A Training Manual for Training of Trainers on Crop Water Requirement and Irrigation Scheduling for Vegetable and Fruit Crops Production

Volume 1

By

Tilahun Hordofa (PhD)
Gobena Dirirsa

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Crop Water Requirement and Irrigation Scheduling for Vegetable and Fruit Crops Production

Tilahun Hordofa, Email: tilahun_hordofa@yahoo.com; Cell Phone: 0911842492
Ethiopian Institute of Agricultural Research, Melkassa Agricultural Research Center,
P.O. Box 436, Tel. 251-022 2250210, Fax: 251-022225 0213

Introduction

All plants require water, air, light and media to survive, grow and reproduce (Fig. 1). The soil acts as a media and gives stability to the plant, stores water and nutrients that the plants can take up through their roots. The sunlight (light) provides the energy which is necessary for plant growth and photosynthesis. The air allows the plants to "breath". Water is needed for photosynthesis, respiration, absorption, translocation and utilization of mineral nutrients.

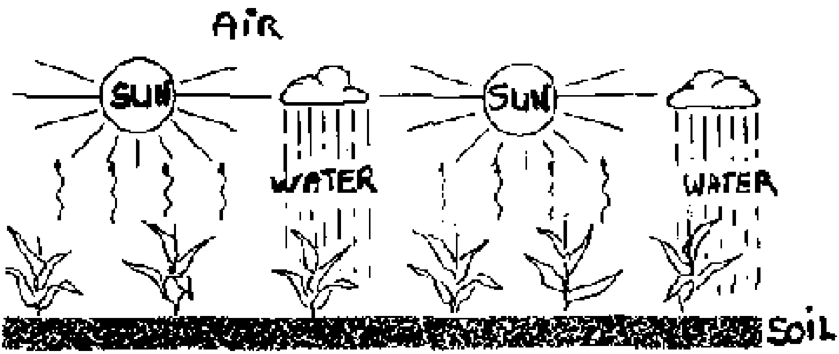


Figure 1. Plants requirement for growth and reproduction

Without water crops cannot grow. Too much water is not good for many crops either. Apart from paddy rice, there are only very few crops which like to grow "with their feet in the water". If there is too much water in the soil there will not be enough air. The excess water must be removed otherwise the soil is water logged, which could also restrict plant growth and development. If there is too little water in the soil will reduce plant growth and development, restricting yield or causing the plant to die and thus it must be supplied from other sources. Therefore, adequate water supply is important for plant growth.

The most well-known source of water for plant growth is rain water. When the rainfall is not sufficient, the plants must receive additional water from other sources. It may be provided partially or entirely by artificial means called Irrigation. The main objective of irrigation is to provide plants with sufficient water to prevent stress that may cause reduced yield or poor quality of harvest. The required timing and amount of applied water is governed by the prevailing climatic conditions, crop and stage of crop, soil moisture holding capacity and the extent of root development as determined by type of crop, stage of growth, and soil. The process by which irrigation water is controlled and used in the agricultural production is called Irrigation Water Management, IWM.

The irrigation is applied on the surface of the soil and water must infiltrate the surface and move downward throughout the root zone. Irrigation water management requires determining when to irrigate and how much water to apply in each application. Thus, Knowledge of crop water requirement and soil properties are essential for management of irrigation water.

1. CROP WATER REQUIREMENT

Crop water requirement is the total quantity of water, regardless of its sources, required by the crop in a given growing season (from the time it is sown to the time it is harvested) for compensating the evapotranspiration loss plus water used for digestion, photosynthesis, transportation of minerals and foods, and also for structural support. The plant roots extract the required water from the soil.

The water transpired by the plant leaves as vapor and water evaporated from wet surfaces plus water used for other processes (digestion, photosynthesis, transportation) is generally referred to as **crop consumptive use (CU) which synonyms to crop water requirement (CWR) or crop evapotranspiration (ETcrop)**. Thus, CU exceeds ETcrop by the amount of water used for digestion, photosynthesis, transportation etc. Since this difference is usually less than one percent, ETcrop and CU are normally assumed to be equal. Therefore, the term crop water requirement, crop evapotranspiration and consumptive use could be used interchangeably.

Climate is one of the most important factors determining the crop water requirements needed for unrestricted optimal growth and yield. The water requirement of a plant is usually expressed in mm/day, mm/month or mm/season. Suppose the water need of a certain plant in a very hot, dry climate is 10 mm/day. This means that each day the plant requires a water layer of 10 mm over the whole area on which the plant is grown. It does not mean that this 10 mm has to indeed be supplied by rain or irrigation every day. It is, of course, still possible to supply, for example, 50 mm of irrigation water every 5 days. The irrigation water will then be stored in the root zone and gradually be used by the plants.

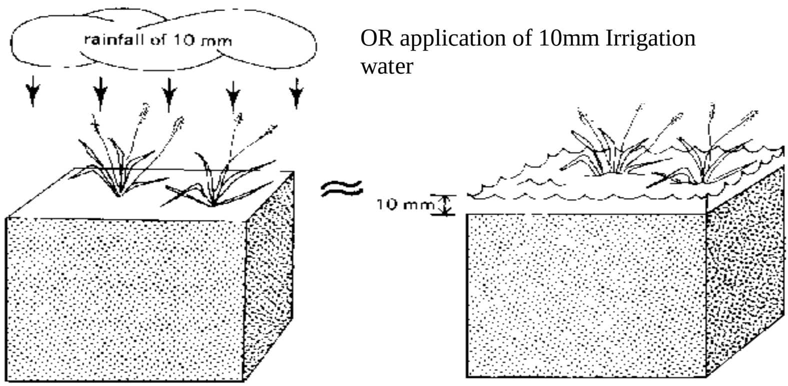


Figure 2. Representation daily water requirement of 10mm

2.1. Factors Affecting ETcrop

The water requirements of plants varied with the plant species and varieties, length of growing season, plant growth stages and climate.

2.1.1. Climate factors affecting ETcrop

A certain plant grown in a sunny, dry humidity and windy climate needs per day more water than the same plant grown in a cloudy and cooler climate. When it is dry, the crop water requirement is higher than when it is humid. In windy climates, the plants will use more water than in calm climates. The time of the year during which crops are grown is also very important. A certain crop variety grown during the cooler months will need substantially less water than the same crop variety grown during the hotter months. Climatic factors which influence the plant water requirement are shown Fig. 3.

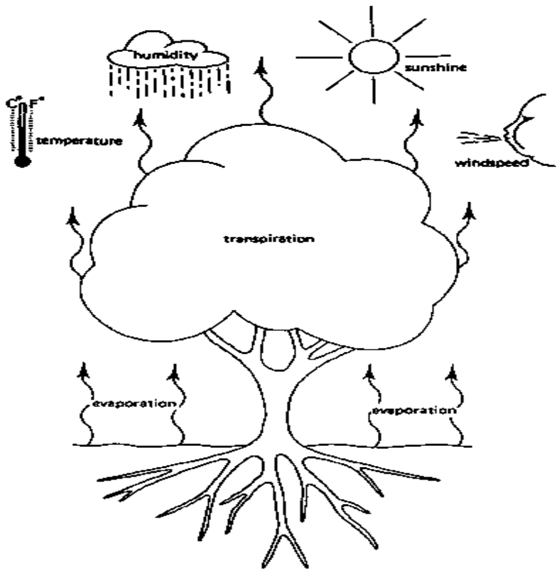


Figure 3. Major climatic variables affecting ET

2.1.2. Crop type affecting ETcrop

Tomato requires less water than pepper and more water than onion. Moreover, fully grown tomato will need more water per day than a fully developed onion. Shorter duration plants require less water than longer duration crops

Table 1 gives some Indicative values for the duration of the total growing season and the crop water requirement for the vegetable crops. There is a large variation of values not only between crops, but also within one crop type. It should, however, be noted that these values are only rough approximations and it is much better to obtain the values locally. In general, it can be assumed that the growing period for a certain crop is longer when the climate is cool and shorter when the climate is warm.

2.1.3. Growth stages affecting ETcrop

The duration of the total growing season has an enormous influence on the seasonal crop water requirement. Fully grown tomato will need more water than at early and late growth stage of the same plant. As has been discussed before, the crop water needs or crop evapotranspiration consists of transpiration by the plant and evaporation from the wet surface. When the plants are very small the evaporation will be more important than the transpiration. The ETcrop increases gradually from crop development stage to the beginning of mid-season. The maximum crop water requirement is reached at the end of the crop development stage which is the beginning of the mid-season stage until it reaches repining stage. When the plants are fully grown the transpiration is more important than the evaporation. The ETcrop also gradually declines from the end of mid-season stage which is the beginning of the ripening stage till maturity (Fig. 4).

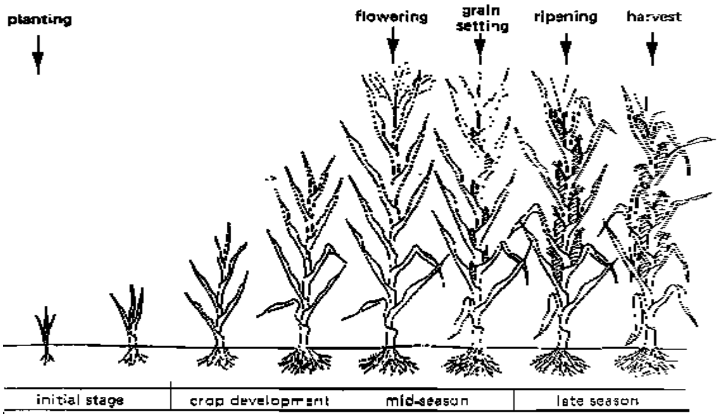


Figure 4. Plant growth stages

2.2 DETERMINATION OF ETCROP

The ETcrop can be determined directly by field experimentation, field lysimeter or it can be estimated indirectly from weather data with predetermined crop coefficient value.

2.2.1. Direct measurement

Field Measurement

In a field experimental, soil moisture is monitored using available methods. The ET for a particular time period can be expressed in the following form of equation:

$$ETcrop = SM_1 - SM_2 + IR + Re + U - D - SR \quad (2.1)$$

where ETcrop is the ET for the time period ΔT (between time of SM_1 and SM_2 reading,

mm); SM_1 is the soil water content at the beginning of the time period ΔT (mm); SM_2 is the soil water content at the end of the time period ΔT (mm); IR is the irrigation amount applied within the time period (mm); Re is the effective rainfall within this time period (mm); U is the upward flux or capillary rise within the time period (mm); D is the deep drainage or percolation within the period (mm); and SR is the surface runoff within the period (mm).

Measurement using lysimeter

A lysimeter can be defined as a large container filled with soil, which is located in the field (to represent the field condition) and isolated from the surrounding field-soil hydrologically, permitting determination of any term of the hydrologic equation (e.g., evapotranspiration, percolation, etc.) when the others are known.

Types of lysimeters

Lysimeters can be grouped into two main categories:

(a) Weighing lysimeter
(b) Nonweighing or drainage lysimeter

The weighing lysimeter has various weighing principles and devices. It may be based on weighing with varieties of scales and balances or on electronic weighing with strain gauge load cells, or a combination of both mechanical and electronic devices, or on hydraulic weighing systems.

The non-weighing lysimeters are also called "volumetric" or "drainage" or "compensation" lysimeters. All the water balance variables in eq. (2.1) be measured using soil moisture measuring devices.

2.2.2. Indirect estimation of ETcrop

Crop water use is influenced by the dynamics of the soil–plant–atmosphere system. In this continuum, water availability is implicit as the most significant limiting factor for growth and final yield. Because of the diversity of physiological, anatomical, and aerodynamic characteristics, different crops have different abilities to use water. It is difficult to evaluate the water needs of each crop individually. In this context, a reference crop evapotranspiration (ETo) concept has been idealized by which the ET of other crops is computed through a conversion factor called crop coefficient. This is known as the two-step approach to determine ETcrop and given by:

ETc = Kc x ETo (2.2)

where ETc is the evapotranspiration of a particular crop for a particular period (mm), Kc is the crop coefficient of the respective crop for the crop period (growth stage) concerned, and ETo is the reference evapotranspiration (mm).

2.3. Determination of Reference Evapotranspiration, ETo

The ETo describes the evaporating power of the atmosphere and as a result determined from meteorological data (air temperature, relative humidity, wind speed, sunshine hours). It was defined by FAO-1992 (Smith et al. 1992) as the rate of evapotranspiration from a hypothetic crop with an assumed crop height (12 cm) and a fixed canopy resistance (70 s m^{-1}) and albedo (0.23), which would closely resemble the evapotranspiration from an extensive surface of green grass cover of uniform height, the green grass actively growing, completely shading the ground and having adequate water.

The ETo could be computed from local climatic data, using various methods/ models. Four method among others used to compute ETo expressed in mm/ day were:

a) Blaney-Criddle method → ETo = C [P*(0.46T + 8)]

where, T is mean daily temperature (0C) for the month; P is mean daily percentage of total annual day time hours and C is adjustment factor

b) Radiation method → ETo = C* (W*Rs)

where, Rs is measured mean incoming radiation (mm/day); W is temperature and altitude dependent weightage factor and C is adjustment factor

c) Penman method → ETo = c*[W*Rn+(1+W) *f(u)*(ea – ed)]

It is now better to use Penman-Monteith method instead.

d) Pan Evaporation method → ETo = Ep * Kp

where, Kp is pan coefficient for different conditions of humidity and wind, pan environment and type of pan and are given in Table 1.

Primarily the choice of method must be based on the type of climate data available and on the accuracy required in determining crop water requirement. Further information and detailed procedure for estimating ETo by the four methods mentioned with worked out examples is given in 'Crop Water Requirements, FAO Irrigation and Drainage paper No. 24.

A method to estimate ETo from pan evaporation data is given below.

