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1 Introduction

The main purpose of irrigation is to supplement the soil water reserve in order to operate optimal crop production in regions where it would not otherwise be possible. However, to apply irrigation efficiently, it is essential to measure the requirements of the crop and then applying the correct volume of water in the correct place and at the correct time. This organised way on which water is supplemented, is called irrigation scheduling.

In order to schedule correctly, water must be available on demand at all times. If water is only available to a producer e.g. every four weeks, if he has a turn to use water every four weeks and has no storage dam, he cannot schedule correctly. A distinction must also be made between intensive irrigation and supplementary irrigation. In the latter case, the soil water supply is only supplemented during occasional drought periods in humid climates, or the crop is only supplied with water during critical growth stages. Strictly spoken, scheduling does not apply in supplementary irrigation. The same amount of water used for irrigation at all times with the same cycle length, is also seen as an incorrect concept of scheduling according to the above definition. The water is applied regularly, but obviously the wrong amounts of water at incorrect times.

If irrigation scheduling is applied incorrectly, it can lead to over- or under-irrigation. Under-irrigation mainly damages the size and quality of the harvest, while over-irrigation damages the root system that can cause the crop to die. Although plant roots do not grow in dry soil, it remains healthy and undamaged (within limits) until sufficient water is available again. On the other hand, over-irrigation reduces the air content of the soil, which promotes the contamination by anaerobic pathogens, such as *Phytophthora*. Even in the absence of the pathogens, a low oxygen level in the soil can damage the roots. It is therefor important that the basic principles of irrigation scheduling should always be maintained.

Various factors influence the amount of water applied, i.e., the standing time:

- The effective root depth of the crop and the critical periods during the growing season of the crop when water stress must be avoided (Section 3).
- The size of the soil water reservoir, which is dependent on the soil water capacity of the specific soil and the allowable water depletion from the soil before irrigation (Section 4)
- The irrigation system's gross application rate on the wetted area and the application efficiency of the water application (Section 5).

The question when to irrigate (i.e. the cycle length) is influenced by the following:

- Climatic factors such as rainfall, humidity, etc. (Section 2).
- The evapotranspiration requirements of the crop (Section 3).
- The soil factors as mentioned above (Section 4).
- The wetted strip width of the irrigation system, i.e. the percentage wetting (Section 5).

The influence of the climate and the crop on irrigation scheduling is discussed fully in this chapter, while the other factors, e.g. the irrigation system (**Chapter 2: Choice of system**) and the soil (**Chapter 4: Soil**), is discussed briefly in this chapter, since they are already discussed fully in the chapters mentioned. