$ is less than 0.45. In that case $K_{c\ end} = K_{c\ end\ (Table)}$.

4.6. Constructing the K_c curve

This section will limit itself to the construction of K_c curves for annual crops, since these are the most common crops grown by smallholder farmers under irrigation. After the determination of the $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ values from Table 21 and adjusting the values as necessary, the next stage is the construction of the K_c curve. Only three point values for K_c are required to describe and construct the curve. A typical K_c curve is shown in Figure 22. Such a curve can be constructed using the following steps:

- Divide the growing period into four general growth stages that describe the crop development (initial, crop development, mid-season, and late season stage). Determine the lengths of growth stages with the aid of Table 20 or preferably use local experience, and identify the three K_c values that correspond to $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ from Table 21.
- Adjust the K_c values to the frequency of wetting and/or climatic conditions of the growth as outlined in the previous section.
- Construct a curve by connecting straight line segments through each of the four growth stages. Horizontal lines are drawn trough $K_{c\ ini}$ in the initial stage and through $K_{c\ mid}$ in the mid-season stage. Diagonal lines are drawn from $K_{c\ ini}$ to $K_{c\ mid}$ within the course of the crop development stage and from $K_{c\ mid}$ to $K_{c\ end}$ within the course of the late season stage.

Figure 22
A typical crop coefficient (K_c) curve (Source: FAO, 1998a)



4.7. Calculating ET_c

After construction of the K_c curve, the next step is the calculation of crop evapotranspiration. From the crop coefficient curve, the K_c value for any period during the growing period can be determined. Once the K_c values have been derived, the crop evapotranspiration (ET_c) can be calculated by multiplying the K_c values by the corresponding ET_o values.

Weekly, ten-day or monthly values for K_c are necessary when ET_c calculations are made on a weekly, ten-day or monthly time basis respectively. A general procedure is to construct the K_c curve, overlay the curve with the length of the weeks, decades or months and to derive graphically from the curve the K_c value for the period under consideration. Assuming that all decades have a duration of 10 days facilitates the derivation of K_c and introduces little error into the calculation of ET_c.

Example 2

A project site is located close to Kutsaga Research Station, the meteorological data of which served as a basis for the calculation of the reference crop evapotranspiration (ET_o) in the previous Chapter. The values of ET_o, using the Penman-Monteith Equation and using CROPWAT, were given in Table 17. Below, the results using the Penman-Monteith Equation, which will be used in this example, are given in mm/day.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_o	4.3	4.1	4.2	3.9	3.3	2.9	3.2	4.2	5.5	6.2	4.9	4.3

Estimate the crop evapotranspiration for a maize crop planted on 15 October on the project site. The soils are heavy textured.

The first step is to establish the length of the growth stages:

Based on local experience, the duration of the initial stage is expected to be 20 days for a maize crop planted on 15 October, because of the favourable weather conditions. The development stage, also from local experience, will be 45 days and the mid-season stage will be 50 days. The late season stage is expected to last 39 days. Therefore the crop will finish around the 15th of March. Since local information is available there is no need to use information given in Table 20.

The second step is to estimate the values of K_c:

Again, loc*al experience is used in order to decide the irrigation frequency during the initial stage. Assuming that during the initial stage irrigation is exercised on a 7 day frequency, for the ET_o of October (6.2 mm/day) a $K_{c\ ini}$ value of 0.59 is obtained from Figure 20 for a fine and medium textured soil.*

The initial estimates for the $K_{c\ mid}$ and $K_{c\ end}$ values are read from Table 21: $K_{c\ mid}$ = 1.20 and $K_{c\ end}$ = 0.35. From the meteorological data for the station, during the mid-season (January) conditions will be sub-humid with RH_{mean} = 76% (Table 2) and u_2 = 2.2 m/sec (Table 16). Using the middle graph of Figure 21, it can be seen that the adjustment factor to be added to the $K_{c\ mid}$ value is zero. Hence no adjustment is needed. As $K_{c\ end}$ = 0.35, which is less than 0.45, no adjustment is required on the value of $K_{c\ end}$.

The K_c curve for maize can now be drawn, for initial planning purposes, as shown in Figure 23 where $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ are 0.59, 1.2 and 0.35 respectively, and the four lengths of growth stages are 20, 45, 50 and 39 days.

Using the ET_o figures and the K_c values derived from Figure 23, the crop evapotranspiration ET_c for maize can be calculated. For a decade within one month, the daily ET_o within the month is multiplied with the corresponding K_c to derive the ET_c. For example, for the first full decade in October ET_c = 6.2 x 0.59 = 3.7 mm/day. For a decade that falls in two months, the weighted average of daily ET_o from each month is multiplied by the corresponding K_c. For example, the ET_c of decade 2 (end of October and early November) is calculated as follows:

ET_o in October = 6.2 mm/day and ET_o in November = 4.9 mm/day. The planting date being 15 October means that decade 2 has 5 days in October and 5 days in November. The weighted ET_o would be: (5/10) x 6.2+ (5/10) x 4.9 = 5.6 mm/day. This proportional ET_o would then be multiplied by the corresponding K_c. Table 22 shows the results for the evapotranspiration of the maize crop, which, as we will see in the next Chapter, is equal to the crop water requirements.

Figure 23
Crop coefficient curve drawn for maize grown close to Kutsaga Research Station

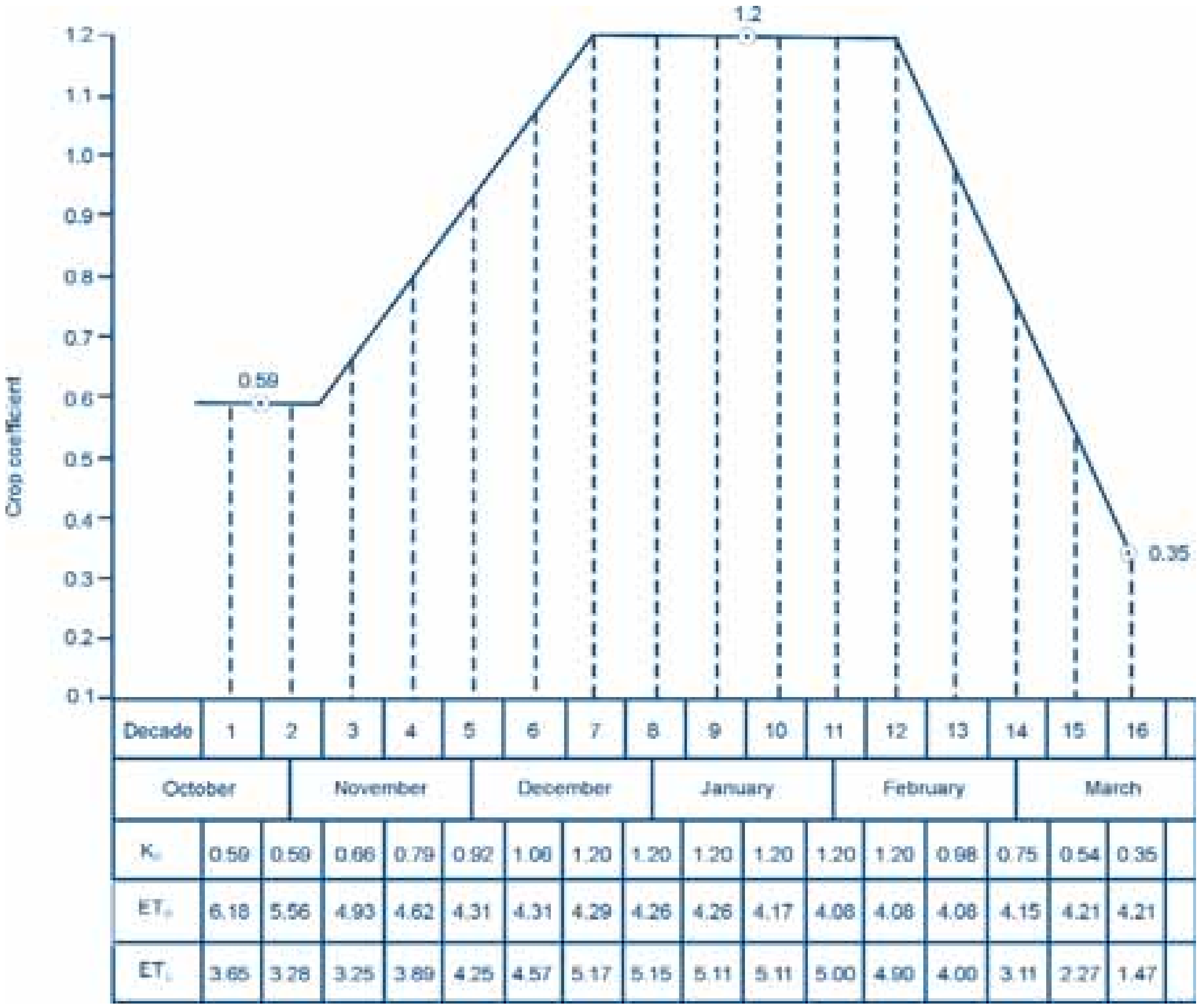


Table 22
Evapotranspiration of a maize crop on a decade by decade basis

Decade	Month	ET_o -Penman-Monteith (mm/day)	Crop coefficient K_c	ET_c - maize (mm/day)
1	Oct	6.2	0.59	3.7
2	Oct/Nov	5.6	0.59	3.3
3	Nov	4.9	0.66	3.2
4	Nov	4.9	0.79	3.9
5	Nov/Dec	4.6	0.92	4.2
6	Dec	4.3	1.06	4.6
7	Dec	4.3	1.20	5.2
8	Dec/Jan	4.3	1.20	5.2
9	Jan	4.3	1.20	5.2
10	Jan	4.3	1.20	5.2
11	Jan/Feb	4.2	1.20	5.0
12	Feb	4.1	1.20	4.9
13	Feb	4.1	0.98	4.0
14	Feb/Mar	4.2	0.75	3.2
15	Mar	4.2	0.54	2.3
16	Mar	4.2	0.35	1.5

Example 3

With the aid of the reference crop evapotranspiration map for Zimbabwe for the peak ET_o month of October, shown in Figure 11, estimate the peak crop water requirements for a maize crop grown at Goto irrigation scheme, which is located at 18°47' South latitude and 31°50' East longitude.

The project area can be located on the map, since the coordinates of the irrigation scheme are given. Plotting it on the maps in Figure 11 and 12, it is found to fall near Wedza town (Figure 12), between the 5.4 mm/day and 5.6 mm/day iso-ET_o lines. Using interpolation between the two lines, the mean monthly ET_o is read to be 5.5 mm/day.

This ET_o is the peak ET_o, which falls in the month of October, and can now be utilized in the estimation of crop water requirements. (ET_c), using Equation 1:

$ET_c = ET_o \times K_c$

In the absence of local data, Table 21 is used for estimating K_c. Assuming that the peak crop water requirements for maize occur during the mid-season growth stage, then K_c = 1.2.

Hence, the peak crop water requirement for maize is:

$ET_c = 5.5 \times 1.2 = 6.6$ mm/day

4.8. Factors affecting ET_c

The main factors affecting ET_c are climatic and soil water related factors, irrigation methods and cultural practices.

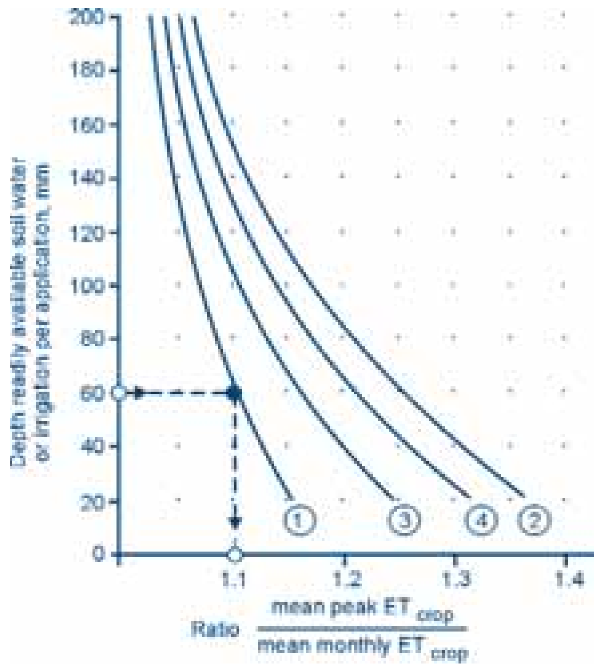
4.8.1. Climatic factors

In calculating the ET_o, average climatic data were used. Since the weather varies from year to year, ET_c will vary from year to year and also from period to period. Monthly ET_c values can vary from one year to the next by 50% or more. For the planning and designing of irrigation projects, the variations with time become very important. When sufficient climatic data are available (≥ 10 years), ET_c could be calculated for each year and a probability analysis could be done. The value of ET_c then selected for design is commonly based on a probability of 75-80%, which could be similar to the probability in water availability.

In most cases, sufficient data are not available to allow a probability analysis to be carried out. Figure 24 (FAO, 1984) can be used to make a first estimate of meeting peak demand in 3 out of 4 years when mean climatic data are used. This calculation is normally done for months of peak demand.

Figure 24

Ratio between peak and mean ET_c for different climates during month of peak water use (Source: FAO, 1984)



1: Arid and semi-arid climates and those with predominantly clear weather conditions during month of peak ET_c.

2: Mid-continental climates and sub-humid to humid climates with highly variable cloudiness in month of peak ET_c.

3 and 4: Mid-continental climates with variable cloudiness and mean ET_c of 5 and 10 mm/day respectively.

Example 4

For the maize crop in Example 2, calculate the ET_c during the month of peak demand so that the peak demand of the crop is met 3 out of 4 years. Assume a heavy textured clay soil with 160 mm/m available moisture, a root zone depth of 0.75 m for maize and a 50% allowable depletion level.

Figure 24 provides for four weather conditions during the period of peak demand. In our case, with the semi-arid climate conditions at Kutsaga Research Station during peak demand, option 1 will apply.

Available moisture = 160 x 0.5 x 0.75 = 60 mm

With this depth of readily available moisture, according to Figure 24 the correction factor is 1.1

The peak ET_c for maize of 5.2 mm/day occurs in the month of December (Table 22) and the corrected peak ET_c = 5.2 x 1.1 = 5.7 mm/day.

Usually, there is some distance between the project area and the meteorological station used in estimating ET_c, and this can have some influence on the project crop water requirements. Therefore, it is important to choose the most representative station, in terms of distance, elevation and micro-relief.

Changes in microclimatic environment because of the project should also be considered. Climatic data are collected before irrigation development has taken place and normally the meteorological stations, from which data are taken, are located where there is no irrigation development (for example airports). Irrigation fields will produce a different microclimate and ET_c may not be equal to the predicted values, based on meteorological data. This is more pronounced for large projects in arid windy climates.

4.8.2. Soil water factors

According to FAO (1992), if plants are sufficiently anchored and there are proper growing conditions (available water and nutrients, soil aeration, etc.), the ET_c is not affected, even when rooting depth is severely restricted. However, the following conditions must be considered:

Available soil water: The effect of soil water content on evapotranspiration varies with crop and is conditioned primarily by the type of soils and water-holding characteristics, crop rooting characteristics and the meteorological factors determining the level of transpiration. When evaporative conditions are lower, the crop may transpire at the predicted evapotranspiration rate even though available soil water depletion is greater. ET_c will be reduced if the rate of water supply to the roots is unable to cope with transpiration losses. This is more pronounced in heavy textured than in light textured soils.

Groundwater: As crop growth is affected by shallow groundwater tables, the ET_c is affected also.

Salinity: ET_c is affected by soil salinity, since the soil water uptake by the crop is reduced due to the higher osmotic potential of saline soil water.

Water and crop yield: Different crops have different critical periods for soil water stress. Therefore the timing and duration of shortage is important with respect to the yield.

4.8.3. Irrigation method

A properly designed, constructed and operated irrigation system will not have any effect on ET_c, with the exception of localized irrigation. Hence, the differences in the amount of water used for irrigation under the one or the other method should not be attributed to the effect of the method on ET_c, but to the corresponding efficiency being achieved under the one or the other method

Localized irrigation (drip, spray jet, etc.) only wets part of the soil and since evapotranspiration includes plant transpiration and the evaporation from the soil, the overall ET_c should be expected to be less under localized irrigation systems. However, ET_c is not affected by the method when the crop is near or at full groundcover. For the period before 70% groundcover reduced ET_c should be expected, since evaporation is limited to the wet areas of the soil only.

4.8.4. Cultural practices.

The use of fertilizers has only a slight effect on ET_c, as long as the nutrient requirements for optimum growth and yield are provided.

The plant population will affect ET_c in the same way as percentage groundcover. For low plant populations, when the soil in the area in-between the rows is kept dry, the evaporation will be less and thus ET_c will be less in relation to a higher plant population.

Tillage produces little, if any, effect on ET_c. Rough tillage will accelerate evaporation from the plough layer, deep tillage may increase water losses when the land is fallow or when the crop cover is sparse.

As far as mulching is concerned, while polyethylene and asphalt mulches are effective in reducing ET_c, crop residues are often considered of little net benefit in reducing ET_c.

Crop residues as a barrier to soil evaporation are ineffective in irrigated agriculture. According to FAO (1984), the lower temperature of the covered soil and the higher reflective capacity of the organic matter are easily outweighed by evaporation of the often re-wetted residue layer.

Windbreaks, depending on the distance covered and the height of the windbreak, can reduce ET_c by 5-30% in windy, warm and dry climate because of their effect on windy velocity.

Anti-transpirants have been used in research for the reduction of ET_c. Their use has so far been limited to research and pilot projects.

Chapter 5
Estimating irrigation requirements

5.1. Crop water requirements versus irrigation requirements

It is important to make a distinction between crop water requirement (CWR) and irrigation requirement (IR). Whereas crop water requirement refers to the water used by crops for cell construction and transpiration, the irrigation requirement is the water that must be supplied through the irrigation system to ensure that the crop receives its full crop water requirement. If irrigation is the sole source of water supply for the plant, then the irrigation requirement will be at least equal to the crop water requirement, and is generally greater to allow for inefficiencies in the irrigation system (see Module 1). If the crop receives some of its water from other sources (rainfall, water stored in the soil, underground seepage, etc.), then the irrigation requirement can be considerably less than the crop water requirement.

The Net Irrigation Requirement (IR_n) does not include losses that are occurring in the process of applying the water. IR_n plus losses constitute the Gross Irrigation Requirement (IR_g).

The estimation of crop water requirement, which is equal to crop evapotranspiration ET_c, was covered in detail in Chapter 4. The calculation of IR is the subject of this chapter. It is important to realize that the estimation of crop water requirements is the first stage in the estimation of irrigation requirements of a given cropping programme. Hence the calculation of crop water requirements and irrigation requirements must not be viewed as two unrelated procedures.

5.2. Importance of estimating irrigation requirements

Estimating the crop water and irrigation requirements for a proposed cropping pattern is an essential part of the planning and design of an irrigation system.

The irrigation requirement (IR) is one of the principal parameters for the planning, design and operation of irrigation and water resources systems. Detailed knowledge of the IR quantity and its temporal and spatial variability is essential for assessing the adequacy of water resources, for evaluating the need of storage reservoirs and for the determining the capacity of irrigation systems. It is a parameter of prime importance in formulating the policy for optimal allocation of water resources as well as in decision-making in the day-to-day operation and management of irrigation systems.

Incorrect estimation of the IR may lead to serious failures in the system performance and to the waste of valuable water resources. It may result in inadequate control of the soil moisture regime in the root zone, it may cause waterlogging, salinity or leaching of nutrients from the soil. It may lead to the inappropriate capacities of the irrigation network or of storage reservoirs, to a low water use efficiency and to a reduction in the irrigated area. Over-estimating IR at peak demand may also result in increased development costs.

5.3. Net irrigation requirements

The net irrigation requirement is derived from the field balance equation:

Equation 20

$$IR_n = ET_c - (Pe + Ge + Wb) + LR_{mm}$$

Where:

IR_n	=	Net irrigation requirement (mm)
ET_c	=	Crop evapotranspiration (mm)
Pe	=	Effective dependable rainfall (mm)
Ge	=	Groundwater contribution from water table (mm)
Wb	=	Water stored in the soil at the beginning of each period (mm)
LR_{mm}	=	Leaching requirement (mm)

5.3.1. Crop evapotranspiration

The crop evapotranspiration (ET_c) is the crop water requirement (CWR) for a given cropping pattern during a certain time period. Its estimation was covered in Chapter 4.

5.3.2. Effective dependable rainfall

Dependable rainfall

Crop water requirements can be partially or fully covered by rainfall. However, while the rainfall contribution may be substantial in some years, in other years it may be limited. Therefore, in planning and designing irrigation projects, the use of mean values of rainfall should be avoided if more than 10 years of annual rainfall data are available, as is the case for Kutsaga Research Station (Table 23). In such cases, by using these data a probability analysis can be carried out so that a dependable level of rainfall is selected. The dependable rainfall is the rain that can be accounted for with a certain statistical probability, determined from a range of historical rainfall records. It can be, for example, the depth of rainfall that can be expected 3 out of 4 years (75% probability of exceedance) or, better still, 4 out of 5 years (80% probability of exceedance). A higher level of dependable rainfall (9 out of 10 years) may need to be selected during the period that crops are more sensitive to water stress and where yields would be severely affected by water stress. Before one carries out a statistical analysis, it is always important to check with the meteorological station

Table 23

Mean monthly rainfall for Kutsaga Research Station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1951	516.2	169.2	59.2	31.8	1.3	1.8	-	-	15.2	67.3	66.5	162.3
1952	237.0	195.8	146.8	42.2	-	-	-	-	26.4	7.1	72.9	132.2
1953	142.5	220.2	58.9	-	5.1	1.3	-	-	4.3	8.1	98.3	193.8
1954	321.8	192.5	171.5	50.3	4.6	4.1	-	-	16.0	-	198.9	330.7
1955	228.1	228.3	414.8	41.4	10.9	1.3	-	1.5	6.9	36.1	81.8	172.5
1956	174.2	171.7	124.7	45.5	75.4	-	4.1	-	-	3.0	189.5	242.3
1957	278.9	413.3	246.1	36.1	1.0	15.5	-	-	24.6	9.7	12.7	198.4
1958	328.4	342.9	32.0	-	5.3	16.3	0.8	-	8.6	62.2	36.8	194.8
1959	117.1	98.8	25.9	73.4	10.2	14.7	2.0	-	-	2.0	108.7	139.8
1960	174.0	99.3	66.5	50.0	3.8	4.3	-	-	-	14.5	47.8	22.5

Example 5

For each month, estimate the dependable rainfall that you would expect to have in 4 out of every 5 years (80% probability of exceedance) for Kutsaga Research Station.

Considering data for the month of January (Table 23), the highest figure is 516.2 mm and the lowest is 117.1 mm. Using 10 mm groupings, we can group the rainfall in the relevant groups as shown in Table 24.

From the grouping in Table 24 it appears that in 8 out of 10 years the rainfall in January has been 171 mm or more. It is therefore safe to assume that the 80% dependable rainfall is at least 171 mm. Using the same approach, the 80% dependable rainfall has been calculated for all months. The result is shown in Table 25.

Table 24

Rainfall grouping for the month of January for Kutsaga Research Station in order to carry out a probability analysis

Group	Frequency	Group	Frequency	Group	Frequency
111-120 mm	1x	251-260 mm	0	391-400 mm	0
121-130 mm	0	261-270 mm	0	401-410 mm	0
131-140 mm	0	271-280 mm	1x	411-420 mm	0
141-150 mm	1x	281-290 mm	0	421-430 mm	0
151-160 mm	0	291-300 mm	0	431-440 mm	0
161-170 mm	0	301-310 mm	0	441-450 mm	0
171-180 mm	2x	311-320 mm	0	451-460 mm	0
181-190 mm	0	321-330 mm	2x	461-470 mm	0
191-200 mm	0	331-340 mm	0	471-480 mm	0
201-210 mm	0	341-350 mm	0	481-490 mm	0
211-220 mm	0	351-360 mm	0	491-500 mm	0
221-230 mm	1x	361-370 mm	0	501-510 mm	0
231-240 mm	1x	371-380 mm	0	511-520 mm	1x
241-250 mm	0	381-390 mm	0	Total number of records =10	

Table 25

80% dependable rainfall for Kutsaga Research Station (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
80% dependable rainfall	171	161	51	31	0	0	0	0	0	0	41	135

nearest to the irrigation project as to whether or not they have already carried out the statistical analysis of the rainfall data.

A rough indication of rainfall probability can be obtained by grouping the rainfall data and then dividing the number of times that monthly rainfall falls within a group by the number of monthly records. Detailed methods of computing rainfall probability will not be covered in this module but can be found in any standard textbook of hydrology.

Effective rainfall

Not all dependable rainfall is effective and some may be lost through surface runoff, deep percolation or evaporation. Only a part of the rainfall can be effectively used by the crop, depending on its root zone depth and the soil storage capacity. Different methods exist to estimate the effective rainfall and the reader is referred to FAO (1992) for details. One of the most commonly used methods is the USDA Soil Conservation Service Method, presented in Table 26. The relationship between average monthly effective rainfall and mean monthly rainfall is shown for different average monthly ET_c. At the time of irrigation, the net depth of irrigation water that can be stored effectively over the root zone is assumed to be equal to 75 mm. Correction factors are presented for different depths that can be effectively stored. Data in Table 26 do not account for the infiltration rate of the soil or rainfall intensity. In the cases where infiltration is low and rainfall intensities are high, considerable water may be lost by runoff, which is not accounted for in this method.

Table 26

Average monthly effective rainfall, as related to average monthly ET_c and mean monthly rainfall, USDA method (Source: FAO, 1984)

		Monthly mean rainfall (mm)															
		12.5	25	37.5	50	63	75	87.5	100	112.5	125	137.5	150	163	175	187.5	200
		Average monthly effective rainfall (mm)*															
Average monthly ET_c (mm)	25	8	16	24													
	50	8	17	25	32	39	46										
	75	9	18	27	34	41	48	56	62	69							
	100	9	19	28	35	43	52	59	66	73	80	87	94	100			
	125	10	20	30	37	46	54	62	70	76	85	92	98	107	116	120	
	150	10	21	31	39	49	57	66	74	81	89	97	104	112	119	127	133
	175	11	22	32	42	52	61	69	78	86	95	103	111	118	126	134	141
	200	11	23	33	44	54	64	73	82	91	100	109	117	125	134	142	150
	225	12	24	35	47	57	68	78	87	96	106	115	124	132	141	150	159
	250	13	25	38	50	61	72	84	92	102	112	121	132	140	150	158	167

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

Effective storage (mm)	20	25	37.5	50	62.5	75	100	125	150	175	200
Storage factor	0.73	0.77	0.86	0.93	0.97	1.00	1.02	1.04	1.06	1.07	1.08

Table 27

Effective dependable rainfall for the maize crop grown near Kutsaga Research Station

	Oct	Nov	Dec	Jan	Feb	Mar
Period under consideration (decade)	1.5	3	3	3	3	1.5
ET_c for maize (mm)	53.5	109.5	145.0	155.0	130.0	54.0
80% dependable rainfall (mm)	0	41	135	171	161	51*
Effective dependable rainfall for maize (mm)	0	29.5	90.5	115.6	102.1	31.4

* *While 51 mm refers to the effective rainfall for the whole month of March, since it is the end of the rainy season it has been assumed that this rainfall falls within the first 1.5 decades of the month. Local experience should be used to determine what to do for other sites or regions.*

Example 6

Consider the maize crop in Examples 2 and 4, grown near Kutsaga Research Station. The soils are heavy textured clays with available moisture of 160 mm/m and irrigation will be done at 50% allowable depletion level. Estimate the effective dependable rainfall, using the USDA method, for each month of the growing period for maize.

The rooting depth of maize is taken as 0.75 m at peak demand. The available moisture is 60 mm (160 x 0.75 x 0.5) (Example 4). This is the net depth of water application, which is the amount of water that can be stored in the soil at time of irrigation (storage capacity).