Data required are:
(i) Mean pan evaporation (E pan mm/days)
(ii) Estimated values of mean relative humidity (RH%)
(iii) Estimated values of mean wind speed (U in Km/day at 2m height)
(iv) Information whether the pan is surrounded by a cropped or dry fallow area

Example 1: ETo determination
Month: July; Class A pan evaporation: 11.3 mm/day; RH mean – medium, U mean- moderate
Pan surrounded by cropped area of several hectares.
Kp = 0.75 from Table 1 as per the information on RH% and wind velocity
ETo = 0.75 * 11.3 = 8.475 mm/ day

Table 1. Pan coefficient (Kp) for open pans for different ground covers, RH and wind speed

Wind velocity (Km/day)	Windward side Distance of green crop (m)	RH mean		
		Low (<40%)	Medium (40-70%)	High (>70%)
Light (<175)	1	0.55	0.65	0.75
	10	0.65	0.75	0.85
	100	0.70	0.80	0.85
	1000	0.75	0.85	0.85
Moderate (175-425)	1	0.50	0.60	0.65
	10	0.60	0.70	0.75
	100	0.65	0.75*	0.80
	1000	0.70	0.80	0.80
Strong (425 – 700)	1	0.45	0.50	0.60
	10	0.55	0.60	0.65
	100	0.60	0.65	0.70
	1000	0.65	0.70	0.75
Very strong	1	0.40	0.45	0.50
	10	0.45	0.55	0.60
	100	0.50	0.60	0.65
	1000	0.55	0.60	0.65

Updated procedures that has got worldwide acceptance for calculating ETo was established by FAO. According to FAO-1992 (Smith et al. 1992), the Penman-Monteith method gives more consistent ETo estimates. The Penman-Monteith method considers almost all the factors that are known to influence ETo, such as temperature, humidity, sunshine hour, and wind speed. Table 2 presents the output of ETo from CROPWAT 8.0 when using the mean monthly climatic data. The CROPWAT 8.0 also estimates decade and daily ETo when monthly and daily climatic data are used. It is also possibility to estimate climatic data in the absence of measured values.

Table 2. Estimated ETo by Penman-Monteith using CROPWAT 8.0 software

Altitude: 20 m.				**Coordinates: -5.33**		**South**	**12.11 East**
Month	MinTemp	MaxTemp	Humid.	Wind	Sunshine	Radiation	ETo-PenMon
	°C	°C	%	km/day	Hours	$MJ/m^2/day$	mm/day
January	22.8	29.6	81	78	4.0	15.7	3.4
February	22.7	30.3	82	69	4.6	16.9	3.7
March	23.0	30.6	80	78	5.1	17.4	3.8
April	23.0	30.2	82	69	5.0	16.4	3.5
May	22.0	28.6	84	69	3.8	13.5	2.9
June	19.2	26.5	81	69	3.3	12.2	2.6
July	17.6	25.1	78	78	3.2	12.3	2.6
August	18.6	25.3	78	78	2.6	12.4	2.6
September	20.5	26.5	78	104	2.0	12.4	2.8
October	22.5	28.0	79	130	2.2	12.9	3.1
November	23.0	28.7	80	104	3.2	14.4	3.3
December	23.0	29.1	82	95	3.8	15.2	3.4
Year	21.5	28.2	80	85	3.6	14.3	3.1

2.4. Determination of Crop Coefficient, Kc

The value of the crop coefficient (Kc) may be obtained from the literature, or may be determined independently from field experimental data of evapotranspiration. Crop coefficient (Kc) is defined as the ratio of the actual evapotranspiration of a disease-free crop grown in a large field adequately supplied with water to the reference evapotranspiration. It is usually expressed as:

$$Kc = \frac{ETcrop}{ETo} \qquad (2.3)$$

where ETcrop and ETo are the crop evapotranspiration and reference crop evapotranspiration at various growth stages, respectively.

The Kc-value could be obtained from the literature, or may be determined independently from field experimental data of evapotranspiration. To determine/establish crop coefficient for a particular crop from field data, field experiment should be designed with treatments providing sufficient water supply (no deficit). For different growth stages, the evapotranspiration of the crop (ETcrop) should be calculated from water balance equation, as described earlier.

The value varies with crop, development stage of the crop, and to some extent with wind speed and relative humidity. For most crops, the Kc-value increases from a low value at times of crop emergence to a maximum value during a period when the crop reaches full development (for most crops at flower initiation), and declines as the crop matures. The Kc-values for different crops are given in Table 3.

Information required in ETcrop computation are:

- Date of planting
- Length of total growing season
- Duration of initial stage (germination to 10% ground cover)
- Duration of crop development stage (from 10% to 80% ground cover)
- Duration of mid-season stage (from 80% ground cover to start of ripening)
- Duration of late season stage (from start of ripening to harvest)

Computation of crop water requirement without the aid of Cropwat 8.0 model

- ETo could be computed from pan evaporation
- Following the setup in Table 4, ETc on daily, monthly and seasonaly can be obtained without any difficulty.

Example 2: Crop water requirement/ ETc determination

Crop:		Onion			
Planting date		1st February			
Total Growing Season		100			
		Initial	**Develop**	**Mid**	**Late**
Growth stages		15	25	40	20
Kc		0.5	0.8	1.0	0.9

Table 3. Crop coefficient values for different crops (Kc-value)

CROP	Crop Development stages					Total growing period
	Initial	Crop development	Mid-season	Late season	At harvest	
Banana						
tropical	0.4 -0.5	0.7 -0.85	1.0 -1.1	0.9 -1.0	0.75-0.85	0.7 -0.8
subtropical	0.5 -0.65	0.8 -0.9	1.0 -1.2	1.0 -1.15	1.0 -1.15	0.85-0.95
Bean						
green	0.3 -0.4	0.65-0.75	0.95-1.05	0.9 -0.95	0.85-0.95	0.85-0.9
dry	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.25-0.3	0.7 -0.8
Cabbage	0.4 -0.5	0.7 -0.8	0.95-1.1	0.9 -1.0	0.8 -0.95	0.7 -0.8
Cotton	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.9	0.65-0.7	0.8 -0.9
Grape	0.35-0.55	0.6 -0.8	0.7 -0.9	0.6 -0.8	0.55-0.7	0.55-0.75
Groundnut	0.4 -0.5	0.7 -0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Maize						
sweet	0.3 -0.5	0.7 -0.9	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
grain	0.3 -0.5*	0.7 -0.85*	1.05-1.2*	0.8 -0.95	0.55-0.6*	0.75-0.9*
Onion						
dry	0.4 -0.6	0.7 -0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8 -0.9
green	0.4 -0.6	0.6 -0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea, fresh	0.4 -0.5	0.7 -0.85	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
Pepper, fresh	0.3 -0.4	0.6 -0.75	0.95-1.1	0.85-1.0	0.8 -0.9	0.7 -0.8
Potato	0.4 -0.5	0.7 -0.8	1.05-1.2	0.85-0.95	0.7 -0.75	0.75-0.9
Rice	1.1 -1.15	1.1 -1.5	1.1 -1.3	0.95-1.05	0.95-1.05	1.05-1.2
Safflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.7	0.2 -0.25	0.65-0.7
Sorghum	0.3 -0.4	0.7 -0.75	1.0 -1.15	0.75-0.8	0.5 -0.55	0.75-0.85
Soybean	0.3 -0.4	0.7 -0.8	1.0 -1.15	0.7 -0.8	0.4 -0.5	0.75-0.9
Sugarbeet	0.4 -0.5	0.75-0.85	1.05-1.2	0.9 -1.0	0.6 -0.7	0.8 -0.9
Sugarcane	0.4 -0.5	0.7 -1.0	1.0 -1.3	0.75-0.8	0.5 -0.6	0.85-1.05
Sunflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.7 -0.8	0.35-0.45	0.75-0.85
Tobacco	0.3 -0.4	0.7 -0.8	1.0 -1.2	0.9 -1.0	0.75-0.85	0.85-0.95
Tomato	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.95	0.6 -0.65	0.75-0.9
Water melon	0.4 -0.5	0.7 -0.8	0.95-1.05	0.8 -0.9	0.65-0.75	0.75-0.85
Wheat	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.2 -0.25	0.8 -0.9
Alfalfa	0.3 -0.4				1.05-1.2	0.85-1.05
Citrus						
clean weeding						0.65-0.75
no weed control						0.85-0.9
Olive						0.4 -0.6