December is the month of peak demand (Table 22) with 5.2 mm/day. The ET_c of maize for the month of December can be estimated by adding the corresponding ET_c values for the 3 decades in the month which is: (4.2 x 5) + (4.6 x 10) + (5.2 x 10) + (5.2 x 5) = 145.0 mm. The 80% dependable rainfall for December was calculated to be 135 mm (Example 5).

Using interpolation in Table 26, with a mean monthly rainfall of 135 mm and an average monthly ET_c of 145.0 mm for December, the effective rainfall is 94.5 mm for a storage of 75 mm. However, our storage is only 60 mm, which means that we need to apply a correction factor of 0.958, as obtained through interpolation from Table 26. Therefore, the effective dependable rainfall for January will be 94.5 x 0.958 = 90.5 mm.

Using the same approach, the effective dependable rainfall during the other parts of the growing season of maize can be calculated, taking into consideration the fact that the roots during the first two weeks are 0.2 m deep and 0.5 m deep during the next two weeks. The results are summarized in Table 27.

5.3.3. Groundwater contribution

The contribution of the groundwater table (Ge) to the ET_c varies with the depth of the water table below the root zone, the soil type and the water content in the root zone. Very detailed experiments will be required to determine the groundwater contribution under field conditions. As a rule, under most smallholder conditions high water tables are rare and as a result groundwater contribution to crop water requirements is normally ignored.

However, Figure 25 can be used to make rough estimates of groundwater contribution (in mm/day) for different depths of groundwater below the root zone and various soil types assuming the root zone is relatively moist.

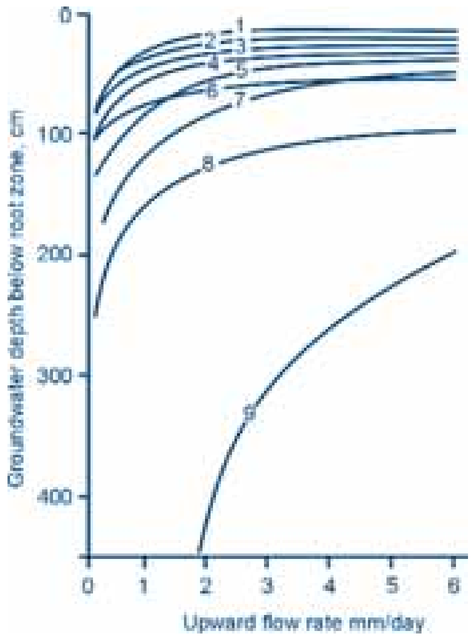
Example 7

Given a sandy loam soil with the groundwater depth below root zone being 80 cm, estimate the contribution of groundwater to ET_c.

Using Figure 25, the first estimate of groundwater contribution to ET_c is 2.7 mm/day.

Figure 25

Contribution of groundwater to moist root zone in mm/day (Source: FAO, 1984)



1	Sticky clay
2	Loamy sand
3	Clay
4	Peat
5	Clay
6	Humus LS
7	Sandy loam
8	Fine sandy loam
9	Very fine sandy loam

5.3.4. Water stored in the soil

At times, and for certain crops, planting takes place right after the rainy season. Some water (Wb) could be left in the soil from the previous irrigation, which can be used for the next crop. This amount can be deducted when determining the seasonal irrigation requirements.

However, it is important to note that water stored in the root zone is not 100% effective due to losses through evaporation and deep percolation. The effectiveness ranges from 40-90%.

In most situations encountered in the planning of smallholder irrigation schemes in East and Southern Africa, the project sites are located in dry areas with very low rainfall. Hence, for planning purposes, the contribution of water stored in the soil is considered negligible in such schemes.

5.3.5. Leaching requirements (LR)

The salinity in the root zone is directly related to the water quality, irrigation methods and practices, soil conditions and rainfall. A high salt content in the root zone is normally controlled by leaching. An excess amount of water is applied during the irrigation, where necessary, for the purposes of leaching. This excess amount of water for leaching purposes is called the Leaching Requirement (LR).

To estimate the LR, both the irrigation water salinity (EC_w) and the crop tolerance to salinity, which is normally expressed as electrical conductivity of the soil saturation extract (EC_e), have to be known. The EC_w can be obtained from laboratory analysis, while the EC_e should be estimated from the crop tolerance data given in Table 28. This table gives an acceptable EC_e value for each crop appropriate to the tolerable degree of yield loss (normally a reduction in yield of 10% or less is accepted).

When estimating the LR, it is important to consider the leaching efficiency (Le). Le varies with the soil type, internal drainage properties of the soil and the field. The value of Le varies from 30-100% and must, therefore, always be measured for the area under investigation.

For sandy loam to clay loam soils with good drainage and where rainfall is low, the leaching requirement can be obtained through the following equations:

Equation 21

For surface and sprinkler irrigation method:

$$LR_{(fraction)} = \frac{EC_w}{5\,EC_e - EC_w} \times \frac{1}{Le}$$

Equation 22

For localized irrigation and high frequency (near daily) sprinkler:

$$LR_{(fraction)} = \frac{EC_w}{2\,Max\,EC_e} \times \frac{1}{Le}$$

Where:

$LR_{(fraction)}$	=	The fraction of the water to be applied that passes through the entire root zone depth and percolates below
EC_w	=	Electrical conductivity of irrigation water (dS/m)
EC_e	=	Electrical conductivity of the soil saturation extract for a given crop appropriate to the tolerable degree of yield reduction (dS/m) (Table 29)
Max EC_e	=	Maximum tolerable electrical conductivity of the soil saturation extract for a given crop (dS/m) (Table 29)
Le	=	Leaching efficiency (in decimals)

The leaching requirement fraction $LR_{(fraction)}$ can also be expressed as the depth of water leached below the root zone $LR_{(mm)}$ divided by the water requirement, taking into consideration the rainfall:

Equation 23

$$LR_{(fraction)} = \frac{LR_{(mm)}}{IR_n + Pe}$$

If assuming that Wb and Ge are both zero, then Equation 20 becomes:

$$IR_n = ET_c - Pe + LR_{(mm)}$$

Substituting this in Equation 23 gives:

$$LR_{(fraction)} = \frac{LR_{(mm)}}{ET_c + LR_{(mm)}}$$

Rearranging the above gives:

$$LR_{(fraction)} \times ET_c + LR_{(fraction)} \times LR_{(mm)} = LR_{(mm)}$$

$$LR_{(fraction)} \times ET_c = LR_{(mm)} \times (1 - LR_{(fraction)})$$

Thus:

$$\frac{ET_c}{(1 - LR_{(fraction)})} = \frac{LR_{(mm)}}{LR_{(fraction)}}$$

Equation 23 can also be arranged as follows:

$$\frac{LR_{(mm)}}{LR_{(fraction)}} = IR_n + Pe$$

Combining the two equations gives:

$$IR_n = \frac{ET_c}{(1 - LR_{(fraction)})} - Pe$$

And finally, the equation for $LR_{(mm)}$, as follows:

Equation 24

$$LR_{(mm)} = \frac{ET_c}{(1 - LR_{(fraction)})} - ET_c$$

Where:

$LR_{(mm)}$ = Leaching requirement for the period under consideration (mm)

ET_c = Crop evapotranspiration or crop water demand for the period under consideration (mm)

$LR_{(fraction)}$ = Leaching requirement fraction

Table 28

Crop tolerance and yield potential of selected crops, as influenced by irrigation water salinity (EC_w) or soil salinity (EC_e)[1] (Source: FAO, 1985)

Yield potential[2]	100%		90%		75%		50%		0%	
Crops	EC values for soil (EC_e) and for water (EC_w)								"maximum"[3]	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
Field crops										
Barley (*Hordeum vulgare*)[4]	8.0	5.3	10	6.7	13	8.7	18	12	28	19
Cotton (*Gossypium Hirsutum*)	7.7	5.1	9.6	6.4	13	8.4	17	12	27	18
Sugarbeet (*Beta vulgaris*)[5]	7.0	4.7	8.7	5.8	11	7.5	15	10	24	16
Sorghum (*Sorghum bicolor*)	6.8	4.5	7.4	5.0	8.4	5.6	9.9	6.7	13	8.7
Wheat (*Triticum aestivum*)[4,6]	6.8	4.0	7.4	4.9	9.5	6.3	13	8.7	20	13
Wheat, durum (*Triticum turgidum*)	5.7	3.8	7.6	5.0	10	6.9	15	10	24	16
Soyabeans (*Glycine max*)	5.0	3.3	5.5	3.7	6.3	4.2	7.5	5	10	6.7
Cowpeas (*Vigna unguiculata*)	4.9	3.3	5.7	3.8	7.0	4.7	9.1	6	13	8.8
Groundnuts (peanuts) (*Arachis hypogea*)	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.6	4.4
Rice (paddy) (*Oriza sativa*)	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11	7.6
Sugarcane (*Saccharum officinarum*)	1.7	1.1	3.4	2.3	5.9	4.0	10	6.8	19	12
Corn (maize) (*Zea mays*)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Flax (*Linum usitatissimum*)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Broadbeans (*Vicia faba*)	1.5	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12	8
Beans (*Phaseolus vulgaris*)	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
Vegetable crops										
Squash, zucchini (courgette) (*cucurbita pepo melopepo*)	4.7	3.1	5.8	3.8	7.4	4.9	10	6.7	15	10
Beet, red (*Beta vulgaris*)[5]	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15	10
Squash, scallop (*Cucurbita pepo melopepo*)	3.2	2.1	3.8	2.6	4.8	3.2	6.3	4.2	9.4	6.3
Broccoli (*Brassica oleracea botrytis*)	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	14	9.1
Tomatoes (*Lycopersicon esculentum*)	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13	8.4
Cucumbers (*Cucumis sativus*)	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10	6.8
Spinach (*Apium graveolens*)	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15	10
Celery (*Apium graveolens*)	1.8	1.2	3.4	2.3	5.8	3.9	9.9	6.6	18	12
Cabbages (*Brassica oleracea capitata*)	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12	8.1
Potatoes (*Solanum tuberosum*)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Corn, sweet (maize) (*Zea mays*)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Sweet potatoes (*Ipomoea batatas*)	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	11	7.1
Peppers (*Capsicum annuum*)	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	8.6	5.8
Lettuce (*Lactuca sativa*)	1.3	0.9	2.1	1.4	3.2	2.1	5.1	3.4	9.0	6.0
Radishes (*Raphanus sativus*)	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	8.9	5.9
Onions (*Allium cepa*)	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.4	5.0
Carrots (*Daucus carota*)	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.0	8.1	5.4
Beans (*Phaseolus vulgaris*)	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
Turnips (*Brassica rapa*)	0.9	0.6	2.0	1.3	3.7	2.5	6.5	4.3	12	8.0

Forage crops										
Wheat grass, tall (*agropyron elongatum*)	7.5	5.0	9.9	6.6	13	9.0	19	13	31	21
Wheargrass, fairway crested (*agropyron crostatum*)	7.5	5.0	9.0	6.0	11	7.4	15	9.8	22	15
Bermuda grass (*Cynodom dactylon*)[7]	6.9	4.6	8.5	5.6	11	7.2	15	9.8	23	15
Barley (forage) (*Hordeum vulgare*)[4]	6.0	4.0	7.4	4.9	9.5	6.4	13	8.7	20	13
Ryegrass, perennial (*Lolium perenne*)	5.6	3.7	6.9	4.6	8.9	5.9	12	8.1	19	13
Trefoil, narrowleaf birdsfoot[8] (*Lotus corniculatus tenuifolium*)	5.0	3.3	6.0	4.0	7.5	5.0	10	6.7	15	10
Harding grass (*Phalaris tuberosa*)	4.6	3.1	5.9	3.9	7.9	5.3	11	7.4	18	12
Fescue, tall (*Festuca elatior*)	3.9	2.6	5.5	3.6	7.8	5.2	12	7.8	20	13
Wheatgrass, standard crested (*Agropyron sibiricum*)	3.5	2.3	6.0	4.0	9.8	6.5	16	11	28	19
Vetch, common (*Vicia angustifolia*)	3.0	2.0	3.9	2.6	5.3	3.5	7.6	5.0	12	8.1
Sudan grass (*Sorghum sudanese*)	2.8	1.9	5.1	3.4	8.6	5.7	14	9.6	26	17
Wildrye, beardless (*Elymus triticoides*)	2.7	1.8	4.4	2.9	6.9	4.6	11	7.4	19	13
Cowpea (Forage) (*Vigna unguiculata*	2.5	1.7	3.4	2.3	4.8	3.2	7.1	4.8	12	7.8
Trefoil, big (*Lotus uliginosus*)	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	7.6	5.0
Sesbania (*Sesbania exaltata*)	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	17	11.0
Sphaerophysa (*Sphaerophysa salsula*)	2.2	1.5	3.6	2.4	5.8	3.8	9.3	6.2	16	11.0
Alfalfa (*Medicago sativa*)	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16	10.0
Lovegrass (*Eragrostis sp.*)[9]	2.0	1.3	3.2	2.1	5.0	3.3	8.0	5.3	14	9.3
Corn (Forage) (Maize) (*Zea mays*)	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15	10
Clover, berseem (*Trifolium alexandrinum*)	1.5	1.0	3.2	2.2	5.9	3.9	10	6.8	19	13
Orchard grass (*Dactylis glomerata*)	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	18	12
Foxtail, meadow (*alopecurus pratensis*)	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Clover, red (*Trifolium pratense*)	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, alsike (*Trifolium hybridum*)	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, ladino (*Trifolium repens*)	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, strawberry (*Trifolium fragiferum*)	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Fruit crops[10]										
Date palm (*Phoenix dactylifera*)	4.0	2.7	6.8	4.5	11	7.3	18	12	32	21
Grapefruit (*Citrus paradisi*)[11]	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8.0	5.4
Orange (*Citrus sinensis*)	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8.0	5.3
Peach (*Prunus persica*)	1.7	1.1	2.2	1.5	2.9	1.9	4.1	2.7	6.5	4.3
Apricot (*Prunus armeniaca*)[11]	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	5.8	3.8
Grape (*vitus sp.*)[11]	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Almond (*Prunus dulcis*)[11]	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.8	6.8	4.5
Plum, prune (*Prunus domestica*)[11]	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.9	7.1	4.7
Blackberry (*Rubus sp.*)	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Boysenberry (*Rubus ursinus*)	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Strawberry (*Fragaria sp.*)	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4	2.7

1 *These data should only serve as a guide to relative tolerances among crops. Absolute tolerances vary depending upon climate, soil conditions and cultural practices. In gypsiferous soils, plants will tolerate about 2 dS/m higher soil salinity (EC_e) than indicated but the water salinity (EC_w) will remain the same as shown in this table.*

2 *EC_e means average root zone salinity as measured by electrical conductivity of the saturation extract of the soil, reported in deciSiemens per metre (dS/m) at 25°C. EC_w means electrical conductivity of the irrigation water in deciSiemens per metre (dS/m). The relationship between soil salinity and water salinity ($EC_e = 1.5\ EC_w$) assumes a 15-20% leaching fraction and a 40-30-20-10% water use pattern for the upper to lower quarters of the root zone.*

3 *The zero yield potential or maximum EC_e indicates the theoretical soil salinity (EC_e) at which stage crop growth ceases.*

4 *Barley and wheat are less tolerant during germination and seedling stage; EC_e should not exceed 4-5 dS/m in the upper soil during this period.*

5 *Beets are more sensitive during germination; EC_e should not exceed 3 dS/m in the seeding area for garden beets and sugar beets.*

6 *Semi dwarf, short cultivars may be less tolerant.*

7 *Tolerance given is an average of several varieties; Suwanne and Coastal Bermuda grass are about 20% more tolerant, while Common and Greenfield Bermuda grass are about 20% less tolerant.*

8 *Broadleaf Birdsfoot Trefoil seems less tolerant than Narrowleaf Birdsfoot Trefoil.*

9 *Tolerance given is an average for Boer, William, Sand and Weeping Lovegrass; Lehman Lovegrass seems about 50% more tolerant.*

10 *These data are applicable when rootstocks are used that do not accumulate Na^+ and Cl^- rapidly or when these ions do not predominate in the soil.*

11 *Tolerance evaluation is based on tree growth and not yield.*

Example 8

The maize crop planted near Kutsaga Research Station (see previous examples) is irrigated by furrow irrigation, using borehole water. Water analyses give EC_w = 1.2 dS/m. The soil is heavy textured with a measured leaching efficiency (Le) of 0.7. Estimate on a month by month basis for the growing season of maize the actual amount of water to be applied to satisfy both the ET_c and the leaching requirement.

Assuming a 90% yield potential for maize, Table 28 gives a value of EC_e = 2.5. Using Equation 21, and including a leaching efficiency of 0.7, gives the following leaching requirement:

$$LR_{(fraction)} = \frac{1.2}{(5 \times 2.5) - 1.2} \times \frac{1}{0.7} = 1.15 \text{ (90\% yield potential or 10\% yield reduction)}$$

Considering the month of January with an ET_c = 155.0 mm (Table 27) and using Equation 24, the leaching requirement is:

$$LR_{(mm)} = \frac{155.0}{1 - 0.15} - 155.0 = 25.0 \text{ mm}$$

The same calculation can be done for all the months in the growing season for maize and the results are given in Table 29.

Table 29

Leaching requirements for maize planted at Kutsaga Research Station for the period under consideration

	Oct	Nov	Dec	Jan	Feb	Mar
Period under consideration (decade)	1.5	3	3	3	3	1.5
ET_c for maize (mm)	53.5	109.5	145.0	155.0	130.0	54.0
Leaching requirement fraction $LR_{(fraction)}$	0.15	0.15	0.15	0.15	0.15	0.15
Leaching requirement $LR_{(mm)}$ (mm)	9.4	19.3	25.6	25.0	22.9	9.5

In most irrigation projects dealt with in the smallholder sub-sector of East and Southern Africa the quality of irrigation water is good and most soils are sandy with good natural drainage. As a result, soil salinity is not an issue except where there are serious drainage problems. As a rule, the leaching requirement is normally ignored when estimating irrigation requirements. In addition, due to irrigation system inefficiencies, water losses due to deep percolation normally satisfy the leaching requirements.

5.4. Calculating net irrigation requirements

All the parameters for the field balance equation given in Equation 17 have now been estimated. Therefore, it is now possible to estimate the net irrigation requirements.

Example 9

For the maize crop grown near Kutsaga Research Station, estimate the net irrigation requirements for the growing season.

The crop evapotranspiration (ET_c) has been estimated in Example 2 and is summarized in Table 27.
The effective dependable rainfall (Pe) has been estimated in Example 6 and is summarized in Table 27.
The Leaching Requirement (LR_{mm}) has been estimated in Example 8 and is summarized in Table 29.
The groundwater contribution (Ge) and water stored at the beginning of the irrigation (Wb) are assumed to be zero.

Therefore, using Equation 20:

IR_n (Oct)	=	53.5 - (0 + 0 + 0) + 9.3	=	62.8 mm
IR_n (Nov)	=	109.5 - (26.7 + 0 + 0) + 19.3	=	102.1 mm
IR_n (Dec)	=	145.0 - (89.8 + 0 + 0) + 25.5	=	80.7 mm
IR_n (Jan)	=	155.0 - (112.5 + 0 + 0) + 27.0	=	69.5 mm
IR_n (Feb)	=	130.0 - (102.2 + 0 + 0) + 22.9	=	50.7 mm
IR_n (Mar)	=	54.0 - (31.4 + 0 + 0) + 9.4	=	32.0 mm
Total				**397.8 mm**

5.5. Calculating gross irrigation requirements

The gross irrigation requirements account for losses of water incurred during conveyance and application to the field. This is expressed in terms of efficiencies when calculating project gross irrigation requirements from net irrigation requirements, as shown below:

Equation 25

$$IR_g = \frac{IR_n}{E}$$

Where:

IR_g = Gross irrigation requirements (mm)

IR_n = Net irrigation requirements (mm)

E = Overall project efficiency

Module 1 gives more detailed information on the different types of efficiencies (overall project, conveyance, field canal, distribution system, farm, field application efficiency).

Different efficiencies are attributed to different irrigation systems. The overall project efficiency values shown in Table 30 can be used for different irrigation systems (for more details, see Module 1).

Table 30
Efficiencies for different irrigation systems

Irrigation system	Overall efficiency
Surface	45%
Sprinkler	75%
Localized	90%

Example 10

Estimate the gross irrigation requirements for the maize crop grown near Kutsaga Research Station under surface and sprinkler irrigation technologies respectively.

The net irrigation requirements have been calculated in Example 9. Using Equation 25 and the overall efficiencies given in Table 30, the gross irrigation requirements for maize have been calculated and the results are shown in Table 31.

Table 31
Gross irrigation requirements for the maize crop grown at Kutsaga Research Station

Month	Net irrigation requirements (mm)	Irrigation efficiency		Surface gross irrigation requirements (mm)	Sprinkler gross irrigation requirements (mm)
		Surface	Sprinkler		
Oct	62.8	0.45	0.75	139.6	83.7
Nov	102.1	0.45	0.75	226.9	136.1
Dec	80.7	0.45	0.75	179.3	107.6
Jan	69.5	0.45	0.75	154.4	92.7
Feb	50.7	0.45	0.75	112.7	67.6
Mar	32.0	0.45	0.75	71.1	42.7
Total	**397.8**			**884.0**	**530.4**

Chapter 6
Estimating crop water and irrigation requirements using computer programmes

In the preceding chapters the procedures for the manual calculation of the ET_o, using the FAO Penman-Monteith Equation, and of the crop water and irrigation requirements were explained. These procedures are long and complicated. Considering that most irrigation engineers and practitioners might need to estimate the crop water requirements for several irrigation projects at any given time, the whole process becomes very long if carried out manually. It is therefore, imperative to computerize the process to speed up calculations and make the work less tedious. Using computer techniques crop evapotranspiration, rainfall, irrigation and drainage can all be combined into a water balance model.

CROPWAT, developed by FAO, is a computer programme designed for such purposes. For details on this programme, the reader is referred to FAO (1992). It can also be downloaded from the Internet (http://www.fao.org/waicent/faoinfo/agricult/agl/aglw/CROPWAT.stm). In this Module, references to CROPWAT will be limited to the illustration of how outputs from the programme can be used in the estimation of crop water and irrigation requirements for the purposes of initial irrigation planning and design.

6.1. The FAO CROPWAT model

CROPWAT is a computer programme that can calculate crop water and irrigation requirements from climatic and crop data. The programme is interactive in nature. In addition, the programme allows the development of irrigation schedules for different management conditions and the estimation of scheme water supply for varying cropping patterns. The use of the programme in the development of irrigation schedules is covered in Chapter 9.

The CROPWAT model is based on a water balance model where the soil moisture status is determined on a daily basis from calculated evapotranspiration and inputs of rainfall and irrigation. Methodologies for crop water requirements and yield response to water (Chapter 8) are used, while the actual evapotranspiration is determined from the soil moisture status.

Several versions of CROPWAT have been released. CROPWAT 5.6 is an update of earlier versions, which were based on the Modified Penman method, and is based on the sole recommended FAO Penman-Monteith method of estimating ET_o. CROPWAT 5.7 facilitates the linkage to the CLIMWAT programme, which is a climatic database of 3 261 stations of 144 countries worldwide (FAO, 1993). This database can also be downloaded from the above-mentioned Internet site. The latest version, CROPWAT 7.0, contains a completely new version in Pascal and overcomes many of the shortcomings of the CROPWAT 5.7. This version is a DOS application, but it runs without any problem in all MS-Windows environments. Finally, CROPWAT for WINDOWS contains a CROPWAT version in Visual Basic to operate in the Windows environment.

The programme uses monthly climatic data (temperature, relative humidity, wind speed, sunshine hours, rainfall) for the calculation of reference evapotranspiration. It has also four different methods to calculate effective rainfall but to be able to do this it requires dependable rainfall as input. Through the input of crop data (growth stages, K_c factors, root zone depth and allowable soil moisture depletion factor), the programme calculates the crop water requirements on a decade (10-day) basis.

The application of CROPWAT in calculating crop water and irrigation requirements is best illustrated by using an example of smallholder irrigation projects in East and Southern Africa, as is shown below.

6.2. Estimating crop water and irrigation requirements for smallholder farmers

In typical smallholder irrigation schemes in East and Southern Africa each farmer is allocated on average a plot of between 0.5 and 1.5 ha (though it can be as little as 0.1 ha in some countries in the region). In the design of the scheme, each farmer is allocated their own infield equipment and is responsible for operating, maintaining and replacing the equipment as an individual. This individual ownership of infield irrigation equipment allows flexibility and more responsibility for maintenance and replacement by the farmers.

Smallholder farmers normally prefer to grow 2-4 crops per season so as to have a variety of crops for home consumption, to allow agronomic considerations (rotations) and also to spread their risk when it comes to marketing. To allow this, the 0.5 to 1.5 ha plots are normally subdivided in to 2, 3 or 4 subplots. Irrigation systems for smallholders are designed in such a way that they allow the irrigation of these subplots one after another.

6.2.1. Cropping programmes and rotations

The preparation of a cropping programme is the first step in calculating crop water requirements, based on which the capacity of the system or the area to be covered by irrigation is determined (Module 3). With the full participation of farmers, a selection of what crops to grow in winter and summer respectively is made. Factors to be considered in crop selection include farmers' wishes and aspirations, financial considerations, climate and soils, water availability, labour requirements, marketing aspects, availability of inputs, rotational considerations and susceptibility to diseases. These factors are normally site specific.

Once the crops are selected, a cropping programme showing the seasonal cropping patterns and indicating the place and the occupying area for each crop is made. Of importance are the sowing or transplanting dates, the length of the growing season and the time needed for harvest and land preparation for the next crop. It must be noted that the time needed for harvest and land preparation should not be included when calculating the crop water requirements. It is therefore useful to indicate on the cropping programme diagram the time needed for harvesting.

In order to reduce the risk of diseases and pests and to avoid elimination of certain nutrients through plant uptake, the cropping programme should allow rotation of the crops between the subplots. Vegetables such as cabbages, carrots, onion, rape, and field crops like wheat, maize, groundnuts, cotton and beans could safely be planted on the same subplot every two years. Crops such as tobacco, tomatoes, okra, peppers and potatoes need a return period of four years, due to their susceptibility to nematodes (see Module 3).

Cropping programmes are not fixed and they belong to the farmers. This should be taken into consideration when planning the irrigation system. For design purposes, a cropping pattern should be made in such a way that the water requirements for other crops that the farmer intends to grow could be satisfied. This involves a careful consideration of all points mentioned above and detailed discussions with the farmers.

As an example, a 10 ha smallholder irrigation scheme to benefit 20 farmers (each with a 0.5 ha plot) is proposed on a site close to Mahalapye climatic station in Botswana. After intensive consultations with the farmers, and taking all technical aspects into consideration, the crops to be grown are: tomatoes, cabbages and rape in summer, and onions, potatoes and green maize in winter. Based on this information, a possible cropping pattern and rotation for the scheme has been worked out and is presented in Tables 32 and 33 respectively.

Table 32
Cropping pattern for Mahalapye proposed irrigation scheme

Crop	Area (%)	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Summer:													
Tomatoes	33.3	------	------	---								------	------
Cabbage	33.3	------	------	------	---								------
Rape	33.3	---	------	------	------	---							
Winter:													
Onions	33.3					------	------	------	------	------			
Potatoes	33.3						------	------	------	------	---		
Green maize	33.3								------	------	------	------	------

Table 33
Crop rotation programme for Mahalapye proposed irrigation scheme

Block	Summer 1	Winter 1	Summer 2	Winter 2	Summer 3	Winter 3
1	Tomatoes 01/11-16/03	Green maize 01/08-29/12	Rape 15/01-15/05	Potatoes 01/06-14/10	Cabbages 01/12-20/04	Onions 01/05-28/09
2	Cabbages 01/12-20/04	Onions 01/05-28/09	Tomatoes 01/11-16/03	Green maize 01/08-29/12	Rape 15/01-15/05	Potatoes 01/06-14/10
3	Rape 15/01-15/05	Potatoes 01/06-14/10	Cabbages 01/12-20/04	Onions 01/05-28/09	Tomatoes 01/11-16/03	Green maize 01/08-29/12

The cropping programme in Table 32 has been developed by considering the sowing dates, the length of the growing season and the time needed for harvest and for land preparation for the next crop. This information should be obtained locally in the project area but if not available, information in Table 20 in Chapter 4 could be used as a guide, taking into consideration the sensitivity of some crops to frost. In the above example it is assumed that no ground frost occurs during winter. In working out the cropping programme, it has been ensured that enough time is left between two crops following each other in a particular plot to allow for land preparation and harvesting. The figures in column 2 of Table 32 indicate the percentage of the area each crop will occupy in the scheme with two crops per year are grown on the same area, which means that the cropping intensity is 200%. This information is important when estimating the crop water requirements.