First figure: Under high humidity (RHmin > 70%) & Low wind speed (U < 5 m/s)
Second figure: Under low humidity (RHmin < 20%) & Strong wind speed (U > 5 m/s)

Important remark on Kc-values

- At initial stage, the Kc-value given above is constant for 15 days from planting.
- At development stage, the Kc-value given above increases linearly from the day it completes initial stage to 80% ground cover, which means for 25 day. Hence, one has to develop linear relationship between Kc-value and days it takes to complete development stage, hence to compute the day to day increase in Kc-value.

  The linear relationship between Kc-value and days to complete the development stage could be obtained from

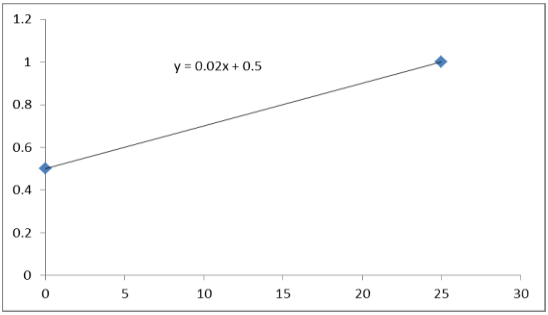
Table 4. Determination of crop water requirement/ ETcrop

Month	ETo (mm day^{-1})	Development stage	No. days	Kc	ETcrop (mm day-1)	ETcrop (mm period-1)	ETcrop (mm/month)
Jan	6.87						
Feb	6.75	Initial	15	0.50	3.38	50.6	
		Development stage	5	0.55	3.78	18.9	
			5	0.65	4.39	21.9	
			3	0.75	5.06	15.2	106.6
March	7.01		2	0.75	5.26	10.5	
			5	0.85	5.96	29.8	
			5	0.95	6.66	33.3	
		Mid-season	19	1.00	7.01	133.2	206.8
Apr	6.09	Mid-season	21	1.00	6.09	127.9	
		Late	5	0.97	5.88	29.4	
			4	0.93	5.66	22.7	179.9
May	6.31	Late season	6	0.90	5.65	33.9	61.0
			5	0.86	5.43	27.1	
Jun	7.06						
Jul	6.86						
Aug	6.7						
Sept	6.21						
Oct	6.18						
Nov	6.76						
Dec	6.88						
Seasonal ETcrop							554.4

Y = ax + b

where, **Y** is the Kc-value at any time for the development stage; x is number of day(s) from completion of initial day; a is the slope and b is the intercept on y-axis.

Slope (a) = Vertical increase = 1.0 – 0.5 = 0.5 = 0.02
Horizontal increase 25 – 0 25

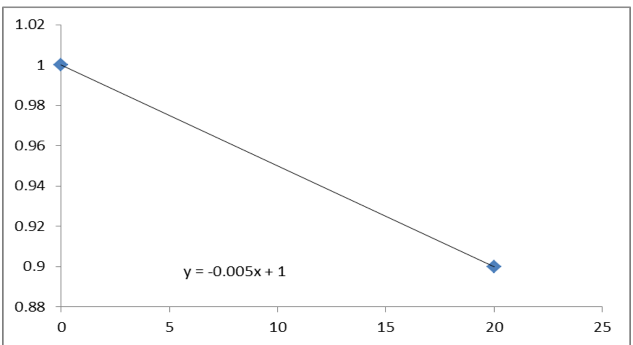


Kc
Days

Figure 5. Kc-value for development stage
Kc = 0.02 x Day(s) + 0.5

- The Kc-value at mid stage is constant and remain constant for 40 days from the day it completes the development stage
- The Kc-value at late-season stage decreases linearly from the day the crop started to show sign of maturity until it completes maturity. In these cases, the crop will take 25 days from the day it shows sign of maturity (leaves start to turn to yellow).

Hence, same linear relationship should be developed: Y = ax + b
Slope (a) = Vertical increase = 0.9 – 1.0 = - 0.1 = - 0.005
Horizontal increase 20 – 0 20
Kc = -0.005 x Day(s) + 1.0



Kc Day

Figure 6. Kc-value for late-season stage

Example 3: CWR determination

Crop: Head cabbage **Location:** Melkassa

RH% = 50 and U_2 = 5 m/s

Length of total growing seasons: 100 days

ETo average condition during the growing season: 5 mm/ day

What is the ETcrop for head cabbage per season?

Solution:

ETcrop = ETo x Kc (Kc from Table 1 for total growing season)
= 5 x 0.8 = 4mm/day
= 4 x 100 = 400 mm/ season

Indicative values of total growing season and crop water requirement are shown in Table 5.

Table 5. Total growing period and crop water requirement for some vegetable and fruit crops

Crop	Total growing period (days)	Seasonal ETcrop (mm)
Cabbage	100 – 150	350 – 500
Carrot	100 – 120	350 – 550
Onion	135 – 175	350 – 550
Pepper	120 – 150	600 – 900
Potato	105 – 150	500 – 700
Tomato	90 – 180	400 – 600
Avocado	300 – 365	1200 – 1600
Banana	300 – 365	1200 – 2200
Citrus	240 – 365	900 – 1200
Mango	300 – 365	1500 – 1700
Papaya	300 – 365	1200 – 1700

3. IRRIGATION WATER REQUIREMENT

Irrigation is generally defined as the artificial application of water by human being to soil for the purpose of supplying the moisture essential for plant growth and production. The total amount of water that must be supplied by irrigation during the crop growth period is termed as **irrigation water requirement (net, IRn)**. The irrigation water requirement of a certain crop is, therefore, the difference between the crop water need and that part of the rainfall which can be used by the crop (the effective rainfall). Mathematically it can be expressed as:

IRn (mm) = ETcrop (mm) – Effective rainfall (mm)

Suppose a tomato crop grown in a certain area has a total growing season of 150 days from February to June. The rainfall incidence, as recorded from the meteorological station, and the ETcrop, as predicted from certain model, are as shown in Table 3.