In Table 33 rotational considerations for the different crops have been considered. Of special concern are those crops that are susceptible to nematodes (*Solanaceae* family, for example potatoes and tomatoes) (see also Module 3). It was ensured that these crops do not follow each other immediately in the same plot so as to avoid the build up of nematodes. For these crops a rotation cycle of minimum four years is required. Another general consideration in coming up with good crop rotations is to identify those crops with special characteristics like leguminous crops (for example green beans and soybeans), that fix nitrogen into the soil. In the crop rotation schedule it must be ensured that crops that can take advantage of the fixed nitrogen follow them (for example, cereals like maize and wheat can follow the legumes). Crops with different rooting patterns (for example, deep rooted crops versus shallow rooted crops) should follow each other in the same plot so that different crops can efficiently exploit the nutrients in all the different soil depths.

6.2.2. Calculating the reference crop evapotranspiration (ET_o) and the effective rainfall

The next stage is to input climatic data (temperature, relative humidity, wind speed, sunshine hours, rainfall) into CROPWAT, so as to calculate the reference crop evapotranspiration (ET_o) and the effective rainfall. As explained before, CROPWAT uses the sole recommended FAO Penman-Monteith method for estimating ET_o. The climatic data required for input into CROPWAT are normally contained in climatic handbooks issued by national meteorological institutions in most countries. Alternatively, different climatic data files on disk saved after earlier sessions or from the CLIMWAT database (FAO, 1993) can be used for the purpose of calculating ET_o and effective rainfall.

Input of the relevant climatic data and dependable rainfall for Mahalapye climatic station result in computer printouts such as those shown in Tables 34 and 35. The USDA Soil Conservation Method is used for the calculation of the effective dependable rainfall.

Table 34

ET_o for Mahalapye, computed by CROPWAT 7.0

Monthly Reference Evapotranspiration ET_o according Penman-Monteith

Meteostation : Mahalapye — Country : Botswana
Altitude : 1 006 m. — Coordinates : - 23.05 South 28.48 East

Month	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sunshine hours	Radiation MJ/m²/day	ET_o PenMon mm/day
January	19.0	31.6	54	138	8.2	23.7	5.7
February	18.5	30.8	61	130	8.7	23.7	5.4
March	16.7	29.7	65	121	7.8	20.4	4.5
April	13.5	27.0	62	112	8.0	18.1	3.7
May	8.0	24.7	64	95	8.4	16.0	2.9
June	4.5	21.8	67	95	8.1	14.3	2.3
July	4.1	22.0	56	95	8.5	15.4	2.5
August	6.8	25.0	56	121	9.2	18.5	3.4
September	11.7	29.1	48	156	8.7	20.7	4.7
October	15.8	31.2	51	181	8.3	22.3	5.6
November	18.0	31.1	55	164	7.7	22.6	5.6
December	18.5	30.8	60	147	6.7	21.3	5.3
Year	12.9	27.9	58	130	8.2	19.7	4.3

CROPWAT 7.0 — Climate file : D:\CROPWAT7.0\CLI\BOT\MAHALAPY.PEN — 25/09/02

Table 35

Effective rainfall for Mahalapye, computed by CROPWAT 7.0

Monthly Rainfall Data		
Climate station : Mahalapye		**Eff. rain method : USDA S.C. Method**
	Rainfall (mm/month)	**Effective Rainfall (mm/month)**
January	92.0	78.5
February	86.0	74.2
March	77.0	67.5
April	25.0	24.0
May	12.0	11.8
June	4.0	4.0
July	2.0	2.0
August	3.0	3.0
September	8.0	7.9
October	29.0	27.7
November	68.0	60.6
December	87.0	74.9
YEAR	493.0	435.9
Eff rain form :	Peff = (Pmon x (125 - 0.2 x Pmon)) / 125 for Pmon <= 250 mm Peff = 125 + 0.1 x Pmon for Pmon > 250 mm	
CROPWAT 7.0	Rainfile : D:\CROPWAT7.0\CLI\BOT\MAHALAPY.CLI	25/09/02

6.2.3. Calculating the crop water and irrigation requirements for each crop

Based on the cropping programme adopted, the next step is to enter the crop data into CROPWAT to enable the programme to calculate the crop water requirements for the different crops. The crop data required are the crop planting dates, the crop coefficient (K_c) values at the different growth stages, the length of growth stages, the crop rooting depth at the different growth stages, the allowable soil moisture depletion levels and the yield response factors (K_y). K_y is a factor to estimate yield reductions due to water stress (see Chapter 8).

This information should be based on local data, obtained through surveys or recommendations of local agricultural research stations and extension service. The methodologies of estimating the above crop data were covered in Chapter 5. CROPWAT also contains data files for 30 different crops, based on global values, which can be retrieved and adjusted for local conditions.

After the input of the crop data, CROPWAT proceeds to calculate the crop water and irrigation requirements of the given cropping pattern, using the entered crop data and the ET_o and effective rainfall values calculated earlier. The calculation of crop water requirements is done on a decade (10-day period) basis. For reasons of simplicity, all months are taken to have 30 days, subdivided into 3 decades of 10 days each. The mistake caused by this assumption is negligible.

The results for the six crops of Mahalapye proposed irrigation scheme are shown in Tables 36 to 47, where for each crop the crop data input is shown together with the corresponding crop water and irrigation requirements as calculated by CROPWAT.

As explained in Section 4.8.1, due to weather changes from year to year ET_c also varies from year to year and also from period to period. For this, it is important to correct the ET_c, by utilizing a correction factor, that is equal to the ratio of mean peak ET_c and mean monthly ET_c. CROPWAT does not have the facility to calculate this corrected ET_c or crop water requirement. If no long term data are available (> 10 years), Figure 24 can be used to make a first estimate of meeting the peak demand in 3 out of 4 years when climatic data are used. In our case, considering a light soil with available moisture of 100 mm/m, a rooting depth of 0.50 m and an allowable depletion level of 50%, the available moisture is 100 x 0.50 x 0.50 = 25 mm. Using Figure 24, the correction factor for Mahalapye proposed irrigation scheme is determined to be 1.15. The calculation of the corrected values is done manually only for the two months of peak demand for each crop (see Section 6.2.4).

Table 36
General crop data for tomatoes

CROP DATA						
Crop name: TOMATO						
Growth stage		**Initial**	**Devel**	**Mid**	**Late**	**Total**
Length stage	[days]	25	30	35	45	135
Crop coefficient	[coeff.]	0.70	→	1.20	0.65	
Rooting depth	[metre]	0.20	→		0.50	0.50
Depletion level	[fract.]	0.40	→	0.50	0.50	
Yield response factor	[coeff.]	0.40	1.10	0.80	0.40	1.05
CROPWAT 7.0	Crop file : D:\CROPWAT7.0\CRO\TOMATO.CRO					26/06/02

Table 37
Crop water and irrigation requirements for tomatoes from CROPWAT 7.0

Crop Evapotranspiration and Irrigation Requirements

Rain climate station : MAHALAPYE **Crop : TOMATOES**
ETo climate station : MAHALAPYE **Planting date: 1 November**

Month	Decade	Stage	Coefficient Kc	ETcrop mm/day	ETcrop mm/dec	Eff.Rain mm/dec	IrReq. mm/day	IrReq. mm/dec
Nov	1	Init	0.70	3.92	39.2	17.1	2.21	22.1
Nov	2	Init	0.70	3.92	39.2	21.1	1.81	18.1
Nov	3	In/De	0.74	4.08	40.8	22.4	1.84	18.4
Dec	1	Deve	0.87	4.68	46.8	23.7	2.31	23.1
Dec	2	Deve	1.03	5.48	54.8	25.4	2.94	29.4
Dec	3	De/Mi	1.16	6.30	69.3	25.7	3.97	43.7
Jan	1	Mid	1.20	6.70	67.0	26.0	4.10	41.0
Jan	2	Mid	1.20	6.87	68.7	26.5	4.22	42.2
Jan	3	Mi/Lt	1.19	6.67	73.4	25.9	4.32	47.5
Feb	1	Late	1.11	6.14	61.3	25.2	3.62	36.2
Feb	2	Late	0.99	5.36	53.6	24.8	2.88	28.8
Feb	3	Late	0.88	4.50	36.0	24.0	1.50	12.0
Mar	1	Late	0.77	3.71	37.1	24.4	1.27	12.7
Mar	2	Late	0.65	2.92	14.6	12.1	0.50	2.5
TOTAL					701.8	324.2		377.6
CROPWAT 7.0								26/06/02

Table 38
General crop data for cabbages

CROP DATA						
Crop name: CABBAGE						
Growth stage		**Initial**	**Devel**	**Mid**	**Late**	**Total**
Length stage	[days]	30	40	35	35	140
Crop coefficient	[coeff.]	0.70	→	1.05	0.95	
Rooting depth	[metre]	0.20	→		0.50	0.50
Depletion level	[fract.]	0.40	→	0.50	0.50	
Yield response factor	[coeff.]	0.40	1.10	0.80	0.40	1.05
CROPWAT 7.0	Crop file : D:\CROPWAT7.0\CRO\CABBAGE.CRO					27/06/02

Table 39
Crop water and irrigation requirements for cabbages from CROPWAT 7.0

Crop Evapotranspiration and Irrigation Requirements

Rain climate station : MAHALAPYE **Crop : CABBAGES**
ETo climate station : MAHALAPYE **Planting date: 1 December**

Month	Decade	Stage	Coefficient Kc	ETcrop mm/day	ETcrop mm/dec	Eff.Rain mm/dec	IrReq. mm/day	IrReq. mm/dec
Dec	1	Init	0.70	3.78	37.8	23.7	1.41	14.1
Dec	2	Init	0.70	3.71	37.1	25.4	1.17	11.7
Dec	3	In/De	0.70	3.83	42.2	25.7	1.50	16.5
Jan	1	Deve	0.75	4.20	42.0	26.0	1.60	16.0
Jan	2	Deve	0.84	4.81	48.1	26.5	2.16	21.6
Jan	3	Deve	0.93	5.23	57.6	25.9	2.88	31.7
Feb	1	De/Mi	1.01	5.59	55.9	25.2	3.07	30.7
Feb	2	Mid	1.05	5.67	56.7	24.8	3.19	31.9
Feb	3	Mid	1.05	5.36	42.8	24.0	2.35	18.8
Mar	1	Mid	1.05	5.04	50.4	24.4	2.60	26.0
Mar	2	Mi/Lt	1.04	4.69	46.9	24.2	2.27	22.7
Mar	3	Late	1.02	4.32	47.5	18.8	2.61	28.7
Apr	1	Late	0.99	3.93	39.3	11.9	2.74	27.4
Apr	2	Late	0.96	3.56	32.0	5.9	2.90	26.1
TOTAL					636.3	312.3		324.0
CROPWAT 7.0								27/06/02

Table 40

General crop data for rape

CROP DATA						
Crop name: RAPE						
Growth stage		**Initial**	**Devel**	**Mid**	**Late**	**Total**
Length stage	[days]	20	20	30	50	120
Crop coefficient	[coeff.]	0.70	→	1.00	0.95	
Rooting depth	[metre]	0.20	→	0.40	0.40	
Depletion level	[fract.]	0.40	→	0.50	0.50	
Yield response factor	[coeff.]	0.40	1.10	0.80	0.40	1.05
CROPWAT 7.0	Crop file : D:\CROPWAT7.0\CRO\RAPE.CRO					24/09/02

Table 41

Crop water and irrigation requirements for rape from CROPWAT 7.0

Crop Evapotranspiration and Irrigation Requirements

Rain climate station : MAHALAPYE **Crop : RAPE**
ETo climate station : MAHALAPYE **Planting date: 15 January**

Month	Decade	Stage	Coefficient Kc	ETcrop mm/day	ETcrop mm/dec	Eff.Rain mm/dec	IrReq. mm/day	IrReq. mm/dec
Jan	2	Init	0.70	3.99	23.9	15.9	1.34	8.0
Jan	3	Init	0.70	3.92	43.1	25.9	1.56	17.2
Feb	1	In/De	0.75	4.14	41.4	25.2	1.62	16.2
Feb	2	Deve	0.88	4.75	47.5	24.8	2.27	22.7
Feb	3	De/Mi	0.98	4.99	39.9	24.0	1.98	15.9
Mar	1	Mid	1.00	4.80	48.0	24.4	2.36	23.6
Mar	2	Mid	1.00	4.50	45.0	24.2	2.08	20.8
Mar	3	Mi/Lt	1.00	4.22	46.4	18.8	2.51	27.6
Apr	1	Late	0.99	3.92	39.2	11.9	2.74	27.4
Apr	2	Late	0.98	3.62	36.2	6.5	2.97	29.7
Apr	3	Late	0.97	3.33	33.3	5.7	2.76	27.6
May	1	Late	0.96	3.04	30.4	5.2	2.52	25.2
May	2	Late	0.95	2.75	11.0	1.5	2.37	9.5
TOTAL					485.4	214.0		271.4
CROPWAT 7.0								24/09/02

Table 42

General crop data for onions

CROP DATA						
Crop name: ONION						
Growth stage		**Initial**	**Devel**	**Mid**	**Late**	**Total**
Length stage	[days]	20	35	45	50	150
Crop coefficient	[coeff.]	0.70	→	1.20	0.65	
Rooting depth	[metre]	0.20	→	0.40	0.40	
Depletion level	[fract.]	0.40	→	0.50	0.50	
Yield response factor	[coeff.]	0.40	1.10	0.80	0.40	1.05
CROPWAT 7.0	Crop file : D:\CROPWAT7.0\CRO\ONION.CRO					24/09/02

Table 43

Crop water and irrigation requirements for onion from CROPWAT 7.0

Crop Evapotranspiration and Irrigation Requirements

Rain climate station : MAHALAPYE **Crop : ONIONS**
ETo climate station : MAHALAPYE **Planting date: 1 May**

Month	Decade	Stage	Coefficient Kc	ETcrop mm/day	ETcrop mm/dec	Eff.Rain mm/dec	IrReq. mm/day	IrReq. mm/dec
May	1	Init	0.70	2.22	22.2	5.2	1.70	17.0
May	2	Init	0.70	2.03	20.3	3.8	1.65	16.5
May	3	Deve	0.78	2.10	23.1	3.0	1.83	20.2
Jun	1	Deve	0.93	2.32	23.2	2.0	2.12	21.2
Jun	2	Deve	1.07	2.46	24.6	1.1	2.36	23.6
Jun	3	De/Mi	1.17	2.77	27.7	0.9	2.68	26.8
Jul	1	Mid	1.20	2.92	29.2	0.8	2.84	28.4
Jul	2	Mid	1.20	3.00	30.0	0.6	2.94	29.4
Jul	3	Mid	1.20	3.36	37.0	0.7	3.30	36.3
Aug	1	Mi/Lt	1.19	3.69	36.9	0.8	3.61	36.1
Aug	2	Late	1.12	3.82	38.2	0.8	3.73	37.3
Aug	3	Late	1.01	3.86	42.5	1.4	3.73	41.0
Sep	1	Late	0.89	3.81	38.1	1.7	3.64	36.4
Sep	2	Late	0.78	3.68	36.8	2.0	3.48	34.8
Sep	3	Late	0.67	3.36	23.5	3.1	2.92	20.4
TOTAL					453.2	27.8		425.4
CROPWAT 7.0								24/09/02

Table 44
General crop data for potatoes

CROP DATA						
Crop name: POTATO						
Growth stage		**Initial**	**Devel**	**Mid**	**Late**	**Total**
Length stage	[days]	30	35	30	40	135
Crop coefficient	[coeff.]	0.50	→	1.15	0.75	
Rooting depth	[metre]	0.30	→	0.30	0.30	
Depletion level	[fract.]	0.40	→	0.50	0.50	
Yield response factor	[coeff.]	0.40	1.10	0.80	0.40	1.05
CROPWAT 7.0	Crop file : D:\CROPWAT7.0\CRO\POTATO.CRO					24/09/02

Table 45
Crop water and irrigation requirements for potato from CROPWAT 7.0

Crop Evapotranspiration and Irrigation Requirements

Rain climate station : MAHALAPYE   **Crop : POTATOES**
ETo climate station : MAHALAPYE   **Planting date: 1 June**

Month	Decade	Stage	Coefficient Kc	ETcrop mm/day	ETcrop mm/dec	Eff.Rain mm/dec	IrReq. mm/day	IrReq. mm/dec
Jun	1	Init	0.50	1.25	12.5	2.0	1.05	10.5
Jun	2	Init	0.50	1.15	11.5	1.1	1.04	10.4
Jun	3	Init	0.50	1.18	11.8	0.9	1.09	10.9
Jul	1	Deve	0.59	1.44	14.4	0.8	1.36	13.6
Jul	2	Deve	0.78	1.95	19.5	0.6	1.89	18.9
Jul	3	Deve	0.97	2.73	30.0	0.7	2.66	29.3
Aug	1	De/Mi	1.11	3.45	34.5	0.8	3.37	33.7
Aug	2	Mid	1.15	3.91	39.1	0.8	3.83	38.3
Aug	3	Mid	1.15	4.41	48.5	1.4	4.28	47.1
Sep	1	Mi/Lt	1.11	4.76	47.6	1.7	4.59	45.9
Sep	2	Late	1.03	4.84	48.4	2.0	4.64	46.4
Sep	3	Late	0.93	4.65	46.5	4.4	4.21	42.1
Oct	1	Late	0.83	4.40	44.0	6.6	3.74	37.4
Oct	2	Late	0.73	4.09	12.3	2.6	3.23	9.7
TOTAL					420.5	26.4		394.1
CROPWAT 7.0								24/09/02

Table 46
General crop data for green maize

CROP DATA						
Crop name: GREEN MAIZE						
Growth stage		**Initial**	**Devel**	**Mid**	**Late**	**Total**
Length stage	[days]	25	50	40	35	150
Crop coefficient	[coeff.]	0.70	→	1.20	0.65	
Rooting depth	[metre]	0.20	→	0.70	0.70	
Depletion level	[fract.]	0.40	→	0.50	0.50	
Yield response factor	[coeff.]	0.40	1.10	0.80	0.40	1.05
CROPWAT 7.0	Crop file : D:\CROPWAT7.0\CRO\GRMAIZE.CRO					24/09/02

Table 47
Crop water and irrigation requirements for green maize from CROPWAT 7.0

Crop Evapotranspiration and Irrigation Requirements

Rain climate station : MAHALAPYE **Crop : GREEN MAIZE**
ETo climate station : MAHALAPYE **Planting date: 1 August**

Month	Decade	Stage	Coefficient Kc	ETcrop mm/day	ETcrop mm/dec	Eff.Rain mm/dec	IrReq. mm/day	IrReq. mm/dec
Aug	1	Init	0.70	2.17	21.7	0.8	2.09	20.9
Aug	2	Init	0.70	2.38	23.8	0.8	2.30	23.0
Aug	3	In/De	0.73	2.80	30.8	1.4	2.67	29.3
Sep	1	Deve	0.81	3.46	34.6	1.7	3.29	32.9
Sep	2	Deve	0.91	4.28	42.8	2.0	4.08	40.8
Sep	3	Deve	1.01	5.05	50.5	4.4	4.61	46.1
Oct	1	Deve	1.11	5.88	58.8	6.6	5.22	52.2
Oct	2	De/Mi	1.18	6.61	66.1	8.6	5.75	57.5
Oct	3	Mid	1.20	6.72	73.9	12.5	5.59	61.4
Nov	1	Mid	1.20	6.72	67.2	17.1	5.01	50.1
Nov	2	Mid	1.20	6.72	67.2	21.1	4.61	46.1
Nov	3	Mi/Lt	1.15	6.30	63.0	22.4	4.06	40.6
Dec	1	Late	1.01	5.46	54.6	23.7	3.09	30.9
Dec	2	Late	0.85	4.53	45.3	25.4	1.99	19.9
Dec	3	Late	0.69	3.75	26.2	16.3	1.42	9.9
TOTAL					726.5	164.8		561.7
CROPWAT 7.0								24/09/02

6.2.4. Calculating the net and gross irrigation requirements for the total scheme

The CROPWAT computer outputs, showing the irrigation requirements for the different crops in the cropping programme, have to be combined to get the irrigation requirements of all crops together, and which are irrigated at the same time. In addition, the corrected crop water requirements for the months of peak demand have to be calculated, as explained in Section 6.2.3. In order to present the crop and irrigation water requirements in a comprehensive way and allow the correction for peak demand, a summary table should be composed showing on a monthly basis the ET_o, the effective rainfall, the corrected ET_c, the irrigation requirements (expressed in mm), as well as the total project requirements (expressed in m^3). The summary table should always be prepared whether the calculations are done by hand or computer. For the Mahalapye proposed irrigation project Table 48 is the summary table and all information is extracted from the CROPWAT outputs. The same table shows that the project gross irrigation requirements for the 10 ha is 112 720 m^3 per year. The peak net crop water requirement occurs in October and is 6.72 mm/day and for green maize (Table 47). This is what is used for design purposes, since it is the worst case to have been be met by the irrigation system.

Table 48

Crop water and irrigation requirements for Mahalapye proposed irrigation scheme

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total[6]
Mean Ref. Crop Evapotransp. ET_o (mm/day)	5.7	5.4	4.5	3.7	2.9	2.3	2.5	3.4	4.7	5.6	5.6	5.3	1548.0
Effective Rainfall (mm/month)	78.5	74.2	67.5	24.0	11.8	4.0	2.0	3.0	7.9	27.7	60.6	74.9	436.1
ET_c (mm/month)[1]													
Tomatoes	209.1	151.0	51.7								119.2	170.9	701.9
Cabbages	147.7	155.4	144.8	71.3								117.1	636.3
Rape	67.0	128.8	139.4	108.7	41.4								485.3
Onions					65.6	75.5	96.2	117.6	98.4				453.3
Potatoes						35.8	63.9	122.1	142.5	56.3			420.6
Green maize								76.3	127.9	198.8	197.4	126.2	726.6
Corrected ET_c[2] (mm/month)													
Tomatoes	240.5	151.0	51.7								119.2	196.5	758.9
Cabbages	169.9	178.7	144.8	71.3								117.1	681.8
Rape	67.0	148.1	160.3	108.7	41.4								525.5
Onions					65.6	75.5	96.2	135.2	113.2				485.7
Potatoes						35.8	63.9	140.4	163.9	56.3			460.3
Green maize								76.3	127.9	228.6	227.0	126.2	786.0
Net Irrigation Req. (mm/month)[3 and 4]													
Tomatoes	162.0	76.8	0.0								58.6	121.6	419.0
Cabbages	91.4	104.5	77.3	47.3								42.2	362.7
Rape	0.0	73.9	92.8	84.7	29.6								281.0
Onions					53.85	71.5	94.2	132.2	105.3				457.0
Potatoes						31.8	61.9	137.4	156.0	28.6			415.7
Green maize								73.3	120.0	200.9	166.4	51.3	611.9
Total Net Irrigation Requirement[5] (mm/month per ha)	84.4	85.0	56.6	44.0	27.8	34.4	52.0	114.2	127.0	76.4	74.9	71.6	848.3
Gross Irrig. Req. (mm/month per ha) Sprinkler (75% eff.)	112.5	113.3	75.5	58.6	37.0	45.9	69.3	152.3	169.3	101.9	99.9	95.5	1 131.0
Project Gross Irrigation Requirement for 10 ha(m^3)	**11 250**	**11 330**	**7 550**	**5 860**	**3 700**	**4 590**	**6 930**	**15 230**	**16 930**	**10 190**	**9 990**	**95 500**	**113 100**

1 Extracted from Tables 36-47. For example ET_c for tomatoes in January (Table 37): 67.0 + 68.7 + 73.4 = 209.1.

2 Correction factor 1.15 is used for the two months of peak demand, which are the months giving the highest ET_c under 1 (see Section 6.2.3.).

3 Each crop occupies 33.3% of the area.

4 The net irrigation requirement for each crop is equal to the corrected ET_c minus the effective rainfall.

5 Is equal to 33.3% of values under 4. For example, total IR_n for January is (0.333 x 161.5) + (0.333 x 91.0) + (0.333 x 0.0) = 84.4.

6 Totals shown may differ from totals in Tables 37, 39, 41, 43, 45 and 47, due to rounding up.

The net irrigation requirements of the scheme can also be calculated using the CROPWAT computer programme, and the results are shown in Table 49 and 50. However, this method is less accurate due to the fact that CROPWAT does not have the facility to calculate the corrected ET_c, as explained in Section 6.2.3. The difference in the total net irrigation requirements, when comparing Table 48 (total 848 mm) and Table 50 (total 804 mm), is 44 mm.

From the example of Mahalapye irrigation scheme, it is clear that making an estimate of the crop water and irrigation requirements for a proposed cropping pattern is an essential step in the design of the irrigation system (pipe and canal dimensions, sprinkler selection, irrigation frequency, etc.).

The irrigation requirements throughout the year should be compared with the availability of water from the source to ensure that that there is adequate water to support the cropping proposals. If not, it will be necessary to adjust the cropping pattern so as to match water availability or to reduce the area proposed to be under irrigation.

In conclusion, it should be realized that the calculation of crop water and irrigation requirements is a theoretical exercise, based on statistical analysis of climatic parameters. However, the climate is very variable. Consequently, the calculation of irrigation water requirements at planning level can only be an approximation and it is not appropriate or recommended to attempt detailed accuracy.

Table 49

Cropping pattern for Mahalapye proposed irrigation scheme from CROPWAT 7.0

CROPPING PATTERN

Name : MAHALAPYE

Nr.	Crop file	Crop name	Plating datedd/mm	Harvesting datedd/mm	Area%
1	TOM-MA	TOMATO	01/11	16/03	34
2	CAB-MA	CABBAGE	01/12	20/04	33
3	RAP-MA	RAPE	15/01	15/05	33
4	ONI-MA	ONION	01/05	28/09	34
5	POT-MA	POTATO	01/06	14/10	33
6	GMA-MA	GREEN MAIZE	01/08	29/12	33

CROPWAT 7.0 Crop pattern file : D:\CROPWAT7.0\CRO\MAHALPYE.PAT 20/09/02

Table 50

Scheme irrigation requirements for Mahalapye proposed irrigation scheme from CROPWAT 7.0

SCHEME IRRIGATION REQUIREMENTS

Rain station : MAHALAPYE
ETo station : MAHALAPYE
Cropping pattern : MAHALAPYE

Crop Nr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	4.2	2.7	0.6	–	–	–	–	–	–	–	2.0	3.1
2	2.2	2.9	2.5	1.9	–	–	–	–	–	–	–	1.4
3	1.0	2.0	2.3	2.8	1.6	–	–	–	–	–	–	–
4	–	–	–	–	1.7	2.4	3.0	3.7	3.3	–	–	–
5	–	–	–	–	–	1.1	2.0	3.8	4.5	2.3	–	–
6	–	–	–	–	–	–	–	2.4	4.0	5.5	4.6	2.2
SQ1	2.5	2.5	1.8	1.6	1.1	1.2	1.7	3.3	3.9	2.6	2.2	2.2
SQ2	77	70	55	47	35	35	52	102	118	80	65	68
SQ3	0.29	0.29	0.21	0.18	0.13	0.13	0.19	0.38	0.46	0.30	0.25	0.26
AR	89.0	100.0	88.7	55.0	56.0	67.0	67.0	100.0	100.0	55.0	67.0	100.0
AQ	0.32	0.29	0.23	0.33	0.23	0.20	0.29	0.38	0.46	0.54	0.37	0.26

SQ1, SQ2, SQ3 = Net scheme irrigation requirements in mm/day, mm/month and ls/h
AR = Irrigated area as percentage of total scheme area
AQ = Irrigation requirements in l/s for actually irrigated area

CROPWAT 7.0 20/09/02

Chapter 7
Soil-water-plant relationship

As mentioned in Chapter 1, soil is one of the three parameters that need to be considered when preparing an irrigation schedule. Without having gone into detail, in the previous chapters examples of calculating crop water and irrigation requirements and effective rainfall using soil data have been given. This chapter will look more in detail into the soil data necessary for irrigation scheduling and how to obtain them as well as into the soil-water-plant relationship.