Irrigation water requirement for the tomatoes can be calculated on a monthly basis and for the total growth period. The total ETcrop of tomatoes over the entire growing season is 786 mm of which 68 mm is supplied by rainfall. The remaining quantity (786 - 68 = 718 mm) has to be supplied by irrigation.

3.1. Effective Rainfall

Not all 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. 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. All rainfall options refer to the computation of the effective rainfall based on the actual rainfall data. One of the follow computation options can be used to compute effective rainfall.

1. **Fixed percentage:** Effective rainfall is a fixed percentage of actual rainfall, being calculated according to:

   Peff = Fixed percentage * P

Where, P is the actual rainfall in mm.

The fixed percentage is to be given by the user to account for the losses due to runoff and deep percolation. The value for fixed percentage has to identified by field experiment for a particular area.

2. **Dependable rainfall (FAO/AGLW formula)**: Based on an analysis carried out for different arid and sub-humid climates, an empirical formula was developed in the Water Service of FAO to estimate dependable rainfall, the combined effect of dependable rainfall (80% probability of exceedance) and estimated losses due to Runoff (RO) and Deep Percolation (DP). This formula may be used for design purposes where 80% probability of exceedance is required. Calculation according to:

Monthly step:

Peff = 0.6 * P - 10 for Pmonth <= 70 mm

Peff = 0.8 * P - 24 for Pmonth > 70 mm

3. **Empirical formula:** Same formula as for Dependable rainfall but with the possibility to change the parameters, which may be determined from an analysis of local climatic records:

Monthly step:

Peff = a * Pmonth - b for Pmonth <= z mm

Peff = c * Pmonth - d for Pmonth > z mm

Values for a, b, c, d and z are correlation coefficients.

3.2. Irrigation Efficiency

While transporting and applying water to the irrigated field, some wastage occurs. Water losses could occur even in best irrigation water management. Thus, some losses of irrigation water are inevitable. When computing irrigation requirement, an efficiency factor needs to be applied to account for losses, therefore, **gross irrigation requirement**.

Gross irrigation requirement, IRg (mm) = Net depth of irrigation, IRn (mm)
Irrigation efficiency
= Management Allowable Depletion (MAD)Irrigation efficiency/ Ea
where Ea is field application efficiency

The most important efficiency terms in connection with irrigation are conveyance, Ec, distribution, Ed, application efficiencies, Ea and overall project efficiencies, Ep and where Ep = Ec x Ed x Ex (Table 6 and 7).

Table 6. Efficiencies for different irrigation systems

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

Table 7. Conveyance, field canal and field application efficiencies (Adapted from: FAO, 1992)

Irrigation System and Type Of Efficiency	USDA	US (SCS)	ICID/ILRI
Conveyance efficiency (E_c)			
- Continuous supply with no substantial change in flow			0.9
- Rotation supply in projects of 3 000-7 000 ha and rotation areas of 70-300 ha, with effective water management			0.8
- Rotational supply in large schemes (> 10 000 ha) and small schemes (< 1 000 ha) with respective problematic communication and less effective management:			
Based on predetermined schedule			0.7
Based on advance request			0.65
Field canal efficiency (E_b)			
- Blocks larger than 20 ha : unlined			0.8
: lined or piped			0.9
- Blocks up to 20 ha : unlined			0.7
: lined or piped			0.8
Field application efficiency (E_a)			
- Surface methods			
light soils	0.55		
medium soils	0.70		
heavy soils	0.60		
Graded border		0.60-0.70	0.53
Basin and level border		0.60-0.80	0.58
Contour ditch		0.50-0.55	
Furrow		0.55-0.70	0.57
Corrugation		0.50-0.70	
- Subsurface		Up to 0.80	
- Sprinkler : hot dry climate		0.60	
: moderate climate		0.70	0.67
: humid and cool		0.80	
- Rice			0.32

Water application efficiency, Ea

$$Ea\ (\%) = \frac{\text{Water stored in the root zone}}{\text{Water delivered to the field}} \times 100$$

Example 4: Irrigation water requirement

Months	Feb	Mar	Apr	May	June	Total
ETcrop (mm/month)	69	123	180	234	180	786
Rainfall: P (mm/month)	20	38	40	80	16	194
Effective rainfall: Pe (mm/month)	2	13	14	39	0	68
Net-irrigation water requirement, IR n(mm)	67	110	166	195	180	718
Gross irrigation requirement, Ea = 0.70	98	157	237	279	257	1026

4. SOIL AND WATER

The soil is an important element in the success of crop production. Their physical, chemical and biological features will partly determine the irrigation provision and greatly influence irrigation management and ultimately crop performance. The soil is a habitat for plants and stores water. This water must be available when plants require it. The water is also is a solvent that, together with the dissolved nutrients, makes up the solution. The soil moisture will also help control two other important components so essential for normal plant growth, viz., soil-air and soil temperature. The availability of soil-water to plants depends upon soil properties such as texture, structure, depth, density, porosity, infiltration and permeability. Therefore, it is essential to now some of important behavior and physical characteristics of the soil in this regard.

4.2. The Soil

Soil is heterogeneous mass and composed of mineral particles and organic matter. The soils originate from the degradation of rocks and are called mineral particles. Some originate from residues of plants or animals (rotting leaves, pieces of bone, etc.), these are called organic particles (or organic matter). The soil particles seem to touch each other, but in reality, have spaces in between. These spaces are called pores. When the soil is "dry", the pores are mainly filled with air. After irrigation or rainfall, the pores are mainly filled with water. Living material is found in the soil. It can be live roots as well as beetles, worms, larvae etc. They help to aerate the soil and thus create favorable growing conditions for the plant roots (Fig. 7).

The soil also stores nutrient and allows the roots of plants to grow and permits the withdrawal of water and nutrient during the plants growth life time. However, the soil characteristics such as texture, structure, bulk density, depth of soil, infiltration or intake characteristics, salinity and water retention characteristics influence farming.

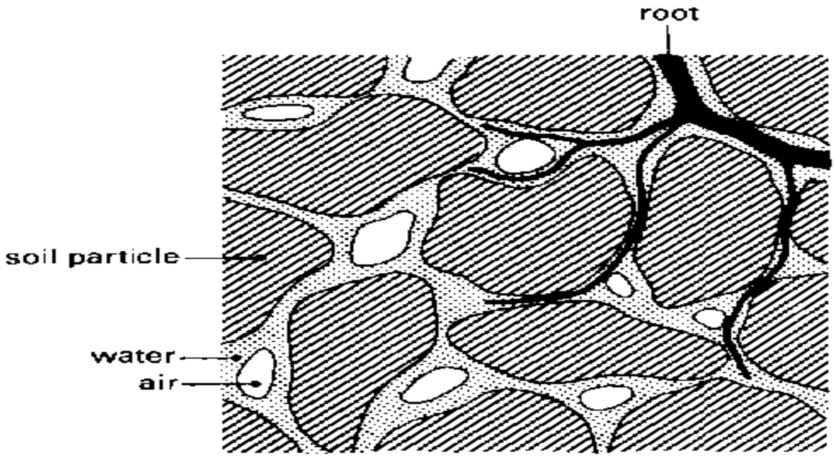


Figure 7. Composition of a soil

4.2.1. Soil profile

If a pit is dug in the soil at least 1 m deep, various layers of different in colour and composition can be seen. These layers are called horizons. This succession of horizons is called the profile of the soil (Fig. 8).