Soil consists of mineral and organic materials that cover much of the earth's surface. It contains living matter, air and water and can support vegetation. The soil functions as a storehouse for plant nutrients, as habitat for soil organisms and plant roots and as a reservoir for water to meet the evapotranspiration demands of plants. It contains and supplies water, oxygen, nutrients and mechanical support for plant growth.

The soil determines how irrigation water should be managed. The amount of water the soil can hold for plant use is determined by its physical and chemical properties. This amount determines the length of time that a plant can be sustained adequately between irrigation and/or rainfall events, the frequency of irrigation and the amount and rate to be applied. Along with plant evapotranspiration, it also determines the irrigation system capacity needed for desired crop yield.

Land grading, deep ploughing, sub-soiling or other tillage practices can modify soil properties within a profile. Shallow tillage practices can affect water infiltration and soil permeability rates. Irrigation planners have to obtain accurate on-site soil information in order to be able to make recommendations.

7.1. Soil texture

Soil texture refers to the particle size or the relative amounts of sand, silt and clay. The mechanical analysis in the laboratory to determine the soil texture, using the USDA soil texture triangle, is described in Module 2. The following general definitions of soil texture classes can help in giving a first rough description of the soil when actually feeling and examining it by hand in the field:

- ❖ *Sand*: Is loose and single grained. The individual grains can be readily seen and felt. Squeezed in the hand when dry, sand falls apart when pressure is released. Squeezed when moist, it forms a cast, but crumbles when touched. The soil remains loose and can only be heaped into a pyramid.
- ❖ *Loamy sand*: Contains a high percentage of sand, but has enough silt and clay to make it somewhat coherent. The individual sand grains can be readily seen and felt. It can be shaped into a ball that easily falls apart.
- ❖ *Silt loam*: As for loamy sand, but the soil can be shaped by rolling into a short, thick cylinder.
- ❖ *Loam*: Has a relatively even mix of different grades of sand, silt and clay. It is friable with a somewhat gritty feel, but is fairly smooth and slightly plastic. It can be rolled into a cylinder of about 15 cm long that breaks when bent.
- ❖ *Clay loam*: As for loam, although the soil can be bent into a U, but no further, without being broken.
- ❖ *Light clay*: Fine-textured soil that usually forms very hard lumps or clods when dry and is very sticky and plastic when wet. The soil can be bent into a circle that shows cracks.
- ❖ *Heavy clay*: The soil can be bent into a circle without showing cracks.
- ❖ *Organic soils*: Vary in organic matter content from 20-95%. They are classified on the degree of decomposition of the organic deposits. The terms muck and peat are commonly used. Muck is well-decomposed organic material and peat is raw, un-decomposed, very fibrous organic material.

Fine-textured soils generally hold more water than coarse-textured soils. Medium-textured soils actually have more water available for plant use than some clay soils, since water in clays can be held at a greater tension that reduces its availability to plants. Table 51 gives guidelines for estimating soil moisture conditions, using the 'feel and appearance' method.

Table 51

Guide for estimating soil moisture conditions, using the 'feel and appearance' method (Source: USDA, 1991)

Available soil moisture	Soil moisture condition	Texture			
		Course: Fine sand Loamy fine sand	Moderate coarse: Sandy loam Fine sandy loam	Medium: Sandy clay loam Loam, silt loam	Fine: Clay loam Silty clay loam
0-25	Dry	Loose. Will hold together if not disturbed. Loose sand grains on fingers	Forms a very weak ball. Aggregated soil grains break away easily from ball	Soil aggregations break away easily. No moisture-staining on fingers. Clods crumble with applied pressure	Soil aggregations easily separate. Clods are hard to crumble with applied pressure
25-50	Slightly moist	Forms a very weak ball* with well-defined marks. Light coating of loose and aggregated sand grains remains on fingers	Forms a weak ball with defined finger marks. Darkened colour. No water-staining on fingers	Forms a weak ball with rough surfaces. No water-staining on fingers. Few aggregated soil grains break away	Forms a weak ball. Very few soil aggregations break away. No water stains. Clods flatten with applied pressure
50-75	Moist	Forms a weak ball with loose and aggregated sand grains remaining on fingers. Darkened colour. Heavy water -staining on fingers. Will not form into a ribbon**	Forms a ball with defined finger marks. Very light soil water -staining on fingers. Darkened colour. Will not slick	Forms a ball. Very light water-staining. Darkened colour. Pliable. Forms a weak ribbon between thumb and forefinger	Forms a smooth ball with defined finger marks. Light soil water-staining on fingers. Ribbons form with thumb and forefinger
75-100	Wet	Forms a weak ball. Loose and aggregated sand grains remain on fingers. Darkened colour. Heavy water -staining on fingers. Will not ribbon	Forms a ball with wet outline left on hand. Light to medium water -staining on fingers. Makes a weak ribbon between thumb and forefinger	Forms a ball with well-defined finger marks. Light to heavy soil water coating on fingers. Ribbons form	Forms a ball. Uneven medium to heavy soil water coating on fingers. Ribbon forms easily between thumb and forefinger
Field Capacity (100)	Wet	Forms a weak ball. Light to heavy soil-water coating on fingers. Wet outline of soft ball remains on hand	Forms a soft ball. Free water appears briefly on surface after squeezing or shaking. Medium to heavy soil-water coating on fingers	Forms a soft ball. Free water appears briefly on soil surface after squeezing or shaking. Medium to heavy soil-water coating on . fingers	Forms a soft ball. Free water appears on soil surface after squeezing or shaking. Thick soil-water coating on fingers. Slick and sticky

* *A ball is formed by squeezing a soil sample firmly in one's hand.*

** *A ribbon is formed by squeezing soil between one's thumb and forefinger.*

7.2. Soil structure

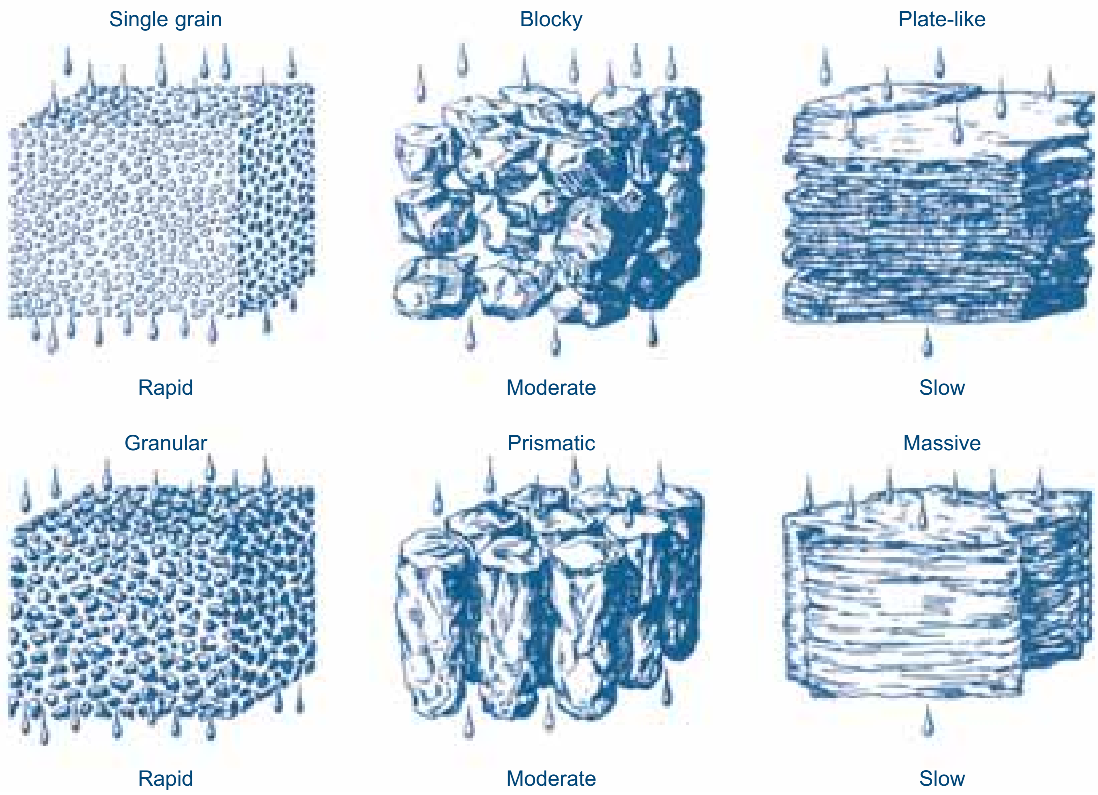
Soil structure is the arrangement and organization of soil particles into natural units of aggregation. These units are separated from one another by weakness planes that persist through cycles of wetting and drying and cycles of freezing and thawing. Structure influences air and water movement, root development, and nutrient supply.

7.2.1. Soil structure types

Structure type refers to the particular kind of grouping that predominates in a soil horizon (Figure 26). Single grained and massive soils are structureless. In single-grained soils, such as loose sand, water percolates rapidly. Water moves very slowly through most clay soils. A more favourable water relationship occurs in the soils that have blocky, granular and prismatic structures. Plate-like structure in fine and medium soils impedes the downward movement of water. Structure can be improved with cultural practices, such as conservation tillage, improving internal drainage, liming or adding sulphur to soil, using grasses in crop rotation, incorporating crop residue and adding organic material or soil amendments. Structure can be destroyed by heavy tillage equipment or excess operations.

Texture, root activity, percent clay, percent organic matter and the warm and cold cycles all play a part in aggregate formation and stability. Some aggregates are quite stable upon wetting and others disperse readily. Soil aggregation helps maintain stability when wet, resist dispersion caused by the impact from sprinkler and/or rain droplets, maintain soil intake rate and resist surface water and wind erosion.

Figure 26
Soil structure types and their effect on downward movement of water (Source: USDA, 1997)



Irrigation water containing sodium can cause dispersing of soil aggregates. Clay mineralogy has a major influence on soil aggregation and shrink-swell characteristics.

7.2.2. Soil pore space

Pore space allows the movement of water, air and roots. Sandy soils have larger pores but less total pore space than silt and clay soils. Gravitational water flows through sandy soils much faster because the pores are much larger. Clayey soils hold more water than sandy soils because clay soils have a larger volume of small, flat-shaped pore spaces that hold more capillary water. Permeability and drainability of soils are directly related to the volume and size and shape of pore space.

7.3. Soil water potential

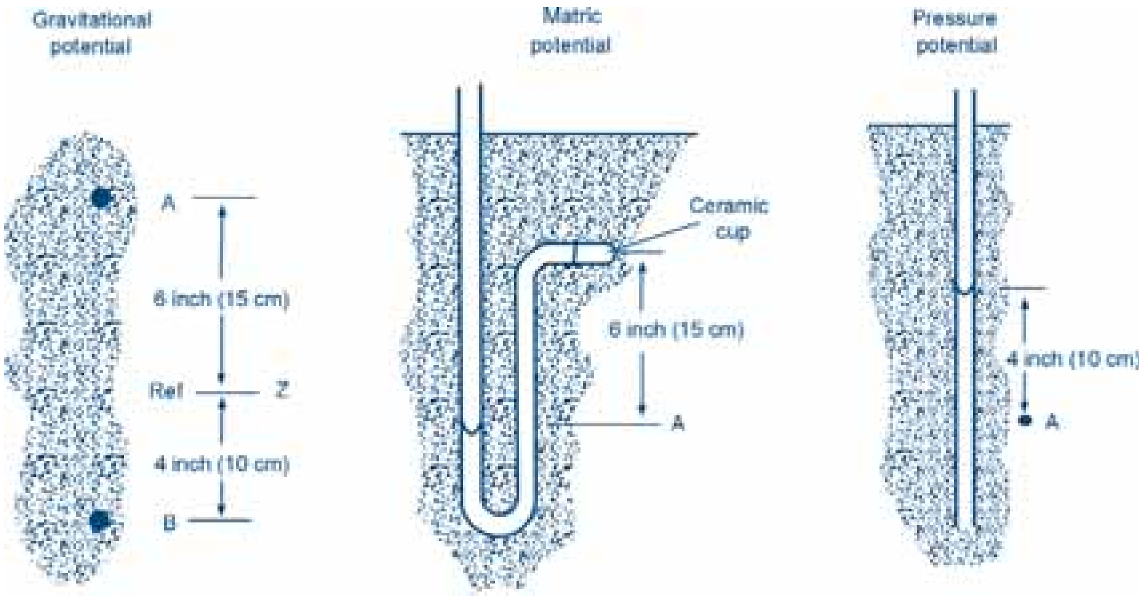
There are two basic methods of characterizing or measuring the water in the soil. The first is to measure the amount of water in the soil. This approach is the basis for the soil condition water content and is explained in Module 2. An alternative to measuring the amount of water in the soil is to measure the energy state of the water. This approach leads to the soil condition water potential (New Mexico State University, 1999).

Water potential measures the ability of soil water to move. Water potential is important to any process where soil water moves, such as infiltration and redistribution within the soil or the removal of water from the soil by evaporation and

Table 52
Components of soil water potential (Source: New Mexico State University, 1999)

Componentname	Factors affecting potential energy	Reference state	Sign
Matric potential	Adsorption of water to soil	Free water	negative "-"
Osmotic or *solute* potential	Dissolved solutes	Pure water	negative "-"
Gravitational potential	Elevation in gravitational field	Reference elevation	positive "+" (above reference elevation) negative "-" (below reference elevation)
Pressure potential	Applied pressure	Atmospheric pressure	positive "+" (applied pressure) negative "-" (applied suction)

Figure 27
Gravitational, matric and pressure potentials (Source: USDA, 1997)



plant uptake. Water potential is the amount of work required per unit quantity of water to transport water in the soil. The four components of soil water potential are presented in Table 52. Figure 27 illustrates the gravitational, matric and pressure potentials. The soil water potential is usually expressed in kPa or pF. Plants therefore need to exert their energy in order to overcome the soil water potential.

7.4.1. Matric potential

Water molecules can form hydrogen bonds with the surface of soil minerals (adsorption) as well as with other water molecules (cohesion). In soil, adsorptive forces develop between the soil mineral surfaces and the soil water. These forces exert a 'pull' on the soil water. This pull between the soil and the water molecules close to the particle surface is distributed throughout the soil water by the cohesive forces between water molecules. As external forces attempt to remove water from the soil, water is restrained or held in the soil by these adhesive and cohesive forces. This places the soil water under tension. This tension or pull on the soil water causes the potential energy of the water to decrease relative to free water (water not held under tension). Therefore, water in soil can be held under tension because of the adsorption of water to the soil particles. Water held under tension has less potential energy per unit quantity of water than reference water (free water); therefore has a lower water potential. The decrease in water potential caused by the adsorption of water to the soil surfaces is called the matric potential component of the soil water potential. If the unit of water is expressed as a weight, then the matric potential at a given point in the soil is the vertical distance between that point in the soil and the water surface of a tensiometer filled with water and connected to the soil through a ceramic cup (see Section 9.1.2). Matric potential is always negative or zero (in saturated soil), since the adsorption of water onto soil surfaces can only lower the potential energy relative to reference water. This potential was formerly called capillary potential or capillary water. Capillarity results from the surface tension of water and its contact angle with the solid soil particles.

7.4.2. Solute potential

The presence of dissolved solutes can decrease the potential energy of water relative to the reference state (pure water). Solutes that reduce the potential energy of water are called osmotically active solutes. Inorganic salts are all osmotically active and many large organic molecules are osmotically active. The reduction in potential energy from dissolved solutes arises partly from the hydration of the solute or the forming of chemical bonds between the solute and water molecule. However, solutes also should lower the potential energy of water in an 'ideal' thermodynamic solution where chemical interactions do not occur. Soil water is not pure water but rather a solution and the presence of osmotically active solutes reduces the soil water potential. The reduction in soil water potential caused by the presence of dissolved solutes is called osmotic or solute potential component of the soil water potential. Osmotic potential is always negative or zero, because dissolved solutes can only lower the potential energy of water.

7.4.3. Gravitational potential

Soil water located higher in the soil profile has higher potential energy than water deeper in the soil profile. The same is true for plant water. The increase or decrease in soil water potential caused by changes in elevation is called the gravitational water potential component of the soil water potential. The reference state for soil water relevant to gravitational forces is an 'arbitrary but specified' elevation. An elevation is chosen arbitrarily where the gravitational potential is defined to be zero. This elevation is usually the soil surface or the water table but it can be any elevation at all. The sign of the gravitational potential can be negative or positive. Soil (or plant) water located at an elevation above the specified reference elevation will have a positive gravitational potential. Water located below the specified reference elevation will have a negative gravitational potential. Although the choice of reference elevation is arbitrary, it must be kept constant during any set of calculations. The difference in gravitational potential from place to place in the soil-plant system is what is important rather than the absolute value of gravitational potential. If the reference elevation is kept constant, then differences in gravitational potential will remain constant, regardless of the specific reference elevation chosen.

7.4.4. Pressure potential

The change in water potential caused by the external application of pressure or suction to the soil water is called the pressure potential component of the soil water potential. The constraint that the pressure must be applied externally distinguishes pressure potential from the tension applied in the development of the matric potential. The pressures exerted on the soil water can come from several sources, but the primary source considered is ponded water or hydrostatic pressure. Water is often ponded on the soil surface during irrigation or heavy rains. This standing water exerts a positive pressure on the water in the soil. In laboratory experiments a negative pressure or suction may be applied to the soil, but this rarely happens in the field. When there is no standing water on a soil, the external pressure applied to the soil is limited to the pressure of the atmosphere. Therefore, the applied pressure is atmospheric pressure. This is the pressure condition specified in the reference state for soil water potential, so without water ponding the pressure potential is zero. When water is ponded on a soil the applied pressure is increased by the weight of the ponded water. This increase in applied pressure increases the potential energy of the water in the soil so the pressure potential component of water potential is positive.

7.5. Water movement in the soil

Soil intake/water infiltration is the process of water entering the soil at the soil/air interface. Water enters the soil through pores, cracks, worm and decayed root holes, and through cavities introduced by tillage. Infiltrated water may evaporate again from the soil surface, may be transpired by the plants or may percolate downward beyond the plant roots and contribute to groundwater.

Water applied to the soil (by rain or irrigation) infiltrates the soil. If the rate of application exceeds the infiltration rate, water will be ponding on the surface or moving over the surface through runoff. The infiltration rate determines the amount of water entering the soil and amount that will subsequently be stored in the root zone.

7.5.1. Infiltration

The following factors affect the infiltration (see also Table 53):

Soil water content: In dry soils, large differences in matric potential drive water into the soil profile and soil is able to store more water than if the soil were initially wet. The surface soil will gradually become saturated as irrigation or rainfall continues and the intake rate decreases to the steady infiltration rate, whether the soil was initially dry or wet (see Module 7 for more information on infiltration rates).

Soil sealing: Formation of a thin compact layer on the soil surface rapidly reduces the rate of water entry through the surface. This layer results from a breakdown in soil structure that is caused by the beating action of raindrops or drops from sprinkler systems and by the action of water flowing over the soil surface. Light cultivation before irrigation can help to break the seal and increase infiltration. Sealing can be prevented by protecting the soil surface with a mulch. Grasses or canopies that fully cover the ground, intercept droplets, dissipate their energy and reduce sealing.

Compaction: Tillage operations may cause compaction and formation of plough pans below cultivation depths if they are done when soils are too wet. Hardpans impede water movement and reduce the infiltration rate. Deep ploughing or sub-soiling helps to improve the water movement. Tillage will only temporarily increase the infiltration rate.

Organic matter: Soil organic matter is the organic fraction of the soil. It includes plant and animal residues at various stages of decomposition and cells and tissues of soil organisms. Organic matter directly influences soil structure, soil condition, soil bulk density, water infiltration, plant growth and root development, permeability, available water capacity, biological activity, oxygen availability, nutrient availability, workability, as well as many other factors that make soil a healthy natural resource for plant growth. Organic matter has a high cation exchange capacity and during its decomposition nitrogen, phosphorous and sulphur are released. Site-specific values should always be used for planning and managing irrigation systems, because site management has a direct influence on organic matter content. Porosity remains high for long periods when organic material is made available by the incorporation of crop residues. The organic matter will also help stabilize the soil aggregates.

Salinity: When salts accumulate in the soil, they will affect and deteriorate some soil properties. Leaching the salts out of the soil profile will help to maintain the soil structure and infiltration rate.

Soil cracking: Infiltration rates change during the time water is applied, typically becoming slower with elapsed time. If infield farming operations are done at higher soil water content levels, infiltration will tend to decrease as the season progresses. Preferential flow paths, such as cracks and worm-holes, influence infiltration and permeability. Water quality, for example suspended sediment, sodicity and SAR, will affect infiltration because they affect the water surface tension.

Soil depth: Soil depth is the distance from soil surface to: a bedrock, a hardpan, a water table, a specific soil depth, or to a root growth restrictive layer. The deeper the soil and the plant roots, the more soil water storage is available for plant use. Crop rooting depth and the resulting total amount of water available to the plant control the length of time plants can go between irrigation or effective rainfall events before suffering from moisture stress. Providing artificial drainage of poorly drained soils increases soil depth for potential root development. Adequate soil drainage must be present for sustained growth of most plants. An abrupt change in soil texture with depth can restrict downward water movement. For example, coarse sand underlying a medium or fine textured soil requires saturation at the interface before substantial water will move into the coarser soil below. When a coarse-textured soil abruptly changes to a medium or fine textured soil with depth, a temporary perched water table develops above the soil with lower permeability. Stratified soils or shallow soils over hard pans or bedrock can also hold excess gravitational water at the interface. The excess water can move upwards because of the increased soil particle surface tension (suction) as plants use the soil water in the upper profiles.

Water table: Water tables can be a barrier to root development because of restricted oxygen supply. Through planned water table management, shallow groundwater can supply all or part of the seasonal crop water needs. The water must be of high quality, salt free and held at or near constant elevation. The water table should be controlled to provide water according to crop needs.

Slope: Slope, or field gradient, is the inclination of the soil surface from the horizontal, expressed as a percentage. For example, 2% slope means a 2 m rise or fall in 100 m horizontal distance. In planning irrigation systems, slope is important in determining the type of irrigation system best suited for the site. It is important in determining optimum and maximum water application rates (or stream flows). Erosion potential from excessive surface irrigation flows increases as the slope and slope length increase. Potential runoff from sprinkler systems also increases as the slope increases, thus raising the opportunity for erosion to occur. To avoid runoff from sprinklers, correction factors to infiltration rate for different slopes are introduced during the design process (Module 8).

Soil erodability: The erodability of a soil should be considered in the planning stage of any irrigation system. The rate and method at which water is applied should be controlled so that it will not cause excessive runoff and erosion. Factors influencing soil erosion, such as stream size for surface systems, surface storage because of residue, micro-basins and vegetative cover, are not related to soil properties. The erodability hazard for surface irrigation mainly takes into account the following soil factors: soil structure, permeability, percent organic matter, percent silt and very fine sand, and field slope.

7.5.2. Deep percolation and surface runoff

Deep percolation is the amount of water that penetrates beyond the depth of the root zone, where it is no longer available to a growing crop. Percolation rate is determined by the permeability of the soil or its hydraulic conductivity. Both these terms describe the ease with which soil transmits water.

Water percolates mainly through large pores in a soil, therefore percolation depends on the relative number and continuity of these pores. Soils with high porosity and coarse open texture have high hydraulic conductivity. For two soils with the same total porosity, the soil with small pores has lower conductivity than the soil with large pores, because resistance to flow is greater in small pores. Soils with pores of many sizes conduct water faster if large pores form continuous paths through the profile.

Surface runoff occurs when the water that has not penetrated the soil runs off and thus is also no longer available to the growing crop.

7.5.3. Depletion

Soil water can be depleted through evapotranspiration. The evapotranspiration will depend upon the availability of the soil water (see Section 4.8.2). Although water is theoretically

Table 53
Factors affecting the infiltration rate (Source: USDA, 1997)

Modifying factors	Increase in infiltration rate	Decrease in infiltration rate
Initial water content	Low initial water content	High initial content
Surface crusting		Surface sealing
Compaction		Compaction results in higher density with less pore to space hold water
Organic content	High organic content improves soil structure and promotes good soil condition	Low organic content provides for a more massive soil structure
Vegetative cover	Root penetration promotes improved soil structure and lower soil density. Worm activity increases, providing macropores for water to follow	Bare soil tends to puddle under sprinkler systems using large droplet sizes increasing soil density at the soil surface
Salinity and sodicity	Calcium salts can flocculate the surface	Sodium salts can disperse and puddle the soil
Cracking	Cracking increases initial intake. Intake rate can be high until cracks close because of added moisture causing soil particles to swell.	On highly expansive soils, intake rate can be very slow after cracks close because the soil particles swell
Hardpan		A very dense layer
Gravel or coarse sand layer, near surface		The soil layer above an abrupt boundary of coarse material must be saturated before water will move into the coarse material below
Ripping, sub-soiling	Ripping when soil is dry can break up hardpans, shatter dense soils, and in general improve the soil condition below the plough depth. The effect is temporary unless the cause of increased density is eliminated	
Soil erosion		Erosion exposes subsurface layers that are lower in organic content, have poor structure, can have increased salinity or sodicity and generally have higher densities
Sediments in water		Colloidal clays and fine sediment can irrigation accumulate on the soil surface

available until wilting point, crop water uptake is reduced well before wilting point is reached. When the soil is sufficiently wet, the soil supplies water fast enough to meet the atmospheric demand of the crop, and water uptake equals ET_c. As the soil water content decreases, water becomes more strongly bound to the soil matrix and is more difficult to extract. When the soil water content drops below a threshold value, soil water can no longer be transported quickly enough towards the roots to respond to transpiration demand and the root begins to experience stress (FAO, 1998a). The fraction of the total available moisture (SM_{ta}) that a crop can extract from the root zone without suffering water stress is the readily available moisture (SM_{ra}):

Equation 26

$$SM_{ra} = P \times SM_{ta}$$

Where:

SM_{ra}	=	Readily available soil moisture
P	=	Allowable depletion or average fraction of the total available soil moisture that can be depleted before moisture stress (reduction in ET_c) occurs
SM_{ta}	=	Total available soil moisture
	=	FC - PWP

According to Hansen and Israelsen (1967), maximum production can be obtained on most crops if not more than 50% of the available soil moisture (= FC-PWP) is removed from the soil during the vegetative, flowering and wet fruit stage. This rule of irrigation at 50% depletion is generally used in the region.

However, according to FAO (1984), with a ET_c that does not exceed 5 mm/day evapotranspiration of most field crops will not be affected or likely to be little affected at soil tension of up to 1 atmosphere. This would correspond to 30% of available soil moisture (by volume) for clay, 40% for loam, 50% for sandy loam and 60% for loamy sand. In other words, in order to maintain the ET_c for optimum growth and yield, the depletion should not exceed the above values when $ET_c < 5$ mm/day.

On the subject of depletion, irrigation practices should also be brought into the picture. Under surface irrigation, in particular borderstrip and basin irrigation, a situation of saturated flow in the whole area takes place, and for a while (until FC is approaching) root aeration is in short supply. To compensate for this, higher depletions are usually allowed. For furrow irrigation, however, since the saturated flow is only in part of the soil, lower depletions can be used as exchange of gases is easier. Under sprinkler irrigation, because of the intermittent water supply to the soil, a non-saturated flow of oxygenated water prevails. Therefore, there is a tendency to use lower depletions. The system, however, that provides the ideal conditions for very low depletions is localized irrigation. It combines the limited area of wetting with the unsaturated flow (see Module 9). A lot of research work has demonstrated that when this system is combined with very low depletions (0.15-0.20 atmosphere soil tension) high yields are obtainable.

Another element that makes depletion more intricate is the type of crop. While for some crops low depletions are necessary, other crops can take higher depletions (Table 54). Because of inconclusive results as indicated above, it is recommended to use the fractions of available soil water shown in Table 54. It should be noted, however, that for the lower fractions (meaning a lower allowable portion of available moisture permitted for depletion by the crop before the next irrigation) especially careful water management is needed.

7.6. Effective root zone depth

In addition to crop water and irrigation requirements (described in Chapters 4-6) and soil, the root zone depth is the third parameter to be considered when preparing irrigation schedules. While examples using root zone depth have already been given in the previous chapters, this chapter looks into the issue more in detail.

Like allowable soil moisture depletion, the root zone depth is another area of interesting controversies. Published data on the depth from where the crops extract most of their water differ greatly. As a rule, for most field crops 40% of the water uptake takes place from the first quarter of the total rooting depth, 30% from the second quarter, 20% from the third quarter and 10% from the fourth quarter (Figure 28). According to FAO (1984), ET_c is not affected even when rooting depth is severely restricted, as long as plants are sufficiently anchored and proper growing conditions, including available water, nutrients, soil aeration, soil temperature and soil structure, prevail. Table 54 provides data on root zone depth and allowable soil moisture depletion levels for different crops.

Figure 28

Average water extraction patterns in a soil without restrictive layers (Source: USDA, 1997)

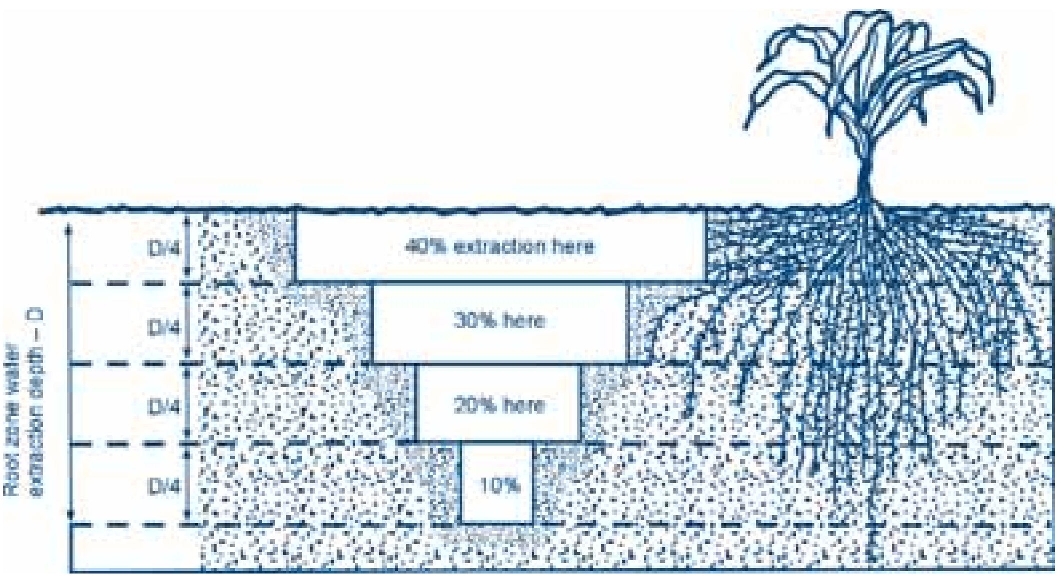


Table 54

Ranges of maximum effective root zone depth (RZD) and allowable soil water depletion fraction (P) for no stress, for common crops (Source: FAO, 1998a)

Crop		Root zone depth (RZD)[1] (m)	Allowable soil moisture depletion (P)[2]
a. Small vegetables			
Broccoli		0.4-0.6	0.45
Brussels sprouts		0.4-0.6	0.45
Cabbages		0.5-0.8	0.45
Carrots		0.5-1.0	0.35
Cauliflowers		0.4-0.7	0.45
Celery		0.3-0.5	0.20
Garlic		0.3-0.5	0.30
Lettuce		0.3-0.5	0.30
Onions	– dry	0.3-0.6	0.30
	– green	0.3-0.6	0.35
	– seed	0.3-0.6	0.35
Spinach		0.3-0.5	0.20
Radishes		0.3-0.5	0.30
b. Vegetables – Solanum Family (*Solanacea*)			
Eggplant		0.7-1.2	0.45
Sweet peppers (bell)		0.5-1.0	0.30
Tomatoes		0.7-1.5	0.40
c. Vegetables – Cucumber Family (*Cucurbitaceae*)			
Cantaloupes		0.9-1.5	0.45
Cucumbers	– fresh market	0.7-1.2	0.50
	– machine harvest	0.7-1.2	0.50
Pumpkin, winter squash		1.0-1.5	0.35
Squash, zucchini		0.6-1.0	0.50
Sweet melon		0.8-1.5	0.40
Watermelon		0.8-1.5	0.40
d. Roots and tubers			
Beet, table		0.6-1.0	0.50
Cassava	– year 1	0.5-0.8	0.35
	– year 2	0.7-1.0	0.40
Parsnips		0.5-1.0	0.40
Potatoes		0.4-0.6	0.35
Sweet potatoes		1.0-1.5	0.65
Turnips (and Rutabaga)		0.5-1.0	0.50
Sugar beet		0.7-1.2	0.553
e. Legumes (*Leguminosae*)			
Beans, green		0.5-0.7	0.45
Beans, dry and pulses		0.6-0.9	0.45
Beans, lima, large vines		0.8-1.2	0.45
Chick peas		0.6-1.0	0.50
Fababeans (broad bean)	– fresh	0.5-0.7	0.45
	– dry/seed	0.5-0.7	0.45
Garbanzo		0.6-1.0	0.45
Green gram and cowpeas		0.6-1.0	0.45
Groundnuts (peanuts)		0.5-1.0	0.50
Lentil		0.6-0.8	0.50
Peas	– fresh	0.6-1.0	0.35
	– dry/seed	0.6-1.0	0.40
Soybeans		0.6-1.3	0.50

Crop		Root zone depth (RZD)[1] (m)	Allowable soil moisture depletion (P)[2]
f. Perennial vegetables (with winter dormancy and initially bare or mulched soil)			
Artichokes		0.6-0.9	0.45
Asparagus		1.2-1.8	0.45
Mint		0.4-0.8	0.40
Strawberries		0.2-0.3	0.20
g. Fibre crops			
Cotton		1.0-1.7	0.65
Flax		1.0-1.5	0.50
Sisal		0.5-1.0	0.80
h. Oil crops			
Castorbeans (Ricinus)		1.0-2.0	0.50
Rapeseed, Canola		1.0-1.5	0.60
Safflower		1.0-2.0	0.60
Sesame		1.0-1.5	0.60
Sunflower		0.8-1.5	0.45
i. Cereals			
Barley		1.0-1.5	0.55
Oats		1.0-1.5	0.55
Spring wheat		1.0-1.5	0.55
Winter wheat		1.5-1.8	0.55
Maize, field (grain) (field corn)		1.0-1.7	0.55
Maize, sweet (sweet corn)		0.8-1.2	0.50
Millet		1.0-2.0	0.55
Sorghum	– grain	1.0-2.0	0.55
	– sweet	1.0-2.0	0.50
Rice		0.5-1.0	0.204
j. Forage			
Alfalfa	– for hay	1.0-2.0	0.55
	– for seed	1.0-3.0	0.60
Bermuda	– for hay	1.0-1.5	0.55
	– spring crop for seed	1.0-1.5	0.60
Clover hay, berseem		0.6-0.9	0.50
Rye grass hay		0.6-1.0	0.60
Sudan grass hay (annual)		1.0-1.5	0.55
Grazing pasture	– rotated grazing	0.5-1.5	0.60
	– extensive grazing	0.5-1.5	0.60
Turf grass	– cool season[5]	0.5-1.0	0.40
	– warm season[5]	0.5-1.0	0.50
k. Sugarcane		1.2-2.0	0.65
l. Tropical fruits and trees			
Bananas	– 1st year	0.5-0.9	0.35
	– 2nd year	0.5-0.9	0.35
Cacao		0.7-1.0	0.30
Coffee		0.9-1.5	0.40
Date palm		1.5-2.5	0.50
Palm tree		0.7-1.1	0.65
Pineapples		0.3-0.6	0.50
Rubber tree		1.0-1.5	0.40
Tea	– non-shaded	0.9-1.5	0.40
	– shaded	0.9-1.5	0.45
m. Grapes and berries			
Berries (bush)		0.6-1.2	0.50
Grapes	– table or raisin	1.0-2.0	0.35
	– wine	1.0-2.0	0.45

Crop		Root zone depth (RZD)[1] (m)	Allowable soil moisture depletion (P)[2]
Hops		1.0-1.2	0.50
n. Fruit trees			
Almond		1.0-2.0	0.40
Apple, cherry, pear		1.0-2.0	0.50
Apricot, peach, other stone fruit		1.0-2.0	0.50
Avocado		0.5-1.0	0.70
Citrus	– 70% canopy	1.2-1.5	0.50
	– 50% canopy	1.1-1.5	0.50
	– 20% canopy	0.8-1.1	0.50
Conifer tree		1.0-1.5	0.70
Kiwi		0.7-1.3	0.35
Olive (40-60% ground coverage by canopy)		1.2-1.7	0.65
Pistachio		1.0-1.5	0.40
Walnut orchard		1.7-2.4	0.50

1 The larger values for RZD are for soils having no significant layering or other characteristics that can restrict rooting depth. The smaller values for RZD may be used for irrigation scheduling and the larger values for modelling soil water stress or for rainfed conditions.

2 The values for P apply for $ET_c \approx 5$ mm/day. The value for P can be adjusted for different ET_c according to $P = P_{table\ 54} + 0.04 \times (5 - ET_c)$.

3 Sugar beet often experience late afternoon wilting in arid climates, even at P < 0.55, with usually only minor impact on sugar yield.

4 The value for P for rice is 0.20 of saturation.

5 Cool season grass varieties include Bluegrass, Ryegrass and Fescue. Warm season varieties include Bermuda grass, Buffalo grass and St. Augustine grass. Grasses are variable in rooting depth. Some root below 1.2 m while others have shallow rooting depths. The deeper rooting depths for grasses represent conditions where careful water management is practiced with higher depletion between irrigations to encourage the deeper root exploration.

While for surface irrigation systems there is a tendency to accept deeper root zone depths in selecting root zone depths for pressurized systems, the decision is based on the majority of feeder roots. Through this approach, water-soluble nutrients such as nitrogen are directed to the majority of feeder roots instead of being leached to depths of smaller concentration of roots. Rainbird International provides the guide for plant feeder root depths (effective root zone depth) as indicated in Table 55.

Knowing the crop water requirements, the type of soil and the root zone depth, the readily-available moisture for the crop can be calculated, which is the amount of water that can be extracted by the crop in the root zone without suffering water stress.

Table 55

Plant feeder root depths (effective root zone depth) (RZD) (Source: Rainbird International)

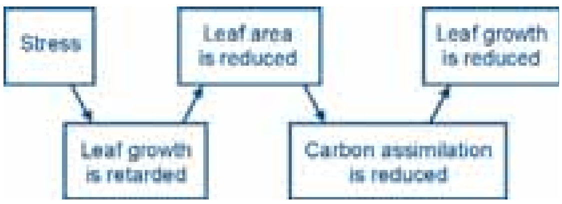
Crop	RZD (mm)	Crop	RZD (mm)	Crop	RZD (mm)
Alfalfa	90-180	Grains	60-75	Strawberries	30-45
Bananas	50	Sorghum	75	Sugarcane	150
Beans	60	Nuts	90-180	Sweet potatoes	90
Beet	60-90	Onions	45	Tobacco	75
Cabbages	45-60	Groundnuts	45	Tomatoes	30-60
Carrots	45-60	Peas	75	Pasture (grass)	45
Cassava	50	Potatoes	60	Pasture (clover)	60
Maize	75	Safflower	150	Citrus, peaches, pears, etc.	90-150
Cotton	125	Soybeans	60		

Chapter 8

Yield response to water

When water supply does not meet the crop water requirements, the ET_c will decrease. Under this condition, water stress will develop in the plant, which will adversely affect crop growth and, ultimately, crop yield. The effect of water stress and crop growth and yield depends on the crop species and variety on one hand and the magnitude and the time of occurrence of water deficit on the other. The effect of the magnitude and the timing of water deficit on crop growth and yield is of major importance in scheduling available but limited water supply over growing periods of the crops, and in determining the priority of water supply amongst crops during the growing season (FAO, 1986).

The most common effect of water stress is a decreased rate of growth and development of foliage. This has a cumulative effect through the season as plant stress early in crop development results in a reduced leaf area. This means that light interception is reduced, carbon assimilation is reduced and therefore the rate of leaf growth is reduced.



Water stress also affects the quality of the produce. Freedom from water stress encourages production of fresh, crisp foliage. In some crops this is desirable (for example lettuce). Crops suffering from intermittent stress tend to be irregular in shape, carrots have forked roots, tomatoes have split skins, and may therefore fetch a lower price at the market. Certain crops, however, need to be stressed at certain times to encourage flowering for example. While water stress may negatively affect the crop, there are also negative effects of over-watering. Over-watered root crops tend to be bland in flavour.

8.1. Critical growth periods

When water deficit occurs during a particular part of the total growing period of a crop, the yield response to water deficit can vary greatly depending on how sensitive the crop is at that growth stage. In general, crops are more sensitive to water deficit during emergence, flowering and early yield formation than they are during early (vegetative, after establishment) and late growth stages (ripening). Local knowledge is valuable in determining critical growth periods for crops. Table 56 shows the critical periods related to moisture stress for several crops grown in Zimbabwe.

8.2. Estimating yield reduction due to water stress

A simple, linear crop-water production function was introduced in FAO (1986) to predict the reduction in crop yield when crop stress was caused by a shortage of soil water:

Equation 27

$$\left[1 - \frac{Y_a}{Y_m}\right] = K_y \times \left[1 - \frac{ET_{c\ adj}}{ET_c}\right]$$

Where K_y relates relative yield decrease $\left[1 - \frac{Y_a}{Y_m}\right]$

to relative evapotranspiration deficit $\left[1 - \frac{ET_{c\ adj}}{ET_c}\right]$

K_y	=	Yield response factor
Y_a	=	Actual crop yield
Y_m	=	Maximum crop yield when there is no water stress and $ET_{c\ adj} = ET_c$
ET_c	=	Crop evapotranspiration for standard conditions (see Section 1.3.2)
$ET_{c\ adj}$	=	Adjusted (actual) crop evapotranspiration (see Section 1.3.3)

K_y values are crop specific and may vary over the growing season. In general, the decrease in yield due to water deficit during the vegetative and ripening period is relatively small, while during the flowering and yield formation periods it will be large. Table 57 gives values of the yield response factor K_y for different crops and different growth stages. K_y values can also be obtained from field experimental data. In the final evaluation of K_y values, use is also made of known yield responses to soil salinity, the depth of the groundwater table and agronomic and irrigation practices.

Table 56

Critical periods for plant moisture stress (Source: USDA, 1997)

Crop	Critical period	Comments
Beans, dry	Flowering through pod formation	Is also sensitive to over-irrigation
Beans, green	Blossom through harvest	
Broccoli	During head formation and enlargement	
Cabbages	During head formation and enlargement	
Cauliflowers	During entire growing season	
Citrus	During entire growing season	Blossom and next season fruit set occurs during harvest of the previous crop
Maize (grain)	From tasseling through silk stage and until kernels become firm	Needs adequate moisture from germination to dent stage for maximum production. During ripening, depletion of 80% or more can be allowed
Cotton	First blossom through boll maturing stage	Any moisture stress, even temporary, ceases blossom formation and boll set for at least 15 days after moisture again becomes available
Fruit trees	During the initiation and early development period of flower buds, the flowering and fruit setting period (maybe the previous year), the fruit growing and enlarging period, and the pre-harvest period	Stone fruits are especially sensitive to moisture stress during last 2 weeks before harvest
Wheat and barley	During boot, bloom, milk stage, early head development and early ripening stages	Critical period for barley is at soft dough stage to maintain a quality kernel
Groundnuts	Throughout season	
Lettuce	Head enlargement to harvest	Water shortage results in sour and strong lettuce. Crop quality at harvest is controlled by water availability to the plant. Recommended allowable depletion P is < 30%
Watermelons	Blossom through harvest	
Onions, dry	During bulb formation	Maintain P at 30-35%. Let soil dry near harvest
Onions, green	Blossom through harvest	Strong and hot onions can result from moisture stress
Peas, dry	At start of flowering until pods are swelling	
Peas, green	Blossom through harvest	
Potatoes	Flowering and tuber formation to harvest	Sensitive to irrigation scheduling. Restrict P to 30-35%. Low quality tubers result if allowed to go into moisture moisture stress during tuber development and growth
Soybeans	Flowering and fruiting stage	
Sugarcane	During period of maximum vegetative growth	
Tobacco	Knee high to blossom	
Tomatoes	When flowers are forming, fruit is setting and fruits are rapidly enlarging	
Vine crops	Blossom through harvest	

Table 57

Yield response factor K_y (Source: FAO, 1986)

Crop		Vegetative period: Early	Vegetative period: Late	Vegetative period: Total	Flowering period	Yield formation	Ripening	Total growing period
Alfalfa				0.7-1.1				0.7-1.1
Bananas								1.2-1.35
Beans				0.2	1.1	0.75	0.2	1.15
Cabbages		0.2				0.45	0.6	0.95
Citrus								0.8-1.1
Cotton				0.2	0.5		0.25	0.85
Grapes								0.85
Groundnuts				0.2	0.8	0.6	0.2	0.7
Maize				0.4	1.5	0.5	0.2	1.25
Onions				0.45		0.8	0.3	1.1
Peas		0.2			0.9	0.7	0.2	1.15
Peppers								1.1
Potatoes		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
Soybeans				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		0.2	1.0					0.9
Tomatoes				0.4	1.1	0.8	0.4	1.05
Watermelons		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

In general, for the total growth period (last column in Table 57), the decrease in yield is proportionally less with the increase in water deficit ($K_y < 1$) for crops such as alfalfa, groundnuts, safflower and sugarbeet, while it is proportionally greater ($K_y > 1$) for crops such as bananas, maize and sugarcane.

Application of the yield response factor for planning, design and operation purposes allows the quantification of water supply and water use in terms of crop, yield and total production for the scheme. Both the likely losses in yield and the adjustments required in water supply to minimize such losses can be quantified (FAO, 1986). Similarly, such quantification is possible when the likely yield losses arise from differences in the K_y of individual growth periods.

Under conditions of limited water distributed equally over the growing season and involving crops with different K_y values, the crop with the higher K_y value will suffer a greater yield loss than the crop with a lower K_y value. For example, the yield decrease for maize ($K_y = 1.25$) will be greater than for sorghum ($K_y = 0.9$). Similarly, the yield response to water deficit in different individual growth periods is of major importance in the scheduling of available but limited supply in order to obtain highest yields.

Example 11

Consider the green maize grown close to Mahalapye climatic station in Botswana (Chapter 6) with general crop data as given in Table 46 and a water requirement of 820 mm. What is the yield reduction, if:

1. *The water supply is 10% less than the total water requirements with the deficit equally spread over the total growing period (150 days)?*
2. *The water supply during the crop development stage in the month of September is 30% less than the water requirements of that month?*

Month	Aug	Sep	Oct	Nov	Dec	Total
Growth period (days)	31	30	31	30	28	150
Water requirement (mm)	100	160	270	220	70	820
K_y	0.4	1.1	1.1-0.8	0.8	0.4	1.05

1. If the water supply is 10% less than the total water requirement of 820, this means a deficit of 82 mm.

$$\left[1 - \frac{ET_{c\ adj}}{ET_c}\right] = \left[1 - \frac{820 - 82}{820}\right] = 0.01$$

$$\left[1 - \frac{Y_a}{Y_m}\right] = K_y \times \left[1 - \frac{ET_{c\ adj}}{ET_c}\right] = 1.05 \times 0.1 = 0.105 \Rightarrow \text{the yield reduction is 10.5\%}$$

This means that the actual yield Y_a is 100-10.5 = 89.5% of maximum crop yield Y_m.

2. If the water supply is 30% less than the total water requirement of 160 mm for the month of September, this means a deficit of 48 mm in that month.

$$\left[1 - \frac{ET_{c\ adj}}{ET_c}\right] = \left[1 - \frac{150 - 48}{150}\right] = 0.3$$

$$\left[1 - \frac{Y_a}{Y_m}\right] = K_y \times \left[1 - \frac{ET_{c\ adj}}{ET_c}\right] = 1.1 \times 0.3 = 0.33 \Rightarrow \text{The yield reduction is 33\%}$$

This means that the actual yield Y_a is 100 – 33 = 67% of the maximum yield Y_m.

Chapter 9
Irrigation scheduling

Once the three parameters (daily water requirements, available soil moisture and effective root zone depth) are known, an irrigation schedule can be established. While estimated values of ET_c, based on climatic data, are sufficient for planning and designing purposes, for more accurate scheduling more accurate field data are necessary. These can be obtained by the use of Class A pans and/or tensiometers. This, however, requires proper recording and some management skills, since timing of the different irrigations will depend on the day to day variability of climatic factors. Farmers should be advised as to when irrigation will take place. If no class A pan or tensiometers are available, the crop water and irrigation requirement calculations as described in Chapters 4-6 can be used as a guideline for irrigation scheduling. Section 9.1 describes the irrigation scheduling based on measurements of daily crop water use using the Class A pan and tensiometers. Section 9.2 describes the manual and computerized irrigation scheduling based on crop water requirements. Section 9.3 presents some possible variations in irrigation scheduling.

9.1. Irrigation scheduling based on measurement of daily crop water use

9.1.1. The use of the Class A pan for irrigation scheduling

The principles of the Class A pan were explained in Section 2.2. In order to be able to use the data, the ratios of ET_c/E_{pan} for different crops at different growing stages and in different areas have to be established through research. Then, by measuring the daily evaporation (E_{pan}), the ET_c can be calculated so that the farmer will know within how many days the allowable soil moisture depletion will be reached. As an example, in Zimbabwe researchers have established the ET_c/E_{pan} correction factors for major crops, such as cotton, groundnuts, maize, soybeans, wheat and tobacco, and they are presented in Tables 58.

Table 58

ET_c/E_{pan} ratios for different crops and varying season lengths in different agro-ecological regions in Zimbabwe (Source: Metelerkamp, 1968)

Weeks after planting[a]	Season length (weeks)						
	16	18	20	22	24	26	28
	ET_c/E_{pan} ratio for cotton and Lowveld wheat (mean ET_c/E_{pan} ratio of 0.7)						
1	0.24	0.24	0.23	0.23	0.23	0.23	0.23
2	0.27	0.27	0.26	0.26	0.25	0.25	0.24
3	0.30	0.29	0.29	0.28	0.27	0.27	0.26
4	0.37	0.35	0.33	0.30	0.29	0.29	0.27
5	0.45	0.44	0.40	0.34	0.33	0.31	0.29
6	0.58	0.57	0.48	0.44	0.40	0.36	0.32
7	0.70	0.68	0.58	0.55	0.47	0.42	0.35
8	0.82	0.77	0.66	0.65	0.55	0.48	0.42
9	0.90	0.84	0.75	0.72	0.64	0.57	0.49
10	0.94	0.90	0.82	0.79	0.70	0.65	0.58
11	0.97	0.94	0.88	0.85	0.77	0.73	0.67
12	0.97	0.97	0.93	0.89	0.83	0.79	0.75
13	0.96	0.97	0.96	0.93	0.87	0.84	0.81
14	0.94	0.96	0.97	0.95	0.92	0.88	0.86
15	0.91	0.94	0.97	0.97	0.94	0.91	0.90
16	0.87	0.91	0.95	0.97	0.96	0.94	0.93
17		0.87	0.93	0.96	0.96	0.95	0.94
18		0.81	0.90	0.94	0.97	0.96	0.95
19			0.87	0.92	0.97	0.97	0.96
20			0.82	0.89	0.96	0.96	0.97

Weeks after planting[a]	Season length (weeks)						
	16	18	20	22	24	26	28
	ET_c/E_{pan} ratio for cotton and Lowveld wheat (mean ET_c/E_{pan} ratio of 0.7)						
21				0.85	0.94	0.95	0.97
22				0.80	0.92	0.94	0.96
23					0.88	0.92	0.95
24					0.81	0.90	0.94
25						0.86	0.92
26						0.82	0.90
27							0.87
28							0.82

Weeks after planting[a]	Season length (weeks)						
	16	18	20	22	24	26	28
	ET_c/E_{pan} ratio for groundnuts (mean ET_c/E_{pan} ratio of 0.8)						
1	0.23	0.23	0.23	0.23	0.23	0.23	0.23
2	0.27	0.26	0.25	0.25	0.24	0.24	0.23
3	0.30	0.28	0.27	0.26	0.25	0.25	0.24
4	0.43	0.38	0.35	0.31	0.30	0.29	0.26
5	0.63	0.57	0.49	0.41	0.40	0.35	0.30
6	0.80	0.75	0.64	0.55	0.53	0.42	0.37
7	0.90	0.88	0.78	0.71	0.64	0.53	0.46
8	0.98	0.95	0.88	0.84	0.74	0.68	0.59
9	1.02	1.00	0.94	0.92	0.83	0.79	0.72
10	1.03	1.02	0.98	0.96	0.88	0.87	0.83
11	1.04	1.03	1.02	0.99	0.93	0.93	0.91
12	1.04	1.04	1.03	1.02	0.97	0.97	0.96
13	1.04	1.04	1.04	1.03	1.00	1.00	0.99
14	1.03	1.04	1.04	1.04	1.02	1.02	1.02
15	1.00	1.03	1.04	1.04	1.03	1.03	1.03
16	0.97	1.01	1.03	1.04	1.04	1.04	1.03
17		0.98	1.02	1.04	1.04	1.04	1.04
18		0.94	1.00	1.03	1.04	1.04	1.04
19			0.98	1.02	1.04	1.04	1.04
20			0.94	1.00	1.04	1.04	1.04
21				0.97	1.03	1.04	1.04
22				0.93	1.02	1.03	1.04
23					1.00	1.02	1.03
24					0.97	1.01	1.02
25						0.98	1.01
26						0.95	0.99
27							0.97
28							0.94

Weeks after planting[a]	Season length (weeks)				
	16	18	20	22	24
	ET_c/E_{pan} ratio for maize, soybeans and Highveld and Middleveld wheat (mean ET_c/E_{pan} ratio of 0.8)				
1	0.25	0.24	0.24	0.24	0.24
2	0.30	0.27	0.27	0.27	0.27
3	0.38	0.34	0.33	0.32	0.31
4	0.49	0.46	0.43	0.42	0.37
5	0.64	0.62	0.56	0.52	0.44
6	0.81	0.78	0.72	0.63	0.54
7	0.91	0.89	0.84	0.75	0.65
8	0.97	0.96	0.92	0.84	0.76
9	1.01	1.00	0.98	0.92	0.85
10	1.03	1.02	1.01	0.98	0.92
11	1.04	1.03	1.03	1.02	0.97
12	1.04	1.04	1.04	1.03	1.00

13	1.03	1.04	1.04	1.04	1.02
14	1.01	1.02	1.03	1.04	1.03
15	0.98	0.99	1.02	1.04	1.04
16	0.92	0.96	1.00	1.03	1.04
17		0.90	0.97	1.02	1.03
18		0.83	0.93	0.99	1.03
19			0.87	0.95	1.02
20			0.78	0.91	1.00
21				0.86	0.98
22				0.79	0.95
23					0.91
24					0.85

Weeks after planting[a]	Season length (weeks)	
	16	18
	ET_c/E_{pan} ratio for Virginia tobacco	
1	0.10	0.10
2	0.11	0.11
3	0.13	0.12
4	0.17	0.15
5	0.40	0.22
6	0.65	0.48
7	0.90	0.79
8	1.00	0.94
9	1.00	1.00
10	1.00	1.00
11	1.00	1.00
12	0.94	1.00
13	0.80	0.96
14	0.54	0.82
15	0.37	0.60
16		0.46
17		0.35
18		0.28

a One week after planting or (for tobacco) transplanting represents the first week of the season, two weeks after planting or transplanting represents the second week of the season, etc.