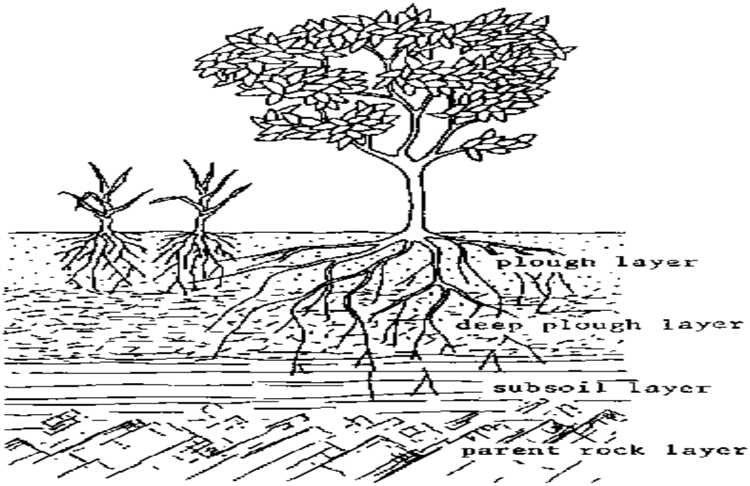


Figure 8. The soil profiles

Figure 8 also shows a plant growing in soil and extends its root system a certain depth into the soil, referred to as the "root zone".

4.2.2. Soil texture

The term soil texture refers to the size range of mineral particles in the soil. These minerals particles are identified by the term 'clay', 'silt' and 'sand'. The texture of a soil is determined mainly by its proportion of clay, silt and sand content.

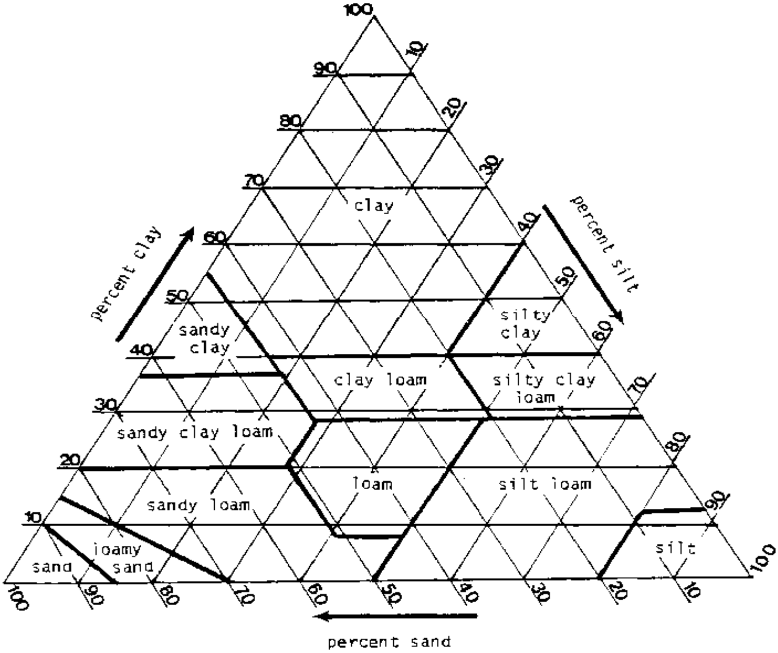


Figure 9. The soil texture triangle (from Handbook No. 436 U.S. Department of Agriculture, Washington, D.C., 1975)

As a general guide a soil is described as:

- Sandy if it has more than 50 % sand and called coarse-textured soils
- Loamy if it has appreciable sand not more than 30 % of clay and called medium-textured soils
- Clayey if it has more than 30 % of clay and less than 50 % of sand and are called fine-textured soils

To make clear distinction in texture, the percentage of sand, silt and clay in a given soil is first determined in a laboratory. Using the data, the texture group is determined by means of a chart called textural triangle chart (Fig. 9). The texture of a soil has a very important influence on the flow of soil water, circulation of air and the rate of chemical transformations which are of importance to plant life.

4.2.3. Soil structure

Soil structure refers to the degree in which individual soil particles aggregate into groups. The particles of coarse-grained soils tend to function as individuals, while the aggregated particles of fine texture soils tend to form granules. The size and shape of these particle groups, and their stability is defined as the soil structure.

Structures are developed and improved by cyclic of wetting and drying, freezing and thawing and combination of these conditions. Organic matter adds stability to the soil aggregate and serves as a cushion against the effect of tillage. Excessive irrigation, plowing, or otherwise working fine textured soils, when either too wet or too dry, tends to destroy the structure. Favorable soil structure particularly in fine textured soils is essential to the satisfactory movement of water and air. The permeability of soils to water, air and roots, provided by favorable soil structure is equally important to crops growth as are adequate supplies of nutrient. The basic types of aggregate arrangements are shown in Fig. 10. Common names for structural types are platy, prismatic, columnar, block, granular and crumb. The most favorable soil structures for agriculture production are usually prismatic, blocky and granular structures. Platy and massive structures which are almost identical in their form impede the downward movement of water. Unlike soil texture, the structure of the soil can be improved.

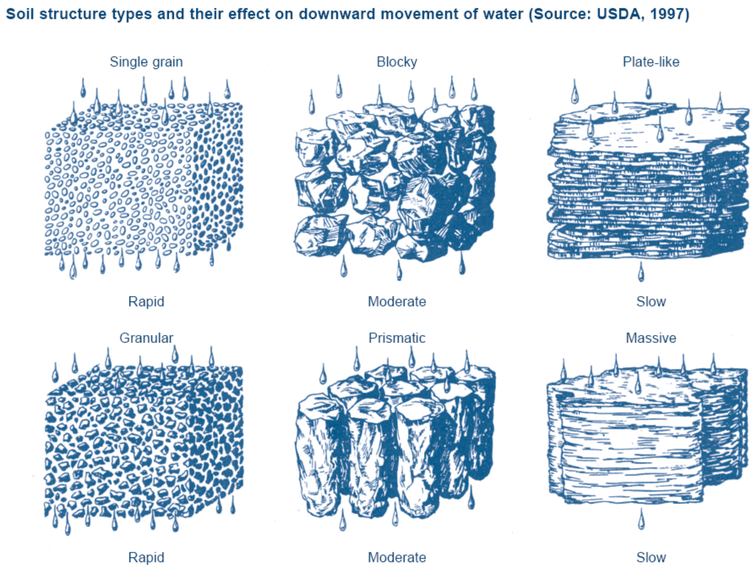


Figure 10. Types of soil structure and their effect on downward movement of water

Both soil texture and structure directly influence the shape, size and volume fraction of soil pores. Soil structure governs characteristics of major concern for plant growth: aeration, temperature, movement of soil solution, microbial activity and root penetration.