Recording of a Class A pan combined with a rain gauge

Two rulers are attached for the measurements. The zero point of the rulers is set at 50 mm from the top of the pan. One of the rulers is set for measurements from zero point to the bottom of the pan (ruler 1), the other from the zero point to the top of the pan (ruler 2).

Every morning, at 08.00 hours, the rulers are read after which the water level in the pan is brought to zero, either by adding water or by removing water after rain. For a day without rain, the water level in the pan will drop because of evaporation and ruler 1 will indicate the drop. During a rainy day with substantial rainfall, the level of the water will rise above zero point and this level can be read on ruler 2. Table 59 gives an example.

Table 59

Example of a Class A pan record keeping, which takes place at 08.00 hours just before bringing the water level to the zero point (readings in mm)

Date (1)	Ruler 1 (2)	Ruler 2 (3)	Rain gauge (4)	Evaporation (5)=(2)+(4) or (5)=(4)-(3)
01-03-2002	6	–	0	6
02-03-2002	4	–	2	6
03-03-2002	–	6	10	4
04-03-2002	–	20	24	4

Example 12

A short season variety of groundnut (16 weeks) is grown in Zimbabwe. The soil is a sandy loam with a water-holding capacity or total available moisture (SM_{ta}) of 100 mm/m. The allowable depletion P is 50%. The planting date is 5 October and a pre-irrigation wetted the first 30 cm of the soil. When should the first irrigation take place?

Assuming that the root zone depth during the first week will not exceed 10 cm or 0.10 m, the readily-available moisture SM_{ra} is:

SM_{ra} = 100 x 0.10 x 0.50 = 5 mm

The ET_c/E_{pan} ratio during the first week after planting is 0.23 for a groundnut crop with a season length of 16 weeks (Table 58).

Based on the readings of the Class A pan and the rain gauge, the daily and accumulated crop water requirements (in mm) are calculated as follows:

	Ruler 1	Ruler 2	Rain gauge	E_{pan}	ET_c/E_{pan}	Daily CWR	Accumulated CWR
6 October	7	–	0	7	0.23	1.61	1.61
7 October	7	–	0	7	0.23	1.61	3.22
8 October	8	–	0	8	0.23	1.84	5.06

From the above calculation it can be seen that on the third day after planting, the accumulated water requirement is 5.06 mm, depleting the 5 mm readily available soil moisture, thus irrigation should take place.

Irrigation scheduling using the Class A pan

Using the evaporation and rain gauge data as well as the ET_c/E_{pan} ratio from Table 58, the daily crop water requirements can be calculated. Then, if the amount of water available in the root zone depth and the allowable depletion are known, the time that irrigation is due can be calculated.

9.1.2. The use of tensiometers for irrigation scheduling

As explained in Section 7.3, water in the soil can be measured by measuring the soil water potential. A relationship exists between soil water content and matric potential, which is sometimes called the soil moisture retention curve and/or desorption curve. It describes the relationship between the volumetric water content (SM_v) and matric potential (y_m). For this, measuring the matric potential will give information on soil water content (see Section 7.3.1). This potential can be measured with a tensiometer. Tensiometers operate by allowing the soil solution to come into equilibrium with a reference pressure indicator through a permeable ceramic cup placed in contact with the soil. Their use is widespread in irrigation areas.

Description of a tensiometer

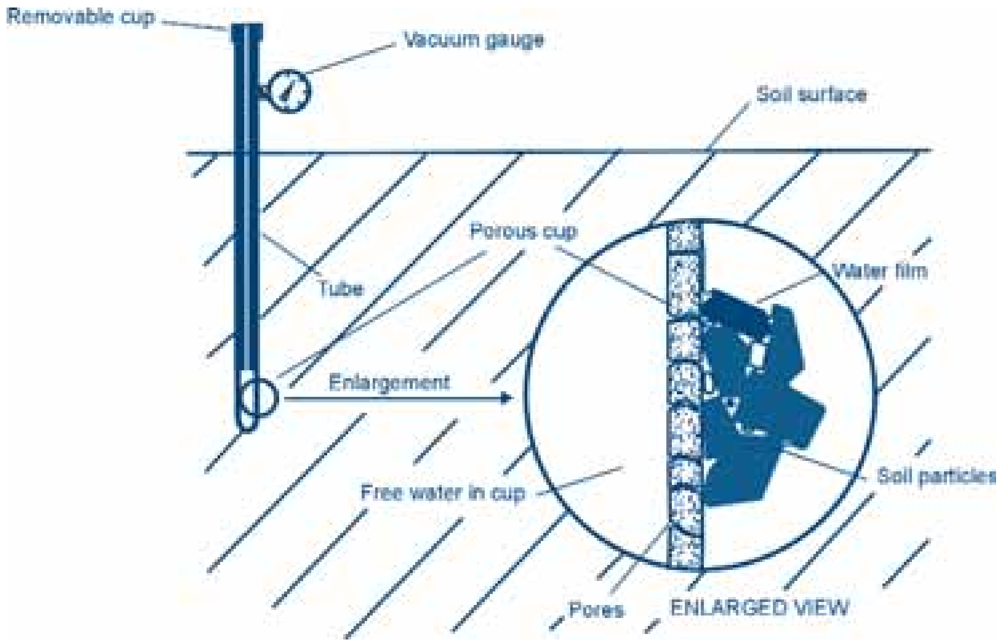
A tensiometer is a closed tube, filled with water. A ceramic cup is sealed to the bottom and a cap closes the other end (Figure 29).

The tube is installed with the ceramic tip placed where a soil water measurement is desired. As the soil dries, it sucks water out of the tensiometer through the porous wall of the ceramic tip, creating a partial vacuum inside the tensiometer that can be read on a vacuum gauge attached below the cap. This value is the matric potential of the soil, which is negative. This power of the soil (soil suction) to withdraw water from the tensiometer increases as the soil dries and the gauge reading rises. Water inside the tensiometer will flow to the soil until the matric potential of the soil surrounding the ceramic cup is in equilibrium with the tension inside the tensiometer. When the soil is irrigated, soil suction is reduced and water is drawn back into the tensiometer by the vacuum. This reduces the vacuum and the gauge reading is lowered. The tensiometer gives on-the-spot, continuous readings, indicating to the user the soil moisture status of the soil when needed.

The gauge of the tensiometer is calibrated in hundredths of a bar (or centibar) and is graduated from 0 to 100. This is equal to 0-100 kPa.

An advantage of the use of tensiometers is that they are not affected by the osmotic potential of the soil solution (the amount of salts dissolved in the soil water), as the salts can move into and out of the ceramic cup unhindered. This is not to say, however, that the plant does not feel the effect of the osmotic potential. Also, tensiometers measure the soil matric potential with good accuracy in the wet range and are suited to applications where water stress and irrigation needs have to be monitored. They are less subject to localized spatial variability than volumetric water content measurements (and are therefore less sensitive to soil disturbance during installation).

Figure 29
Details of the ceramic cup of a tensiometer



There are, however, also some limitations and disadvantages. The most important is its narrow measuring range between 0 (saturation) and a matric potential of about -0.8 bar or atmosphere, because cavitation causes the column of water to break by allowing air into the closed system. Thus, they cannot be used for measurements in the dry end of the spectrum. Also, skilled maintenance is needed to keep the tensiometers operational. Air leaks often occur, they are sensitive to temperature variations and the ceramic cup is sensitive and can easily clog when not stored properly. Tensiometers also give a point measurement and there is no model yet capable of integrating a larger soil volume such as is possible with some sensors. If the ceramic cup loses contact with the soil (in an air pocket created by manuring, for example), then this could cause an apparent 'lack of response' in the instrument. If the tip were in an area of limited root activity, the readings could also 'stall'. Tensiometers also have a slow reaction time.

Different types of tensiometers

Different types of tensiometers are available on the market. A distinction can be made between standard tensiometers and quick-draw tensiometers, the main difference being the response time and their use. The standard type is an instrument that will not be moved too often and that will give reliable readings 24 hours after installation (Figure 30). The depth to which this tensiometer can be used ranges from less than 30 cm to up to 120 cm. It can be installed for irrigation control purposes. The quick-draw type is portable and used when a fast response is wanted (Figure 31). In moist soils, one to two minutes are enough to get a reading, but, depending on the soil type, five to ten minutes will generally give a more reliable figure. This tensiometer is mostly used for measurements to a depth of up to 45 cm. It is handy for carring out sample checks at different places in the irrigated area. It is also a useful tool for extension people wanting to verify the irrigation performance of the different irrigation schemes in their area.

Figure 30
Standard tensiometers (Source: ELE, 2002)

Figure 31
Quick-draw portable tensiometer (Source: ELE, 2002)

Filling a tensiometer

Incorrect filling of the tensiometer is one of the major reasons for failure of operation. When filling the probe with water, air bubbles cling to the wall or dissolve into the water. Using the tensiometer without removing the air will create air leaks when a vacuum is created and the pointer of the gauge drops to zero.

For proper filling, take the following steps into consideration:

1. Saturate the porous tip with water by putting the lower part of the tensiometer in water for one day
2. Fill the probe with water. Pour slowly so that air bubbles are not trapped. If bubbles cling to the wall, nudge it free with a plastified metal wire
3. Close the instrument and let the porous tip air-dry till the gauge reads 45. By creating this under-pressure, air bubbles could have formed inside the probe. Unscrew the cap and remove possible bubbles. The pointer of the gauge reads again zero
4. Repeat step 3 several times until the response time is decreased and no air bubbles can be noticed anymore. The tensiometer is now ready for use.

The filling of the quick draw tensiometer is a little faster because of the smaller diameter of the probe and the use of a null knob (see manufacturers' operations instructions for details).

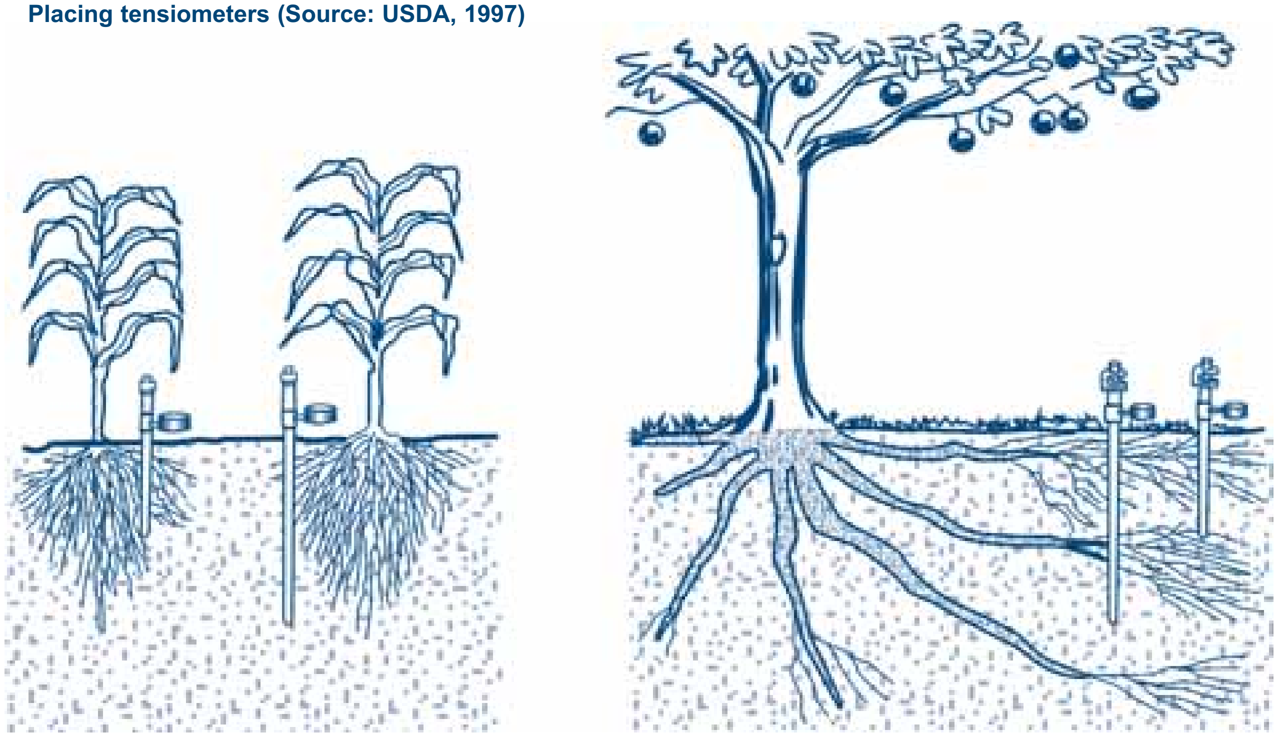
Placing the tensiometer

Install the tensiometer so that the tip is in the active root zone, in good contact with soil, and in a position where irrigation water is sure to wet the soil (Figure 32). Observe the active root zone concentration (normally at one third of the final rooting depth) and depth by digging near an adjacent plant, but not right where the tensiometer is to be installed. In new orchards, place the tip in the root ball since soil texture in the ball may differ from that in the field and water transfer could be impeded. After several weeks the tensiometer can be reinstalled near the drip line of the growing tree. Subsequent moves may occur annually during the rapid growth period, less frequently thereafter.

With furrow irrigation, place the instruments near enough to the furrow so that the water will be certain to reach them. With most row crops, tensiometers are placed in the plant row. With sprinkler irrigation, place the tensiometer where you can 'see' the sprinkler, that is where water from the sprinkler is not blocked by a post, tree trunk, branch, leaves, vines, etc. With drip irrigation, place them 30-45 cm away from an emitter.

For some crops, the instruments may be placed in critical or problem locations where one wants special knowledge of the soil water. These locations may be difficult to wet, may dry out quickly, or may remain excessively wet. Tensiometers are very useful for identifying and helping to solve irrigation or soil-water problems.

Figure 32
Placing tensiometers (Source: USDA, 1997)



Interpretation of readings

A zero reading (= zero soil suction) indicates that the soil is saturated. In this case, all of the soil pores are filled with water. A zero reading may also indicate that the instrument is out of order. Any zero reading 1-2 days after irrigation (surface and sprinkler irrigation systems) is an indication that the instrument should be checked. Under drip irrigation the tensiometer should never show zero.

In medium-textured soils most plants grow best where the soil suction readings are kept between 20 and 60 centibars. At this moisture level, there is good aeration as well as good movement of moisture. In sandy soils the optimum range is usually 10 to 30 centibars. In heavy clay soils, which can store greater amounts of water, maximum readings of 70 centibars may not be harmful to growing plants. The higher values in the ranges relate to approximately 50% depletion of the available moisture for these types of soils.

If soil suction values are allowed to reach 80 centibars, this can be detrimental to the plant, particularly for sandy and sandy loam soils. At this moisture level, the supply of water for the roots is becoming limited and the water films are becoming so thin that the soil moisture movement within the soil is very slow. This means that the moisture withdrawn by a root in a given area is not readily replaced. As a result, under conditions of bright sun and wind, destructive stress conditions can develop in the plant. It is best to keep soil suction values at a maximum of 40-50 centibars and to arrange irrigation so that a saturated condition (0 to 10 centibars of soil suction) is not created for any length of time in the feeder root zone. For those sandy soils that have extremely limited water storage capacity, irrigation is started at lower soil suction values, frequently in the range of 15 to 20 centibars. With drip irrigation systems, where the readings are made approximately 30-45 cm away from the emitter, soil suction should be maintained at a relatively low value, usually in the range from 10 to 25 centibars depending upon soil type.

Storing the tensiometer

The standard type of tensiometer needs special attention when it is not used for long periods in order to avoid clogging of the pores of the ceramic cup by algae or fungi. Water inside the probe should be drained out. The tip should be washed with a detergent using only a soft brush. Let the instrument dry in the air, wrap the porous tip in paper and store in a dry place. When using tensiometers, always avoid touching the ceramic tip with your hands as they will leave a greasy film, blocking the pores of the ceramic tip.

The quick-draw type of tensiometer is kept in a special holder where the porous tip is always immersed in a wet spongy material. It is enough to keep this sponge wet during storage.

Special care should be given to the ceramic cup as it cracks easily and such cracks are not always detected. Once cracked, no vacuum can be established and readings will be incorrect.

9.2. Irrigation scheduling based on crop water requirement calculation

Irrespectively of the mode (computerized or manual) to be adopted in preparing an irrigation schedule, the following parameters will be required:

- Cropping programme
- Daily water requirements of the different crops (ET_c) at the different stages of their growth
- Root zone depth at the different growth stages of each crop (RZD)
- Total available soil moisture (SM_{ta})
- Allowable soil moisture depletion level (P)
- On-site rainfall data

The cropping programme provides the different crops, their rotation and the time of planting and harvesting, as shown in Tables 32 and 33. The ET_c of each crop can be derived either by using CROPWAT, as explained in Chapter 6, or by using the iso-ET_o maps for each month and estimate the K_c values for each growth stage as explained in Chapter 3 and 4. The RZD of each crop at the different stages of growth can be derived preferably from local information or, in their absence, from Tables presented in Section 7.6. The SM_{ta} is usually determined through laboratory analysis during the soil surveys. As explained earlier, the level of P depends on the crop and its stage of growth as well as on the soil type and irrigation system. A rain gauge would also be required on site to record the daily rainfall received.

Irrigation frequency and duration have to be calculated for each crop of the existing cropping pattern (see Section 9.2.1) and a sound irrigation schedule has to be put together in order to irrigate all crops at the time and for the duration they require the water (see Sections 9.2.2-9.2.4).

Once the irrigation schedule is known, simplifications can be introduced in order to make the schedule practical and 'user-friendly' for the farmers, for example irrigation intervals and irrigation duration can be made uniform over a period of 14 days or a month. This is particularly important in smallholder irrigation schemes where a number of small farmers are involved, living at some distance away from the scheme. If they know the irrigation schedules for the rest of the month, they are in a better position to organize their work, household tasks and family life accordingly. In Section 9.2.3, examples of such an adjusted irrigation schedule are worked out.

The rainfall can be taken into consideration at the time the irrigation schedule is applied. By using a rain gauge and by recording the amount of rainfall on a daily basis, this amount can be weighted against part of, or one or more irrigation applications. Therefore, the irrigation cycle is interrupted and a number of days are skipped, depending on the amount of rainfall, the daily water requirements and the moisture to be replenished in the root zone depth of the soil.

9.2.1. Irrigation frequency

Irrigation frequency is defined as the frequency of applying water to a particular crop at a certain stage of growth and is expressed in days. In equation form it reads:

Equation 28

$$IF = \frac{SM_{ra}}{ET_c} \text{ or } IF = \frac{SM_{ta} \times P \times RZD}{ET_c}$$

Where:

IF	=	Irrigation frequency (days)
SM_{ra}	=	Readily available soil moisture (= SM_{ta} x RZD x P) (mm)
SM_{ta}	=	Total available soil moisture (= FC – PWP) (mm/m)
P	=	Allowable depletion (decimal)
RZD	=	Effective root zone depth (m)
ET_c	=	Crop evapotranspiration or crop water requirement (CWR) (mm/day)

Example 13

Assume that the daily ET_c of onions, grown at Mahalapye irrigation scheme, is 3.86 mm/day during the 3rd decade of August. The SM_{ta} from the soil analysis was determined to be 140 mm/m. The rooting depth from local information at the late growth stage of onion is 0.45 and the adopted depletion (P) 50% or 0.5. What would be the irrigation frequency for onions?

The readily available moisture within the root zone depth will be:

SM_{ra} = 140 x 0.45 x 0.5 = 31.5 mm

The irrigation frequency, which is the number of days it would take the onion to consume the 31.5 mm would be:

$$IF = \frac{31.5}{3.86} = 8.16 \text{ or } 8 \text{ days}$$

Example 14

Given a maize crop with a daily ET_c in September of 5 mm/day. The total available moisture is 100 mm/m, the root zone depth is 1 m and the allowable depletion level is 50%. What is the irrigation frequency and what is the depletion in the different parts of the root zone system between two irrigations, if 40% of the moisture is extracted from the 1st quarter of the root zone depth, 30% from the 2nd quarter, 20% from the 3rd quarter and 10% form the 4th quarter?

$$IF = \frac{100 \times 0.50 \times 1}{5} = 10 \text{ days}$$

The root zone depth being 1 m, the amount of water extracted and the moisture depletion from each quarter or each 25 cm of soil depth is calculated. The 100 x 0.5 = 50 mm of total water extraction in 10 days can be apportioned as calculated in column 3. The depletion is calculated in column 5:

Soil depth (cm)	Water extracted (%)	Water extracted (mm)	SM_{ta} (mm)	Depletion (%)
0-25 cm	40	50 x 0.4 = 20	25	20/25 x 100 = 80
26-50 cm	30	50 x 0.3 = 15	25	15/25 x 100 = 60
51-75 cm	20	50 x 0.2 = 10	25	10/25 x 100 = 40
76-100 cm	10	50 x 0.1 = 5	25	5/25 x 100 = 20

It transpires from the above example that the top half of the root zone system, from where 40% + 30% = 70% of the water is extracted, was in reality stressed above the established level of 50%, while the area of the least extraction in the lower half (20% + 10% = 30%) enjoyed better growing conditions than envisaged.

While the basic assumption is not necessarily based on documented data, it appears that by reducing the root zone depth to where the majority of the feeder roots concentrate, we may end up with a better depletion for the majority of the root zone depth and provide better growing conditions. This approach was successfully applied on vegetables and citrus trees under extreme desert conditions (Savva *et al*. 1984).

There are two major disadvantages to this approach. Firstly, more effective water control is required. While this is attainable with pressurized irrigation systems, it is more difficult to achieve with surface irrigation systems. The second disadvantage is the more frequent irrigation, which will carry additional labour cost for labour intensive systems such as surface and semi-portable sprinkler systems. Whether this cost can be covered by the expectations of higher yield depends on the prevailing economics for each crop at different times and places. Most certainly this is an area where research can play an important role.

Example 15

Consider a pressurized irrigation system, thereby reducing the plant feeder root depth of the maize crop to 75 cm as recommended in Table 55. If a 50%, 30% and 20% root distribution is then assumed respectively for the 1st, 2nd and 3rd 25 cm depth in Example 14, what is the depletion in the different depths of soil, assuming again an allowable depletion of 50%?

$$IF = \frac{100 \times 0.50 \times 0.75}{5} = 7.5 \text{ days}$$

The root zone depth being 0.75 m, the amount of water extracted and the moisture depletion from each third or each 25 cm of soil depth is calculated. The 75 x 0.5 = 37.5 mm of total water extraction in 7.5 days can be apportioned as calculated in column 3. The depletion is calculated in column 5.

Soil depth (cm)	Water extracted (%)	Water extracted (mm)	SM_{ta} (mm)	Depletion (%)
0 –25 cm	50	37.5 x 0.5 = 18.75	25	18.75/25 x 100 = 75
26 – 50 cm	30	37.5 x 0.3 = 11.25	25	11.25/25 x 100 = 45
51 – 75 cm	20	37.5 x 0.2 = 7.50	25	7.50/25 x 100 = 30

9.2.2. Manual calculation of the irrigation scheduling programme for a drag-hose sprinkler irrigation system

Irrigation schedule for each crop

Referring to Mahalapye drag-hose sprinkler irrigation scheme, for which the crop water requirements were calculated in Chapter 6, the irrigation schedule for each crop is presented in Tables 60-65. The readily-available soil moisture SM_{ra} = 140 x RZD x P. The irrigation frequency IF = SM_{ra}/ET_c. The net irrigation requirement IR_n = IF x ET_c and the gross irrigation requirement IR_g = IR_n/E_a, where E_a is the field application efficiency, which is assumed to be 75% for the drag-hose sprinkler system. The duration of each month was assumed to be 30 days (3 decades) for the results to be comparable with CROPWAT (Section 9.2.4). The impact of rainfall on the irrigation schedule has not been accounted for as yet. It will be discussed later.