4.2.4. **Soil depth**

Soil depth refers to the thickness of the soil materials which provide structural support, nutrients, and water for plants. The depth of soil in which to store satisfactory amounts of water should be given due emphasis. Shallow soils require frequent irrigation water to keep crops growing. Deep soils of medium texture and loose structure permit plants to root deeply, provide for storage of large volumes of /irrigation water in the soil, and consequently sustain satisfactory plant growth during relatively long periods between rain/irrigation.

The volume of water actually absorbed by the same plant roots and consumed to produce a crop may be practically the same for shallow and deep soils, provided the plants are grown under the same climatic condition. Under irrigated condition, more water is required during the crop growth season to irrigate a given crop on a shallow soil than is required for the same crop under a deep soil. The larger number of irrigation required for shallow soils and greater unavoidable water losses at each irrigation on shallow soils account for differences in practical water requirement for different soils during the season.

4.2.5. Soil bulk density

Bulk density refers to the soil overall density/compactness of a soil and should be distinguished from the soil density of the solid soil constituents, usually called the particle density. The bulk density is affected by structure of the soil, i.e., its looseness or degree of compaction, as well as by its swelling and shrinkage characteristics, which are dependent upon clay content and wetness. In sandy soil, soil bulk density can be as high as 1.6 gm/cm^3, where as in loams and clay soils, it can be as low as 1.0 gm/cm^3.

4.2.6. Soil porosity

Roots require oxygen for respiration and other metabolic activities. They also absorb water and dissolved nutrients from the soil, and produce carbon-dioxide, which has to be exchanged with oxygen from the atmosphere. This aeration process requires open pore space in the soil. If roots are to develop well, water plus nutrient and air must be available simultaneously. The soils contain small pores (micro-pores) and large pores (macro-pores). The small pores are used for the storage of water and the large pores are used as channels for the exchange of air and provide adequate drainage condition.

Course-textured soils (sandy soils) have a small percentage of total pore spaces, while fine textured soils (clays) have a greater percentage of total pore space.

4.2.7. Soil infiltration

Soil infiltration refers to the downward flow of water through the soil surface. It is one of the important soil properties having greater importance to irrigation. The infiltration rate depends on physical properties of the soil, such as texture, structure, porosity, moisture content of the soil, degree of compaction, organic matter etc. Knowledge of the soil infiltration rate is a prerequisite for efficient soil and water management. Typical infiltration rate for different soil texture is given in Table 8.

Table 8. Infiltration rates related to soil texture

Soil texture	Representative, I (mm hr^{-1})	Normal range of I ($mm\ hr^{-1}$)	Category
Sandy	50	20 – 250	Rapid
Sandy loam	20	10 – 80	Moderate rapid
Loam	10	10 – 20	Moderate
Clay loam	8	2 – 15	Moderately slow
Silty clay	2	0.3 – 5	Slow
Clay	0.5	0.1 – 8	Very slow

5. IRRIGATION SCHEDULING

Irrigation scheduling is the process of determining when to irrigate and how much irrigation water to apply. In theory, water could be given daily. But, as this would be very time and labour consuming, it is preferable to have a longer irrigation interval. The irrigation water will be stored in the root zone and gradually be used by the plants. The irrigation interval has to be chosen in such a way that the crop will not suffer from water shortage. Different approaches can be used for scheduling irrigation water application. In this manual, irrigation scheduling is based on MAD. The maximum depth which can be given has to be determined and may be influenced by the soil type and the root zone depth.

The **soil type** influences the maximum amount of water which can be stored in the soil per meter depth of the soil. Sand can store only a little water or, in other words, sand has low available water content. On sandy soils it will thus be necessary to irrigate frequently with a small amount of water. Clay has high available water content. Thus, on clayey soils, larger amounts can be given, less frequently. The **root depth** of a crop also influences the maximum amount of water which can be stored in the root zone. **If the root system of a crop is shallow, little water can be stored in the root zone and frequent - but small - irrigation applications are needed. This is the case**

for most vegetable crops except pepper and tomato. With deep rooting crops more, water can be taken up and more water can be applied, less frequently. Young plants have shallow roots compared to fully grown plants. Thus, just after planting or sowing, the crop needs smaller and more frequent water applications than when it is fully developed.

Root zone water content near FC at planting insures rapid early growth and normal root development. Moisture stress from flower initiation to seed formation should be avoided and should be given sufficient irrigation to meet the day-to-day ETcrop demand with a frequency that maintains high soil moisture in the root zone.

Most crops in deep, uniform soils use moisture more slowly from the lower root zone than from the upper soil. The top quarter is the first to be exhausted of available moisture, the plant then has to draw its moisture from the lower three-quarters of root depth (Fig. 11). Monitoring the soil moisture at mid of the plant root zone depth is essential to maintain adequate moisture and to sustain better growth and reproduction of the plant.

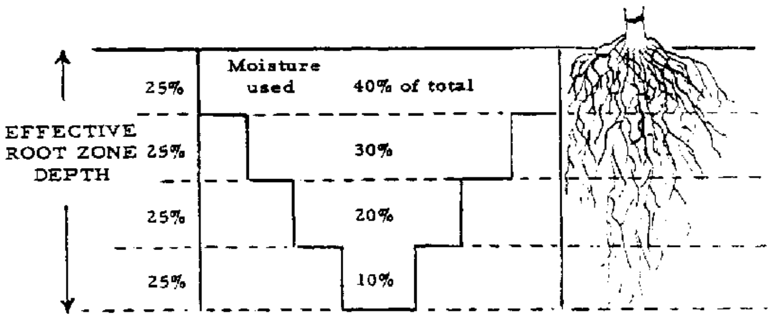


Figure 11. Typical water extraction pattern in uniform soil profile

5.2. Irrigation Scheduling Methods

Irrigations can be scheduled using methods varying from simple soil water monitoring using the feel and appearance method to sophisticated computer assisted programs that predict plant growth. Scheduling involves continual updating of field information and forecasting future irrigation dates and amounts. Crop yield and quality can be improved with most plants by maintaining lower soil-water tensions (higher moisture levels). Thus, it is wise to irrigate when the soil profile can hold a full irrigation. Waiting until a predetermined percent of soil AWC is used can cause unnecessary stress.

5.2.1. Fixed irrigation interval

This is by far the most common practices used in many developing countries. Irrigation turns are mutually agreed and fixed among the growers and irrigation to crops is applied according to fixed pre-determined schedule. This method does not give due consideration to crop water requirements. The crops are either under irrigated or over irrigated, depending upon the crop growth stage and climatic conditions. In general, crops are over irrigated at establishment and maturity stage when crop water requirement is minimum and are generally under irrigated during vegetative, flowering and fruit development stages when crops need maximum water for growth, flowering and fruit bearing. Most vegetable crops are sensitive to soil moisture deficit requiring attention to keep the irrigation schedule within allowable/ manageable moisture deficit level. To attain high yield and quality vegetable crops, irrigation should not be avoided during most sensitive growth stages as indicated in Table 9.