Table 60

Manually-calculated irrigation schedule for tomatoes

Decade	ET_c (mm/day)	RZD (m)	P	SM_{ra} (mm)	IF* (days)	IR_n (mm)	IRg (mm) sprinkler
01/11 - 10/11	3.92	0.15	0.40	8.40	2.14 (2)	7.84	10.45
11/11 - 20/11	3.92	0.20	0.40	11.20	2.86 (3)	11.76	15.68
21/11 - 30/11	4.08	0.30	0.40	16.80	4.12 (4)	16.32	21.76
01/12 - 10/12	4.68	0.40	0.45	25.20	5.38 (5)	23.40	31.20
11/12 - 20/12	5.48	0.45	0.45	28.35	5.17 (5)	27.40	36.53
21/12 - 30/12	6.30	0.50	0.50	35.00	5.56 (5)	31.50	42.00
01/01 - 10/01	6.70	0.50	0.50	35.00	5.22 (5)	33.50	44.67
11/01 - 20/01	6.87	0.50	0.50	35.00	5.09 (5)	34.35	45.80
21/01 - 30/01	6.67	0.50	0.50	35.00	5.24 (5)	33.35	44.47
01/02 - 10/02	6.14	0.50	0.50	35.00	5.70 (6)	36.84	49.12
11/02 - 20/02	5.36	0.50	0.50	35.00	6.53 (6)	32.16	42.88
21/02 - 30/02	4.50	0.50	0.50	35.00	7.55 (7)	31.50	42.00
01/03 - 10/03	3.71	0.50	0.50	35.00	9.43 (9)	33.39	44.52
11/03 - 15/03	2.92	0.50	0.50	35.00	11.98 (12)	35.04	46.72

* *The figure between brackets gives the IF rounded up in full days.*

Table 61

Manually-calculated irrigation schedule for cabbages

Decade	ET_c (mm/day)	RZD (m)	P	SM_{ra} (mm)	IF* (days)	IR_n (mm)	IRg (mm) sprinkler
01/12 - 10/12	3.78	0.15	0.40	8.40	2.22 (2)	7.56	10.08
11/12 - 20/12	3.71	0.20	0.40	11.20	3.01 (3)	11.13	14.84
21/12 - 30/12	3.83	0.30	0.40	16.80	4.38 (4)	15.32	20.43
01/01 - 10/01	4.20	0.40	0.45	25.20	6.00 (6)	25.20	33.60
11/01 - 20/01	4.81	0.45	0.45	28.35	5.89 (6)	28.26	37.68
21/01 - 30/01	5.23	0.50	0.50	35.00	6.69 (6)	31.38	41.84
01/02 - 10/02	5.59	0.50	0.50	35.00	6.26 (6)	33.54	44.72
11/02 - 20/02	5.67	0.50	0.50	35.00	6.17 (6)	34.02	45.36
21/02 - 30/02	5.36	0.50	0.50	35.00	6.52 (6)	33.35	44.47
01/03 - 10/03	5.04	0.50	0.50	35.00	6.94 (7)	35.28	47.04
11/03 - 20/03	4.69	0.50	0.50	35.00	7.46 (7)	32.83	43.77
21/03 - 30/03	4.32	0.50	0.50	35.00	8.10 (8)	34.56	46.08
01/04 - 10/04	3.93	0.50	0.50	35.00	8.90 (8)	31.44	41.92
11/04 - 20/04	3.56	0.50	0.50	35.00	9.83 (9)	32.04	47.72

* *The figure between brackets gives the IF rounded up in full days.*

Table 62

Manually-calculated irrigation schedule for rape

Decade	ET_c (mm/day)	RZD (m)	P	SM_{ra} (mm)	IF* (days)	IR_n (mm)	IRg (mm) sprinkler
15/01 - 20/01	3.99	0.15	0.40	8.40	2.11 (2)	7.98	10.64
21/01 - 30/01	3.92	0.20	0.40	11.20	2.86 (3)	11.76	15.68
01/02 - 10/02	4.14	0.25	0.40	14.00	3.38 (3)	12.42	16.56
11/02 - 20/02	4.75	0.30	0.45	18.90	3.98 (4)	19.00	25.33
21/02 - 30/02	4.99	0.35	0.45	22.05	4.42 (4)	19.96	26.61
01/03 - 10/03	4.80	0.40	0.50	28.00	5.83 (6)	28.80	38.40
11/03 - 20/03	4.50	0.40	0.50	28.00	6.22 (6)	27.00	36.00
21/03 - 30/03	4.22	0.40	0.50	28.00	6.63 (6)	25.32	33.76
01/04 - 10/04	3.92	0.40	0.50	28.00	7.14 (7)	27.44	36.59
11/04 - 20/04	3.62	0.40	0.50	28.00	7.73 (7)	25.34	33.79
21/04 - 30/04	3.33	0.40	0.50	28.00	8.40 (8)	26.64	35.52
01/05 - 10/05	3.04	0.40	0.50	28.00	9.21 (9)	27.36	36.48
11/05 - 15/05	2.75	0.40	0.50	28.00	10.18 (10)	27.50	36.67

* *The figure between brackets gives the IF rounded up in full days.*

Table 63

Manually-calculated irrigation schedule for onions

Decade	ET_c (mm/day)	RZD (m)	P	SM_{ra} (mm)	IF* (days)	IR_n (mm)	IRg (mm) sprinkler
01/05 - 10/05	2.22	0.15	0.40	8.40	3.78 (4)	8.88	11.84
11/05 - 20/05	2.03	0.20	0.40	11.20	5.55 (5)	10.15	13.53
21/05 - 30/05	2.10	0.25	0.45	15.75	7.50 (7)	14.70	19.60
01/06 - 10/06	2.32	0.30	0.45	18.90	8.14 (8)	18.56	24.75
11/06 - 20/06	2.46	0.35	0.45	22.05	8.96 (9)	22.14	29.52
21/06 - 30/06	2.77	0.40	0.50	28.00	10.11 (10)	27.70	36.93
01/07 - 10/07	2.92	0.40	0.50	28.00	9.59 (9)	26.28	35.04
11/07 - 20/07	3.00	0.40	0.50	28.00	9.33 (9)	27.00	36.00
21/07 - 30/07	3.36	0.40	0.50	28.00	8.33 (8)	26.28	35.04
01/08 - 10/08	3.69	0.40	0.50	28.00	7.59 (7)	25.83	34.44
11/08 - 20/08	3.82	0.40	0.50	28.00	7.33 (7)	26.72	35.63
21/08 - 30/08	3.86	0.40	0.50	28.00	7.25 (7)	27.02	36.03
01/09 - 10/09	3.81	0.40	0.50	28.00	7.35 (7)	26.67	35.56
11/09 - 20/09	3.68	0.40	0.50	28.00	7.61 (7)	25.76	34.35
21/09 - 30/09	3.36	0.40	0.50	28.00	8.33 (8)	26.88	35.84

* *The figure between brackets gives the IF rounded up in full days.*

Table 64

Manually-calculated irrigation schedule for potatoes

Decade	ET_c (mm/day)	RZD (m)	P	SM_{ra} (mm)	IF* (days)	IR_n (mm)	IRg (mm) sprinkler
01/06 - 10/06	1.25	0.20	0.40	11.20	8.96 (9)	11.25	15.00
11/06 - 20/06	1.15	0.20	0.40	11.20	9.73 (9)	10.35	13.80
21/06 - 30/06	1.18	0.20	0.40	11.20	9.49 (9)	16.52	22.03
01/07 - 10/07	1.44	0.25	0.45	15.75	10.93 (11)	15.84	21.12
11/07 - 20/07	1.95	0.25	0.45	15.75	8.08 (8)	15.60	20.80
21/07 - 30/07	2.73	0.25	0.45	15.75	5.77 (6)	16.38	21.84
01/08 - 10/08	3.45	0.30	0.50	21.00	6.09 (6)	20.70	27.60
11/08 - 20/08	3.91	0.30	0.50	21.00	5.37 (5)	19.55	26.07
21/08 - 30/08	4.41	0.30	0.50	21.00	4.76 (5)	22.05	29.40
01/09 - 10/09	4.76	0.30	0.50	21.00	4.41 (4)	19.04	25.39
11/09 - 20/09	4.84	0.30	0.50	21.00	4.34 (4)	19.36	25.81
21/09 - 30/09	4.65	0.30	0.50	21.00	4.52 (4)	16.80	24.80
01/10 - 10/10	4.40	0.30	0.50	21.00	4.77 (5)	22.00	29.33
11/10 - 14/10	4.09	0.30	0.50	21.00	5.13 (5)	20.45	27.27

* *The figure between brackets gives the IF rounded up in full days.*

Table 65

Manually-calculated irrigation schedule for green maize

Decade	ET_c (mm/day)	RZD (m)	P	SM_{ra} (mm)	IF* (days)	IR_n (mm)	IRg (mm) sprinkler
01/08 - 10/08	2.17	0.20	0.40	11.20	5.16 (5)	10.85	14.47
11/08 - 20/08	2.38	0.20	0.40	11.20	4.71 (5)	11.90	15.87
21/08 - 30/08	2.80	0.25	0.40	14.00	5.00 (5)	14.00	18.67
01/09 - 10/09	3.46	0.30	0.45	18.90	5.46 (5)	17.30	23.07
11/09 - 20/09	4.28	0.40	0.45	25.20	5.89 (6)	25.68	34.24
21/09 - 30/09	5.05	0.50	0.45	31.50	6.24 (6)	30.30	40.40
01/10 - 10/10	5.88	0.60	0.50	42.00	7.14 (7)	41.16	54.88
11/10 - 20/10	6.61	0.70	0.50	49.00	7.41 (7)	46.27	61.69
21/10 - 30/10	6.72	0.70	0.50	49.00	7.29 (7)	47.07	62.76
01/11 - 10/11	6.72	0.70	0.50	49.00	7.29 (7)	47.07	62.76
11/11 - 20/11	6.72	0.70	0.50	49.00	7.29 (7)	47.07	62.76
21/11 - 30/11	6.30	0.70	0.50	49.00	7.78 (8)	50.40	67.20
01/12 - 10/12	5.46	0.70	0.50	49.00	8.97 (9)	49.14	65.52
11/12 - 20/12	4.53	0.70	0.50	49.00	10.82 (11)	49.83	66.44
21/12 - 30/12	3.75	0.70	0.50	49.00	13.07 (13)	48.75	65.00

* *The figure between brackets gives the IF rounded up in full days.*

Farm irrigation schedule

For easy use by the extension staff and farmers, the above schedules are summarized in Table 66. As the duration of each irrigation affects the irrigation turns among the different crops, the same table provides the duration of irrigation assuming a sprinkler system providing the water with field application efficiency E_a of 75% or 0.75. This system provides six sprinklers per 0.5 ha holding. This is because of the high ET_c encountered in this scheme, as compared to the example given in Module 8, where three sprinklers are sufficient for 0.5 ha. The holding is divided into three portions to accommodate three crops per season. The sprinklers operate on a 12 m x 12 m spacing, applying 5.69 mm/hr. To cover each crop (one-third of the area per crop) twelve sprinkler positions are needed. Since six sprinklers can operate at any time, it will take two shifts to cover each crop.

In practice, it should be expected that the farmers would round up the duration of irrigation to the nearest quarter of an hour. Naturally, this will slightly reduce the field application efficiency. Tables 67-69 present the sequence of irrigation of the three different crops, grown during the period November-May, based on this approach. The gross

Table 66

Summary irrigation schedule on a monthly basis

Month	Irrigation frequency in days and corresponding hours per sprinkler position												Comments
	Tomatoes		Cabbages		Rape		Onions		Potatoes		Green maize		
	IF days	pos. hrs	IF days	pos. hrs	IF days	pos. hrs	IF days	pos. hrs	IF days	pos. hrs	IF days	pos. hrs	
January	5	8.0	6	6.6	2 3	1.9 2.9							A range of frequency is provided during the initial stage of crops, where transplanting is practiced. The first is used until the plants are established. There after the second frequency is followed.
February	6	7.5	6	8.0	4	4.7							
March	9	7.8	7	8.3	6	6.3							
April			8	7.4	7	6.4							
May					9	6.4	4 5	2.0 2.4					
June							9	5.2	9	2.6			
July							9	6.3	8	3.7			
August							7	6.3	5	5.2	5	2.8	
September							7	4.5	4	4.5	6	6.0	
October									5	5.2	7	10.8	
November	2 4	1.8 3.8									7	11.0	
December	5	6.4	2 4	1.8 3.6							11	11.6	

Table 67
Irrigation programme for tomatoes

Interval (1)	Hours (days) (2)	Hours for per position (3)=(2)x2	Date 2 positions (4)	IR_g (mm) (5)=(2)x5.69	IR_n (mm) (6)=(5)x0.75	Starting irrigation (7)	Finishing irrigation* (8)
2	1.75	3.5	01 Nov	9.96	7.47	06:00 hours	10.00 hours
2	1.75	3.5	03 Nov	9.96	7.47	06:00 hours	10.00 hours
2	1.75	3.5	05 Nov	9.96	7.47	06:00 hours	10.00 hours
2	1.75	3.5	07 Nov	9.96	7.47	06:00 hours	10.00 hours
4	3.75	7.5	11 Nov	21.34	16.00	06:00 hours	14.00 hours
4	3.75	7.5	15 Nov	21.34	16.00	06:00 hours	14.00 hours
4	3.75	7.5	19 Nov	21.34	16.00	06:00 hours	14.00 hours
4	3.75	7.5	23 Nov	21.34	16.00	06:00 hours	14.00 hours
4	3.75	7.5	27 Nov	21.34	16.00	06:00 hours	14.00 hours
4	3.75	7.5	31 Nov	21.34	16.00	06:00 hours	14.00 hours
5	8	16	05 Dec	45.52	34.14	06:00 hours	22.30 hours
5	8	16	10 Dec	45.52	34.14	06:00 hours	22.30 hours
5	8	16	15 Dec	45.52	34.14	06:00 hours	22.30 hours
5	8	16	20 Dec	45.52	34.14	06:00 hours	22.30 hours
5	8	16	25 Dec	45.52	34.14	06:00 hours	22.30 hours
5	8	16	30 Dec	45.52	34.14	06:00 hours	22.30 hours
5	8	16	05 Jan	45.52	34.14	06:00 hours	22.30 hours
5	8	16	10 Jan	45.52	34.14	06:00 hours	22.30 hours
5	8	16	15 Jan	45.52	34.14	06:00 hours	22.30 hours
5	8	16	20 Jan	45.52	34.14	06:00 hours	22.30 hours
5	8	16	25 Jan	45.52	34.14	06:00 hours	22.30 hours
5	8	16	30 Jan	45.52	34.14	06:00 hours	22.30 hours
6	7.5	15	06 Feb	42.67	32.00	06:00 hours	21.30 hours
6	7.5	15	12 Feb	42.67	32.00	06:00 hours	21.30 hours
6	7.5	15	18 Feb	42.67	32.00	06:00 hours	21.30 hours
6	7.5	15	24 Feb	42.67	32.00	06:00 hours	21.30 hours
6	7.5	15	02 Mar	42.67	32.00	06:00 hours	21.30 hours
9	7.75	15.5	11 Mar	44.10	33.07	06:00 hours	22.00 hours
Total				**971.57**	**728.63**		

* *Assuming 30 minutes between positions to move the sprinklers from one position to the next position*

irrigation requirement is equal to the number of hours per sprinkler position times the sprinkler application rate, which is 5.69 mm/hour. The net irrigation requirement is equal to the gross irrigation requirement times the application efficiency, which is 75% or 0.75.

Looking at Tables 67-69, it is noticeable that the optimum irrigation frequency scenario, based on the appropriate depletion, was simplified by averaging the days of frequency and rounding up the duration of irrigation per sprinkler position. The next step is to amalgamate the individual crop schedules to monthly farm irrigation schedules and to ensure that no overlap occurs among the different crops. Table 70 provides such a programme for the month of January.

The outcome of this presentation demonstrates that the preparation of an irrigation programme for a farm, where several crops are grown at the same time, is a time-consuming process when an optimum schedule is the basis for the programme. This becomes more intricate during the month when all crops are at the period of their peak demand, which is February in our example. At times, in order to accommodate timely water application for one crop, compromises were made either by increasing or reducing the frequency by a day or two of another crop. This is possible, because of the flexibility of the sprinkler system. However, under surface irrigation it is more difficult to accommodate the optimum schedule. This is why smallholders tend to apply a fixed frequency irrespective of the crop, and its stage of growth.

Table 68
Irrigation programme for cabbages

Interval (1)	Hours (days) (2)	Hours for per position (3)=(2)x2	Date 2 positions (4)	IR_g (mm) (5)=(2)x5.69	IR_n (mm) (6)=(5)x0.75	Starting irrigation (7)	Finishing irrigation* (8)
2	1.75	3.5	01 Dec	9.96	7.47	06:00 hours	10.00 hours
2	1.75	3.5	03 Dec	9.96	7.47	06:00 hours	10.00 hours
2	1.75	3.5	05 Dec	9.96	7.47	06:00 hours	10.00 hours
2	1.75	3.5	07 Dec	9.96	7.47	06:00 hours	10.00 hours
4	3.5	7	11 Dec	19.92	14.94	06:00 hours	13.30 hours
4	3.5	7	15 Dec	19.92	14.94	06:00 hours	13.30 hours
4	3.5	7	19 Dec	19.92	14.94	06:00 hours	13.30 hours
4	3.5	7	23 Dec	19.92	14.94	06:00 hours	13.30 hours
4	3.5	7	27 Dec	19.92	14.94	06:00 hours	13.30 hours
4	3.5	7	31 Dec	19.92	14.94	06:00 hours	13.30 hours
6	6.5	13	07 Jan	36.99	27.74	06:00 hours	19.30 hours
6	6.5	13	13 Jan	36.99	27.74	06:00 hours	19.30 hours
6	6.5	13	19 Jan	36.99	27.74	06:00 hours	19.30 hours
6	6.5	13	25 Jan	36.99	27.74	06:00 hours	19.30 hours
6	6.5	13	31 Jan	36.99	27.74	06:00 hours	19.30 hours
6	8	16	07 Feb	45.52	34.14	06:00 hours	22.30 hours
6	8	16	13 Feb	45.52	34.14	06:00 hours	22.30 hours
6	8	16	19 Feb	45.52	34.14	06:00 hours	22.30 hours
6	8	16	25 Feb	45.52	34.14	06:00 hours	22.30 hours
7	8.25	16.5	04 Mar	46.94	35.21	06:00 hours	23.00 hours
7	8.25	16.5	11 Mar	46.94	35.21	06:00 hours	23.00 hours
7	8.25	16.5	18 Mar	46.94	35.21	06:00 hours	23.00 hours
7	8.25	16.5	25 Mar	46.94	35.21	06:00 hours	23.00 hours
7	8.25	16.5	01 Apr	46.94	35.21	06:00 hours	23.00 hours
8	7.5	15	09 Apr	42.67	32.00	06:00 hours	21.30 hours
8	7.5	15	17 Apr	42.67	32.00	06:00 hours	21.30 hours
Total				**846.43**	**634.77**		

* *Assuming 30 minutes between positions to move the sprinklers from one position to the next position*

In the above process of preparing the individual crop schedules and the farm irrigation programme, no account was taken of the contribution of rainfall. This is because it is impossible to predict when rainfall occurs. There is so much variability of the rainfall events, both in terms of time and amount, that the use of the effective dependable rainfall calculations can cause serious problems with the irrigation schedules. To accommodate the contribution of rainfall, the extension agent and the farmers must firstly ensure daily measurements of the rainfall at 8.00 hours using the rain gauge installed at the site. It is equally important to keep records on when water was applied to each crop. The question is, how much of this rainfall will be effective? Assuming that substantial rainfall was recorded right after irrigation was completed, then such an event does not contribute to the crop water requirements as it will be lost to deep percolation. If, however, such an event took place just before irrigation is due, then its contribution will be substantial. Again, if the intensity of the rainfall is very high a large amount of the water will be lost to surface runoff.

In different countries, rules of thumb have been developed on the effectiveness of rainfall, based on local observations. In Zimbabwe, for example, rainfall up to 5 mm is considered as being ineffective in the Highveld and Middleveld. In the Lowveld, where evaporation is very high, 10 mm of rain is considered as being ineffective. Example 16 demonstrates the process.

Table 69

Irrigation programme for rape

Interval (1)	Hours (days) (2)	Hours for per position (3)=(2)x2	Date 2 positions (4)	IR_g (mm) (5)=(2)x5.69	IR_n (mm) (6)=(5)x0.75	Starting irrigation (7)	Finishing irrigation* (8)
2	2	4	14 Jan	11.38	8.54	06:00 hours	10.30 hours
2	2	4	16 Jan	11.38	8.54	06:00 hours	10.30 hours
2	2	4	18 Jan	11.38	8.54	06:00 hours	10.30 hours
3	3	6	21 Jan	17.07	12.80	06:00 hours	12.30 hours
3	3	6	24 Jan	17.07	12.80	06:00 hours	12.30 hours
3	3	6	27 Jan	17.07	12.80	06:00 hours	12.30 hours
3	3	6	30 Jan	17.07	12.80	06:00 hours	12.30 hours
4	4.75	9.5	04 Feb	27.03	20.27	06:00 hours	16.00 hours
4	.75	9.5	08 Feb	27.03	20.27	06:00 hours	16.00 hours
4	4.75	9.5	12 Feb	27.03	20.27	06:00 hours	16.00 hours
4	4.75	9.5	16 Feb	27.03	20.27	06:00 hours	16.00 hours
4	4.75	9.5	20 Feb	27.03	20.27	06:00 hours	16.00 hours
4	4.75	9.5	24 Feb	27.03	20.27	06:00 hours	16.00 hours
4	4.75	9.5	28 Feb	27.03	20.27	06:00 hours	16.00 hours
6	6.25	12.5	06 Mar	35.56	26.67	06:00 hours	19.00 hours
6	6.25	12.5	12 Mar	35.56	26.67	06:00 hours	19.00 hours
6	6.25	12.5	18 Mar	35.56	26.67	06:00 hours	19.00 hours
6	6.25	12.5	24 Mar	35.56	26.67	06:00 hours	19.00 hours
6	6.25	12.5	31 Mar	35.56	26.67	06:00 hours	19.00 hours
7	6.5	13	07 Apr	36.99	27.74	06:00 hours	19.30 hours
7	6.5	13	14 Apr	36.99	27.74	06:00 hours	19.30 hours
7	6.5	13	21 Apr	36.99	27.74	06:00 hours	19.30 hours
7	6.5	13	28 Apr	36.99	27.74	06:00 hours	19.30 hours
9	6.5	13	07 May	36.99	27.74	06:00 hours	19.30 hours
Total				**654.38**	**490.76**		

* *Assuming 30 minutes between positions to move the sprinklers from one position to the next position.*

Table 70

Farm irrigation programme (0.5 ha holding) for the month of January

Tomatoes		Cabbages		Rape	
Irrigation dates	Completion of irrigation[a]	Irrigation dates	Completion of irrigation	Irrigation dates	Completion of irrigation
05/01	22.30 hours	07/01	19.30 hours		
10/01	22.30 hours	13/01	19.30 hours	14/01	10.30
15/01	22.30 hours	19/01	19.30 hours	16/01	10.30
				18/01	10.30
20/01	22.30 hours			21/01	12.30
				24/01	12.30
25/01*[b] (26/01)[c]	22.30 hours	25/01*	19.30 hours	27/01	12.30
30/01* (31/01)	22.30 hours	31/01* (01/02)	19.30 hours	30/01*	12.30

a *Irrigation starts at 0.600 hours daily.*

b ** indicates overlap.*

c *Irrigation dates between brackets are the corrected dates to avoid overlap.*

Example 16

Assume that a rainfall of 20 mm occurred in the Highveld of Zimbabwe in January, two days after irrigation was completed. At the time of this event, tomatoes, cabbage and rape were being grown. The ET_c and IF for each crop were:

	Tomatoes	Cabbages	Rape
ET_c (mm/day)	6.9	4.8	4.0
IF (days)	5	6	3

For how many days would the next irrigation be delayed for each crop?

Since the first 5 mm of rainfall is not considered as being effective, the potentially effective rainfall is 20 - 5 = 15 mm. Such an amount would satisfy the water requirements of tomatoes for 2 days (15/6.9 = 2.2), of cabbages for 3 days (15/4.8 = 3.1) and of rape for 3 days (15/4 = 3.75). Therefore, the next irrigation of each crop can be delayed by the corresponding number of days (2 for tomatoes, 3 for cabbages and rape).

9.2.3. Manual calculation of the irrigation scheduling programme for a surface irrigation system

The method for preparing irrigation schedules for surface irrigation systems is similar to the one used for the drag-hose sprinkler irrigation system, which was discussed in the previous section. The only differences are the less efficient water application, associated with surface irrigation systems, and the need for relatively higher flows.

Below, an example of irrigation scheduling for a surface irrigation system in Zimbabwe is given. The assumed field application efficiency, E_a, is 50%. The calculations are done in the same way as for the drag-hose sprinkler irrigation system, and Table 71 summarizes the irrigation frequency IF, the net irrigation requirement IR_n and the gross irrigation requirement IR_g for beans, onions and tomatoes grown during the period of April-September. Each crop covers a quarter of the area of the scheme. One quarter of the area is left empty in preparation for green maize to be planted in October. Since each farmer is allocated 0.5 ha, each crop covers a net area of 0.125 ha or 1 250 m^2 per farmer.

Referring to Table 71, it is noticeable that there is a great variation in the irrigation frequency and in the required gift (IR_n and IR_g) from crop to crop, month to month and at times within the same month. This makes the application of a farm irrigation programme more complicated. To simplify matters, a monthly average irrigation frequency and the corresponding average gross gift are used as a basis for the preparation of farm and scheme irrigation schedules or programmes. Table 72 provides the simplified schedule for the three crops during the month of June, including the contact time (see Module 7).

In order to calculate the duration of irrigation per furrow, border strip or basin, the cumulative infiltration rate curve is required (Figure 33). From this Figure the time the water should be in contact with the soil (contact time) was estimated for each crop, as shown in the last column of Table 72. For more details the reader is referred to Module 7.

Figure 33
Cumulative infiltration rate curve

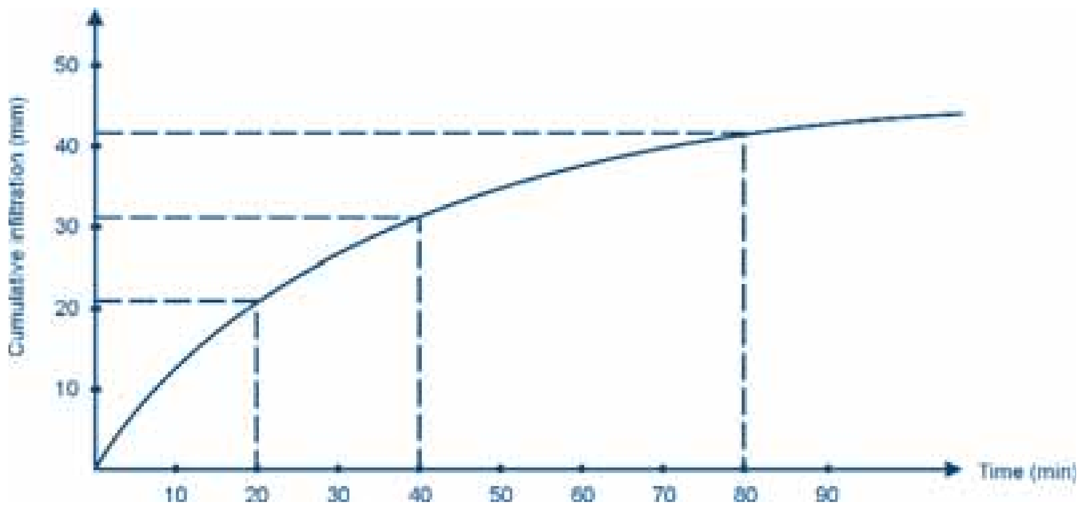


Table 71
Summary irrigation schedule on a monthly basis for the surface irrigation system with E_a = 50%

Month	Beans				Onions				Tomatoes			
	No. of Irrig.	IF (days)	IR_n (mm)	IR_g (mm)	No. of Irrig.	IF (days)	IR_n (mm)	IR_g (mm)	No. of Irrig.	IF (days)	IR_n (mm)	IR_g (mm)
April	1	4	8.0	16.0								
	2	4	8.0	16.0								
	3	5	9.8	19.6								
	4	6	11.5	23.0								
	5	5	10.7	21.4								
	6	5	11.0	22.0					1	4	10.5	21.0
May	7	5	13.4	26.8	1	3	6.4	12.8	2	4	10.1	20.2
	8	5	14.0	28.0	2	3	6.4	12.8	3	5	12.4	24.8
	9	5	15.3	30.6	3	4	8.5	17.0	4	6	14.2	28.4
	10	7	21.9	43.8	4	4	7.9	15.8	5	6	13.9	27.8
	11	7	22.2	44.4	5	5	9.9	19.8	6	5	12.0	24.0
					6	4	8.4	16.4				
					7	4	8.5	17.0				
June	12	7	21.5	43.0	8	4	8.8	17.6	7	6	14.7	29.4
	13	7	20.9	41.8	9	4	9.9	19.8	8	6	15.9	31.8
	14	7	20.1	40.2	10	4	9.9	19.8	9	6	16.6	33.2
	15	7	20.3	40.6	11	4	10.8	21.6	10	6	17.3	34.6
					12	4	11.1	22.2	11	9	28.1	56.2
					13	4	11.5	23.0				
					14	4	12.8	25.6				
July	16	7	20.4	40.8	15	7	22.8	45.6	12	8	25.8	51.9
	17	7	20.5	41.0	16	6	20.5	41.0	13	8	26.5	53.0
	18	7	20.7	41.4	17	6	20.9	41.8	14	8	27.3	54.6
	19	7	21.5	43.0	18	6	21.1	42.2				
					19	6	23.1	46.2				
August					20	6	23.8	47.6	15	8	28.5	57.0
					21	5	20.9	41.8	16	7	25.4	50.8
					22	5	21.3	42.6	17	7	25.6	51.2
					23	5	22.0	44.0	18	7	25.7	51.4
					24	5	22.3	44.6	19	7	26.2	52.4
					25	5	22.9	45.8				
September					26	5	23.1	46.2				
					27	5	23.5	47.0				
					28	5	23.7	47.4				
					29	5	24.0	48.0				
					30	5	23.9	47.8				

Table 72
Simplified irrigation schedule for beans, onions and tomatoes during the month of June

Crop	Irrigation frequency (days)	Gross gift (IR_g) (mm per irrigation)*	Contact time (minutes)
Beans	7	42	80
Onions	4	21	20
Tomatoes	6	31.5	40

* *Rounded.*

The scheme under consideration covers 15 ha (net area). The design flow at the top of the field is 66 l/sec and the maximum duration of irrigation was set to 10 hours per day. The water flow into the scheme would then be 2 376 m^3/day (0.066 m^3/sec x 10 hours x 3 600 sec). Assuming that one quarter of the total area, or 3.75 ha (15/4), is covered by one crop (which is three quarters of the area, or 11.25 ha, for the three crops) and that one quarter of the total area, or 3.75 ha, is empty, the per crop daily needed flow and duration of irrigation are calculated as shown in Table 73.

The figures in the last column of Table 73 demonstrate that not all crops can be irrigated in one day. In fact, it will take about 15 hours or 1.5 days to cover all crops.

Assuming a rotational distribution of water among the group, and taking into consideration that one farmer can handle 15 siphons, the water will be distributed to a limited number of farmers at a time. Table 74 presents the calculations needed to derive the number of farmers to irrigate at the same time and for each crop.