Table 9. Sensitive growth periods of vegetable crops for water shortage

Crop	Growth periods sensitive to water deficit
Cabbage	During head enlargement and ripening
Carrot	Throughout the growth period
Onion	Bulb enlargement, particularly during rapid bulb growth > vegetative period (and for seed production at flowering)
Pepper	Throughout but particularly just prior and at start of flowering
Potato	Period of stolonization and tuber initiation, yield formation > early vegetative period and ripening
Tomato	Flowering > yield formation > Vegetative period, particularly during and just transplanting
Avocado	Flowering and fruiting
Banana	Throughout but particularly during first part of vegetative period, flowering and yield formation
Citrus	Flowering and fruit set > fruit enlargement
Mango	Flowering and fruiting
Papaya	Flowering and fruiting

5.2.2. Computational method

The depth of irrigation water which can be given during one irrigation application is however limited. The maximum depth which can be given has to be determined and may be influenced by the soil type and the root zone depth.

Once it is determined that after how many days the crop should be irrigated then the amount of irrigation to be applied can be computed by working out daily evapotranspiration rate of the crop to be irrigated.

ETc = ETo x Kc

where, ETc = Evapotranspiration rate mm/day; ETo = Reference evapotranspiration rate mm/day and Kc = Crop co-efficient.

ETc can be calculated by a number of methods, most popular being Penman-Monteith Method using local agro-meteorological data. Tables are available which contains Kc values of common crops for different growth stages and for different climate regions. Once ETo and Kc Values are known then it is simple multiplication to calculate daily evapotranspiration (ETc). Then daily ETc is multiplied with the number of days the crop is to be irrigated, to find out the amount of irrigation to be applied.

Step-wise computation of irrigation scheduling for a particular crop

To compute proper irrigation scheduling for crops, it is necessary to know the type of crop, growth stage, effective root zone, available water holding capacity of the soil and daily evapotranspiration rate (ETc) of the crop. Then follow the procedure given below step by step to compute irrigation scheduling.

Step 1. Compute ETo and obtain appropriate Kc-values to get daily ETcrop demand

Step 2. Find out the root zone depth at different growth stages

Step 3. Find out the TASW in the root zone for the respective growth stages

Step 4. Find out MAD

Step 5. Divide step 4 by daily ETcrop (step 1), this will give irrigation interval in days

Step 6. Multiply step 5 with ETcrop (step 1). This will give net irrigation requirement for the given growth stage

Step 7. Divide step 6 with application efficiency, Ea. This will give gross irrigation requirement, IRg.

Step 8. Find out additional irrigation water requirement for leaching out the soil, if needed from:

$$Dw = \frac{IRn}{1 - LR}$$

Once irrigation interval and amount are fixed, it is a matter of computing the discharge and time required to refill the soil moisture. The time required to refill the soil moisture can be obtained from the following relationship:

$$T = \frac{Dw}{I}$$

where T is time required to refill the soil, moisture depleted in hrs, Dw is the depth of irrigation water to be applied in mm and I is infiltration rate of the soil in mm hr^{-1}.

The discharge rate, Q, for a particular field can be obtained from:

$$Q\ (l/s) = \frac{A * d}{T*3600}$$

where Q is in lt./sec, A is area to be irrigated in m^2, d in mm and T in hr

Example 5. Irrigation scheduling based on daily climatic records

Soil type: Medium soil

Total Available Soil water (FC – PWP): 180 mm/m

Crop: Onion

Growth stage	Initial	Development	Mid-season	Late season	Total
Days	25	30	35	20	110

Maximum root depth: 50 cm.

Allowable/ manageable depletion (p): 25%

Soil depth at planting: 30 cm

TASW at 30 cm soil depth: 180 * 0.3= 54 mm

Net irrigation requirement after planting = 54 * p= 54*0.25= 13.5 mm

We need to wait until 13.5 mm depth of water is depleted.

Referring Table 10, 13.5 mm did not occur instead 14.11 mm happened after 12 days from the day of planting in follow-up of day to day computation for ETc and irrigation requirement. Hence, the same procedure should be followed for second irrigation. The root depth increases linearly from the date of planting until it reached 55 days. In order to obtain the root depth after 12 days, one has to develop linear equation and obtain the maximum root depth after 12 days.

Linear relationship between root depth and days from planting:

Y = aX + b = 0.3636*X+30

where Y is root depth (cm); a is slope, X is number of days from planting and b is intercept.

After 12 days the root depth considered is 34.4 cm. Just follow the above procedure to obtain the date of second irrigation (Fig. 12).

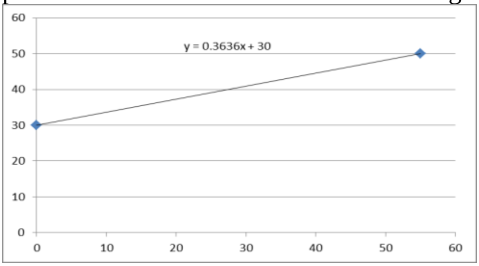


Figure 12. Crop root depth development

Table 10. Crop water requirement, irrigation requirement, net depth of irrigation and cumulative net depth of deficit irrigation

Date	ETo (mm/day)	Kc	CWR (mm/day)	Rainfall (mm/day)	Eff. RF (mm/day)	Deficit Irrg. . Req, (mm/day)	*Net Irrg. Application (mm)*	Cum. Deficit Cum. Irr. Req (mm/period)
12/1/2017	4.74	0.50	2.37	30	16	-13.63	0	-13.63
12/2/2017	5.36	0.50	2.68	0	0	2.68	0	-10.95
12/3/2017	5.3	0.50	2.65	0	0	2.65	0	-8.30
12/4/2017	5.48	0.50	2.74	0	0	2.74	0	-5.56
12/5/2017	5.04	0.50	2.52	0	0	2.52	0	-3.04
12/6/2017	4.64	0.50	2.32	0	0	2.32	0	-0.72
12/7/2017	4.83	0.50	2.42	0	0	2.415	0	1.70
12/8/2017	5.33	0.50	2.67	0	0	2.665	0	4.36
12/9/2017	5.11	0.50	2.56	0	0	2.555	0	6.92
12/10/2017	4.63	0.50	2.32	0	0	2.315	0	9.23
12/11/2017	4.87	0.50	2.44	0	0	2.435	0	11.67
12/12/2017	4.88	0.50	2.44	0	0	2.44	14.11	0.00
12/13/2017	5.08	0.50	2.54	0	0	2.54		2.54
12/14/2017	4.53	0.50	2.27	0	0	2.265		4.80
12/15/2017	5.34	0.50	2.67	0	0	2.67		7.47
12/16/2017	5.19	0.50	2.60	0	0	2.595		10.07
12/17/2017	5.43	0.50	2.72	0	0	2.715		12.78
12/18/2017	5.39	0.50	2.70	0	0	2.695	15.48	0.00
12/19/2017	5.23	0.50	2.62	0	0	2.615		2.61
12/20/2017	5.09	0.50	2.55	0	0	2.545		5.16
12/21/2017	4.95	0.50	2.48	0	0	2.475		7.63
12/22/2017	4.77	0.50	2.39	0	0	2.385		10.02
12/23/2017	4.76	0.50	2.38	0	0	2.38		12.40
12/24/2017	4.79	0.50	2.40	0	0	2.395		14.79
12/25/2017	4.94	0.50	2.47	0	0	2.47		17.26

….. Continue same procedure till crop matures.