Table 75 summarizes the irrigation schedule for the scheme on a crop by crop basis.

Table 73

Flow rate and duration of irrigation for each crop during the month of June

Crop	Area (ha) (1)	IR_g (mm) (2)	Scheme flow (m^3/hr) (3)	Daily irrigation requirements (m^3) (4)=(1)x(2)x10	Irrigation duration (hours/day) (5)=(4)/(3)
Beans	3.75	42	237.6	1 575	6.63
Onions	3.75	21		788	3.32
Tomatoes	3.75	31.5		1,181	4.97

Table 74

Gross irrigation requirement, contact time and number of farmers irrigating at the same time

Crop	Area (m^2) (1)	IR_g (m) (2)	Water required (m^3) (3)=(1)x(2)	Contact time (min) (4)	Required flow (l/sec) (5)=((3)x1000)/(4)	Scheme flow (l/sec) (6)	Number of farmers (7)=(6)/(5)
Beans	1 250	0.042	52.50	80	10.9	66	6
Onions	1 250	0.021	26.25	20	21.9		3
Tomatoes	1 250	0.0315	39.38	40	16.4		4

Table 75

Summary irrigation schedule for the month of June

Crop	Date of irrigation	IR_g (mm)	Duration of irrigation or contact time (min)	Scheme duration of irrigation (hours)
Beans	5 June	42	80	6.6
	12 June	42	80	6.6
	19 June	42	80	6.6
	26 June	42	80	6.6
Onions	1 June	21	20	3.3
	5 June	21	20	3.3
	9 June	21	20	3.3
	13 June	21	20	3.3
	17 June	21	20	3.3
	21 June	21	20	3.3
	25 June	21	20	3.3
Tomatoes	1 June	31.5	40	5.0
	7 June	31.5	40	5.0
	13 June	31.5	40	5.0
	19 June	31.5	40	5.0
	25 June	31.5	40	5.0

Even with the simplified approach, at times two crops call for irrigation during the same day. While this is possible to accommodate when onions and tomatoes (1 June) or beans and onions (5 June) overlap, it will not be possible to accommodate beans and tomatoes within the same day (19 June) since the duration of irrigation will exceed the 10 hours set at design level. However, farmers can continue irrigating beyond the 10 hours on this particular day and complete irrigation in 11.6 hours (5 + 6.6).

With respect to the rainfall impact on the irrigation schedule, the same approach used for the sprinkler example is also applicable here.

9.2.4. Irrigation scheduling using computer programmes

Computerized irrigation scheduling allows for the storage and easy transfer of data, easy access to data and calculations using the most advanced and complex methods for predicting crop evapotranspiration, as has been shown in Chapter 6 using the FAO CROPWAT model. It has also been shown how the computerized programme can easily access databases for climate and crop characteristics to allow for quick calculations of irrigation water requirements. Computerized irrigation scheduling has enabled the use of real-time weather data from on-site weather stations to improve efficiency. Having said this, it is important to know that irrigation scheduling programmes are no better than the data used or the ability of the user to interpret the output.

The FAO CROPWAT model for irrigation scheduling will be elaborated in this section. The programme provides the possibility to:

- ❖ Develop and plan indicative irrigation schedules
- ❖ Evaluate field irrigation programmes in terms of efficiency of water use and yield reduction
- ❖ Simulate field irrigation programmes under water deficiency conditions, rainfed conditions, supplementary irrigation, etc.

Data required

The water balance method is used for calculation of irrigation schedules in CROPWAT, which means that the incoming and outgoing water flows from the soil profile are monitored. For the irrigation scheduling, the programme requires data on crop evapotranspiration, rainfall, crop data and soil data.

Crop evapotranspiration or crop water requirements: This is defined as the daily water needs of the crop. The process of deriving these requirements was explained in detail in Chapter 4.

Rainfall: Depending on the objective of the irrigation scheduling, monthly rainfall averages, rainfall at different levels of probability, historical data or actual data are used.

Crop data: Data on rooting depth and allowable depletion are required. To assess the effect of water stress on yield, the yield response factor is also required (see Chapter 8).

Soil data: The soil parameters important for irrigation scheduling and required for irrigation scheduling using the FAO CROPWAT programme are described below:

- ❖ Total available soil moisture content (SM_{ta}), defined as the difference in soil moisture content between field capacity (FC) and wilting point (PWP). This is the total amount of water available to the crop and depends on texture, structure and organic matter content
- ❖ Initial soil moisture depletion indicates the dryness of the soil at the start of irrigation. This is expressed as a depletion percentage from FC
- ❖ Maximum rooting depth will in most cases be determined by the genetic characteristics of the plant. In some cases the root depth can be restricted by limiting layers
- ❖ Maximum rain infiltration rate allows for an estimate of the surface runoff for the effective rain calculation. This is a function of rain intensity, soil type and slope class

In Chapter 6, an example was given for the calculation of crop water requirements for a 10 ha smallholder irrigation scheme to benefit 20 farmers at a site close to Mahalapye climatic station in Botswana. A cropping pattern (Table 32) and crop rotation programme (Table 33) were developed together with the farmers and the crop water requirements were calculated using CROPWAT. This example will be carried forward to use the data generated for the irrigation scheduling on this scheme, using CROPWAT.

Crop data, crop water requirements and effective rainfall were explained and calculated in Chapter 6. The soil data for the same example are:

- ❖ Total available soil moisture content (SM_{ta}): 140 mm/m (medium soil)
- ❖ Maximum rooting depth: set at 900 cm (a default value to indicate no limitations).
- ❖ Maximum rain infiltration rate: set at 40mm/day
- ❖ Initial soil moisture depletion: 0% (soil assumed to be fully wetted)

CROPWAT will provide a summary of the inputs on soil data in the way presented in Table 76.

Table 76
Soil data

SOIL DATA		
Soil type: Medium		
Total available soil moisture (TAM) :	140.0 mm/m	
Maximum rain infiltration rate :	40 mm/day	
Maximum rooting depth :	900 cm	
Initial soil moisture depletion (% TAM) :	0 %	
(-> Initial available soil mositure :	140.0 mm/m)	
CROPWAT 7.0	Soil file: D:\CROPWAT7.0\SOI\MEDIUM.SOI	30/09/02

Irrigation scheduling options

CROPWAT allows a range of options, depending on the objective of the user and the design restrictions that the irrigation system imposes. The scheduling options refer to two different categories:

- Timing options – related to WHEN irrigation is to be applied
- Application options – HOW MUCH water is to be given per irrigation turn

Timing options

The user can select from eight options: one for evaluation and simulation, two for optimal irrigation, two for practical irrigation, two for deficit irrigation and one for rainfed conditions.

Option 1 (for evaluation and simulation): Defined by the user, who decides when irrigation has to take place, based on historical irrigation dates from actual field data or simulated dates. This option is to evaluate irrigation practices, to simulate any alternative irrigation schedule and, in particular, to refine irrigation schedules developed through the use of other options.

Option 2 (for optimal irrigation): Irrigation is exercised when readily available moisture (SM_{ra}) is depleted. It is defined as 100% SM_{ra} (or RAM, the expression used in CROPWAT). This is the most common way to schedule irrigations. It results in minimum irrigations, but also in irregular intervals and may thus not be easy to implement in the field.

Option 3 (for optimal irrigation): Irrigation will take place when soil moisture reaches a defined percentage of readily-available moisture. It is used to set a safety moisture level to allow for possible delays to irrigation (80% SM_{ra}) or to allow for a stress level for agronomic reasons (120% SM_{ra}).

Option 4 (for practical irrigation): Irrigation water is applied on fixed interval turns. This method is most suitable for surface irrigation systems with rotational water distribution. It is an easy-to-implement method that has been used in several smallholder schemes. For example, Musikavanhu irrigation scheme in Zimbabwe schedules irrigation at 7-day intervals. However, this option may result in some over-irrigation in the initial stages and under-irrigation in the peak season.

Option 5 (for practical irrigation): Irrigation water is applied whenever a predetermined amount of water has been depleted, thus allowing a fixed water application at each turn.

Option 6 (for deficit irrigation): Irrigation water is applied whenever a critical reduction in evapotranspiration is reached, predetermined by user for each stage in percentage of the reduction in evaporation:

Equation 29

$$\text{Deficit} = 100 \times \left[1 - \frac{ET_a}{ET_{max}}\right]$$

Where:

ET_a = Actual evapotranspiration ($ET_{c\ adj}$)

ET_{max} = Crop evapotranspiration (ET_c)

Option 7 (for deficit irrigation): Irrigation water is applied whenever a critical yield reduction level is reached, determined by sensitivity of growing stage (see Chapter 8).

Option 8 (for rainfed conditions): No irrigation is applied. This option allows for the evaluation of the rainfall impact as related to the crop water requirements. It gives a 10-day overview of deficit, evapotranspiration and rainfall losses.

Application options

The user can select from four options: one for evaluation and simulation, two for optimal irrigation and one for practical irrigation.

Option 1 (for evaluation and simulation): The user determines the application depth at each turn. This option is combined with Timing Option 1, described earlier.

Option 2 (for optimal irrigation): The application depth will bring soil moisture content back to field capacity. The depth applied will be equal to the depleted soil moisture in the root zone. The application depth will vary, as the season progresses, with changing root depth and allowable depletion levels at each growth stage.

Option 3 (for optimal irrigation): The application depth will bring moisture levels to a fixed amount below or above field capacity. It is useful to allow for leaching for salinity control (application larger than field capacity) or to accommodate possible rainfall (application lower than field capacity).

Option 4 (for practical irrigation): Where irrigation is restricted by conditions set by the irrigation system, application depth is fixed by the user and is normally adapted to the irrigation method. This option is normally used for most surface irrigation systems, where it is not easy to vary application depths.

Example of irrigation scheduling for a drag-hose sprinkler irrigation system

The example of the drag-hose sprinkler irrigation system in Section 9.2.2 will also be used to do the irrigation scheduling using CROPWAT. The irrigation efficiency is 75% and Timing Option 2 is used. Soil data are given in Table 76. The results for tomatoes, cabbages and rape are presented in Tables 77-79. The meaning of the different columns in the tables is as follows:

Column 4: Crop stage in which irrigation occurs:
A = Initial phase
B = Development stage
C = Mid-season
D = Late season

Column 5: P as % of SM_{ta}

Column 6: TX = Actual evapotranspiration rate on the day before irrigation, in % of ET_c

Column 7: Average actual evapotranspiration calculated over the irrigation interval period, in % of ET_c

Column 9: Deficit indicates the soil moisture depletion level after irrigation:
A zero value represents a refill to field capacity
A positive value represents an under-irrigation, equal to the amount needed to refill the root to field capacity

Column 10: Loss is the excess of water lost to deep percolation of any irrigation depth or rain exceeding refill to field capacity

Column12: The flow is calculated based on IR_g (Column 11)

Referring to Tables 77-79, it is noticeable that CROPWAT scheduling provides detailed irrigation schedules in addition to other information relevant to irrigation.

It provides information on the potential water use by crop, which is the ET_c, and it compares it with the actual water used by the crop. In the above examples, where the optimum option (Option 2) was adopted, both the actual and the potential water use by the crop is the same. If however, deficit irrigation was opted for (Option 6 or 7), then the actual water use would be less than the potential use.

The contribution of rainfall to the crop water requirements is assessed by providing information on the amount of rainfall, the effective rainfall, the rain lost and the efficiency of rain. The efficiency of rain is derived by dividing the effective rain by the total rain. The actual irrigation requirement is the actual water use by the crop minus the effective rainfall.

At the end of the season some water is left in the soil profile. It is expressed as soil moisture deficit at harvest, representing the soil moisture depletion at the end of the season. It provides a check as to whether the last irrigation was really needed. The total net irrigation (IR_n, or NetGift in the tables) equals the actual irrigation requirement minus the moisture deficit at harvest. The total gross irrigation (IR_g, or Gr.Gift in the tables) is the IR_n divided by the field application efficiency (E_a).

The scheduling efficiency is calculated, by the software, in the water balance as water lost due to deep percolation and is a consequence of inadequate scheduling. Yield reduction is also provided on the printout, representing reduction in yield due to soil moisture stress.

Table 77

Irrigation scheduling for tomato from CROPWAT 7.0

IRRIGATION SCHEDULING

Rain station :	**MAHALAPYE**	**Crop :**	**TOMATOES**
Eto station :	**MAHALAPYE**	**Soil :**	**Medium**
Planting date :	**1 November**	**Total Soil Moist :**	**140 mm/m**
		Init Soil Moist :	**140 mm/m**
Timing :	**At critical depletion (100% RAM)**		
Application :	**Refill up to Field Capacity**	**Field Efficiency :**	**75%**

No. Irr.	Int. days	Date	Stage	Deplet. %	TX %	ETa %	NetGift mm	Deficit mm	Loss mm	Gr.Gift mm	Flow l/s/ha
1	6	7 Nov	A	48	100	100	15.7	0.0	0.0	20.9	0.40
2	4	11 Nov	A	44	100	100	15.7	0.0	0.0	20.9	0.60
3	10	21 Nov	A	45	100	100	19.6	0.0	0.0	26.1	0.30
4	11	2 Dec	B	48	100	100	24.6	0.0	0.0	32.8	0.35
5	10	12 Dec	B	49	100	100	29.3	0.0	0.0	39.0	0.45
6	10	22 Dec	B	53	100	100	35.3	0.0	0.0	47.1	0.54
7	9	31 Dec	C	51	100	100	35.4	0.0	0.0	47.2	0.61
8	10	10 Jan	C	52	100	100	36.2	0.0	0.0	48.2	0.56
9	10	20 Jan	C	53	100	100	37.4	0.0	0.0	49.8	0.58
10	10	30 Jan	C	52	100	100	36.6	0.0	0.0	48.8	0.56
11	8	7 Feb	D	51	100	100	35.5	0.0	0.0	47.3	0.68
12	6	13 Feb	D	50	100	100	35.3	0.0	0.0	47.0	0.91
13	10	23 Feb	D	54	100	100	37.5	0.0	0.0	50.0	0.58
END	22	16 Mar	D	33	100	100					

Total Gross Irrigation	525.1 mm	Total Rainfall	374.5 mm
Total Net Irrigation	393.8 mm	Effective Rain	285.0 mm
Total Irrigation Losses	0.0 mm	Total Rain Loss	89.5 mm
Moist Deficit at harvest	23.0 mm		
Actual Water use by Crop	701.8 mm	Actual Irrig. Req.	416.8 mm
Potential Water use by Crop	701.8 mm		
Efficiency Irrigation Schedule	100.0 %	Efficiency Rain	76.1 %
Deficiency Irrigation Schedule	0.0 %		

No yield reductions

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A simple comparison between the manual and the computerized irrigation schedules, for the three crops under consideration, shows that under both methods the total IR_n and IR_g are very close, as summarized in Table 80. It should be noted, however, that no rainfall was incorporated in the manual schedule. Hence, for the purpose of this comparison, the actual water use by crop of CROPWAT will be considered as IR_n. Also in the manual calcualtion the IR_n and IR_g were calculated after the duration of irrigation and the irrigation frequency were rounded.

Another element to be considered in preparing irrigation schedules for individual crops is that at the end an overall farm or scheme irrigation programme is required. CROPWAT 7.0 does not provide for the amalgamation of the individual crop schedules to a scheme schedule. This must be done manually.

In view of the above, it is recommended that where possible CROPWAT be used for the preparation of the individual crop irrigation schedules and the scheme irrigation programme is prepared manually. This is the least time-consuming process.

Table 78

Irrigation scheduling for cabbage from CROPWAT 7.0

IRRIGATION SCHEDULING

Rain station :	**MAHALAPYE**	**Crop :**	**CABBAGES**
Eto station :	**MAHALAPYE**	**Soil :**	**Medium**
Planting date :	**1 December**	**Total Soil Moist :**	**140 mm/m**
		Init Soil Moist :	**140 mm/m**

Timing :	**At critical depletion (100% RAM)**		
Application :	**Refill up to Field Capacity**	**Field Efficiency :**	**75%**

No. Irr.	Int. days	Date	Stage	Deplet. %	TX %	ETa %	NetGift mm	Deficit mm	Loss mm	Gr.Gift mm	Flow l/s/ha
1	6	7 Dec	A	48	100	100	15.1	0.0	0.0	20.2	0.39
2	4	11 Dec	A	44	100	100	15.1	0.0	0.0	20.2	0.58
3	11	22 Dec	A	46	100	100	18.7	0.0	0.0	24.9	0.26
4	10	1 Jan	B	42	100	100	19.5	0.0	0.0	26.0	0.30
5	11	12 Jan	B	44	100	100	23.2	0.0	0.0	30.9	0.33
6	10	22 Jan	B	47	100	100	28.1	0.0	0.0	37.5	0.43
7	10	1 Feb	B	49	100	100	31.9	0.0	0.0	42.6	0.49
8	11	12 Feb	C	51	100	100	35.7	0.0	0.0	47.6	0.50
9	10	22 Feb	C	52	100	100	36.3	0.0	0.0	48.4	0.56
10	16	10 Mar	C	51	100	100	35.6	0.0	0.0	47.5	0.34
11	16	26 Mar	D	50	100	100	35.3	0.0	0.0	47.0	0.34
12	12	7 Apr	D	55	100	100	38.7	0.0	0.0	51.6	0.50
13	12	19 Apr	D	54	100	100	37.6	0.0	0.0	50.2	0.48
END	2	20 Apr	D	5	100	100					

Total Gross Irrigation	494.6 mm	Total Rainfall	361.1 mm
Total Net Irrigation	370.9 mm	Effective Rain	261.8 mm
Total Irrigation Losses	0.0 mm	Total Rain Loss	99.4 mm
Moist Deficit at harvest	3.6 mm		
Actual Water use by Crop	636.3 mm	Actual Irrig. Req.	374.5 mm
Potential Water use by Crop	636.3 mm		
Efficiency Irrigation Schedule	100.0 %	Efficiency Rain	72.5 %
Deficiency Irrigation Schedule	0.0 %		

No yield reductions

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Table 79

Irrigation scheduling for rape from CROPWAT 7.0

IRRIGATION SCHEDULING

Rain station :	**MAHALAPYE**	**Crop :**	**RAPE**
Eto station :	**MAHALAPYE**	**Soil :**	**Medium**
Planting date :	**15 January**	**Total Soil Moist :**	**140 mm/m**
		Init. Soil Moist :	**140 mm/m**

Timing : **At critical depletion (100% RAM)**
Application : **Refill up to Field Capacity** **Field Efficiency :** **75%**

No. Irr.	Int. days	Date	Stage	Deplet. %	TX %	ETa %	NetGift mm	Deficit mm	Loss mm	Gr.Gift mm	Flow l/s/ha
1	6	21 Jan	A	50	100	100	16.0	0.0	0.0	21.4	0.41
2	6	27 Jan	A	43	100	100	15.7	0.0	0.0	21.0	0.40
3	4	31 Jan	A	40	100	100	15.7	0.0	0.0	21.0	0.61
4	12	12 Feb	B	49	100	100	23.2	0.0	0.0	30.9	0.30
5	10	22 Feb	B	52	100	100	28.6	0.0	0.0	38.2	0.44
6	13	7 Mar	C	55	100	100	30.8	0.0	0.0	41.1	0.37
7	6	13 Mar	C	50	100	100	28.2	0.0	0.0	37.6	0.73
8	10	23 Mar	C	55	100	100	30.6	0.0	0.0	40.8	0.47
9	10	2 Apr	D	56	100	100	31.3	0.0	0.0	41.7	0.48
10	10	12 Apr	D	51	100	100	28.6	0.0	0.0	38.1	0.44
11	10	22 Apr	D	52	100	100	29.4	0.0	0.0	39.2	0.45
12	11	3 May	D	54	100	100	30.3	0.0	0.0	40.4	0.43
13	12	15 May	D	55	100	100	30.7	0.0	0.0	41.0	0.40
END	1	15 May	D	0	100	100					

Total Gross Irrigation	452.4 mm	Total Rainfall	241.0 mm
Total Net Irrigation	339.3 mm	Effective Rain	146.4 mm
Total Irrigation Losses	0.0 mm	Total Rain Loss	94.7 mm
Moist Deficit at harvest	3.6 mm		
Actual Water use by Crop	485.7 mm	Actual Irrig. Req.	339.3 mm
Potential Water use by Crop	485.7 mm		
Efficiency Irrigation Schedule	100.0 %	Efficiency Rain	60.7 %
Deficiency Irrigation Schedule	0.0 %		

No yield reductions

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Table 80

Total net and gross irrigation requirements derived from manual and CROPWAT irrigation schedules

Crop	Manual irrigation schedule		CROPWAT irrigation schedule	
(mm)	Total IR_n (mm)	Total IR_g (mm) (mm)	Total IR_n	Total IR_g
Tomatoes	728.6	971.6	701.8	935.7
Cabbages	634.8	846.4	636.3	848.4
Rape	490.8	654.4	485.7	647.6

9.3. Variations in scheme irrigation scheduling

The three basic components of a scheme schedule are:

- The delivery flow rate to the various canals within the system
- The delivery frequency or timing of the deliveries
- The duration of the deliveries

The schedule selected is a function of delivery system flexibility and farm irrigation requirements. The more flexible on-demand irrigation delivery systems may allow the farmer to specify flow rate, irrigation frequency and/or duration. The more rigid ones, such as rotational systems, may have severe restraints on any of the components. Characteristics of some scheduling variations are described below.

9.3.1. Rigid schedules

This schedule is usually predetermined by the scheme by-laws, scheme policy, or other means. The schedule is often determined before the start of the irrigation season-based on historical crop water requirements, or simply by allocating expected water supplies proportionally to land ownership or other criteria. Some kind of rotational schedule is usually implied. Capital costs are the least with this type of schedule, as canals and structures are designed for continuous supply at peak demand periods.

9.3.2. Rotational schedules

Fixed rotation

This schedule implies a fixed flow rate, fixed irrigation frequency and fixed duration. It is a type of fixed interval-fixed amount schedule. Intervals are, for example, weekly, bi-weekly or monthly. The irrigation interval and amount are often determined by the peak use period on a scheme. The average allowable depletion (P) at peak use periods, along with application and distribution efficiencies, determines the amount of water delivery.

This type of schedule is easy to administer from a schematic point of view. Very little communication, planning, or monitoring is required as compared to other systems. Canals are easy to design and operate for the fixed flow rate and durations. However, except at peak, the supply does not equal demand and efficiencies are low early and late in the season. The excessive water applied early and late in the season may result in nutrient leaching, waterlogging, and salinity problems. Since cropping patterns, soils, and even climatic conditions may vary widely in a scheme, fixed rotation schedules are seldom adequate, even during peak demand periods.

Varied frequency rotation

In this variable interval-fixed amount scheduling method, flow rate and irrigation duration remain constant but the irrigation frequency is modified. This type of schedule represents a significant improvement over the fixed rotation type. The interval is generally varied in accordance with the changing water use of the crops in the scheme. For example, irrigations may be scheduled to occur when a fixed average deficit has built up in the scheme area. Monocrop and perennial crop schemes are ideally suited for this type of schedule, provided that soils and climatic conditions in the scheme are similar. The method is suited to deep-rooted crops and soils with high water-holding capacities. Some advantages of this system are that irrigation systems (especially surface systems) are easily designed and operated for a fixed or constant depth of water application. High efficiencies are possible in early and late season (in contrast to the previous method). The disadvantages of this method are that schemes with a variety of crops, planting dates and soil types may not permit the efficiency benefits to be realized without severe consequences for yields. Even with uniform crops and planting dates, such a schedule may result in problems during germination and crop emergence unless additional irrigations are planned to insure germination and plant emergence (for example, in the case of soil crusting). This method does not account for changing soil water reservoir or sensitivity of crops through the season. Improved communications between the irrigation management committee and water baillifs and farmers is required.

Varied rate rotation

In this type of fixed interval-variable amount scheduling method, irrigation frequency and duration are fixed and the flow rate is varied to approximate seasonal demands. Monocrop or perennial crop areas with deep uniform soils are best suited for this schedule. As with the varied frequency system, this method may result in greater efficiencies than with fixed rotations, as over-applications early and late in the season are minimized. However, small stream sizes are often difficult to manage in farm and scheme canals. Flow control structures must be capable of adjustment to the required rates. As surface irrigation systems are most efficiently operated for fixed application depths, this may also present a problem for farm-level management. The farmer must generally become a better water manager to deal with the efficient application of variable rate and amounts. Again, communication from the irrigation management committee down to farm-level must be adequate.

Varied duration rotation

In this fixed interval-variable amount scheduling method, the flow rate and frequency are fixed, but delivery durations vary through the season in tune with irrigation demands. Again, conditions should be similar through the scheme in terms of crops and soils. Flow rates are constant and manageable from farm to scheme levels. For surface irrigation systems, which can best be operated by applying a fixed depth of water, farmers may be able to irrigate only part of their farm at any one delivery. They must learn to sequence their irrigations between different fields and crops as the need arises. If the farmers learn to manage their variable durations, significant improvements in efficiency may result early and late season without adverse yield consequences. Communicating the irrigation durations down to farm-level is a key element in this approach.

Varied frequency and rate rotation

In this variable interval-variable amount scheduling method, only the irrigation duration is fixed and the intervals are varied in tune with crop water needs. In theory, this method would result in high efficiencies and high yields, as the crop's needs should be matched in terms of both timing and amount. However, this requires similar crops and conditions throughout the scheme area if frequency and rate are to be varied similarly throughout the scheme. It requires increased sophistication by the farmers, whose crops must fit a scheme pattern. They must also have the flexibility and knowledge to allocate water deliveries in time, place and amount on their farm. Gates and control structures must be capable of handling variable flow rates. Increased communication is required from scheme to plot-level.

Varied duration and rate rotation

This fixed interval-variable amount scheduling method sets only the irrigation frequency. This method should theoretically, result in high efficiencies. It would, however, result in adverse yield consequences, except with perennial or monocrop systems, or perhaps with deep-rooted crops on soils with high water-holding capacities. This system has the same limitations as the varied rate or duration systems. Flow structures must be capable of handling variable rates. It is difficult to plan and administer this schedule at scheme-level. The farmer must have a flexible farm system in terms of application depths, and must have the knowledge to apply water in tune with crop requirements if the duration and rate are to be dictated at scheme-level. Again, good communication from scheme to farm-level is required.

Varied duration and frequency rotation

This combination results in a variable interval-variable amount schedule, which is theoretically in tune with scheme crop water requirements. Frequencies should be established with respect for the crop's requiring the shorter intervals, if possible. Again, similarity in cropping patterns and soils between various parts of the scheme is important. The fixed rate allows fixed-rate delivery structures to be efficiently operated. Efficiencies can be maximized throughout the season if the farmers can develop the flexibility and knowledge to apply variable depths, or to allocate the available water to their various crops and fields throughout the season. This method also requires very good communication from scheme to farm/plot-level.

9.3.3. Flexible schedules

In a flexible schedule, the farmer has control of one or more of the three scheduling components. The degree of flexibility is dependent on the system design and the management capabilities at scheme-level. Compromises between the farmers' needs and capabilities of the delivery system are generally required. On the systems with greatest flexibility, over-sizing of canals, offline reservoirs, and automation may be required to meet demand and to avoid spillage and overtopping. On the less flexible systems (for example, restricted/arranged), the main requirements are adequate system capacities and control, along with good communication between farmers and water authorities.

9.3.4. On-demand irrigation

On-demand irrigation imposes no limits on rate, frequency, or duration of water delivery. This type of schedule implies that the water authorities impose no external controls on the water use. The system capacity is designed based on certain assumptions, for example the probability that maximum 85% of the farmers irrigate at the same time. Although this system is often ideal from the farmer's point of view, sometimes the economics of scheme implementation cannot justify such a system.

Variations of on-demand irrigation, used mostly with pressurized systems, can improve the economics of such systems. For example, limits are sometimes imposed on the flow rate and the pressure. Also at times the probability level can be based on a small group of farmers rather than individual farmers. Farmers would then be expected to rotate irrigation among themselves within each group. Such an arrangement would then be considered as a combination of a flexible and a rigid schedule.

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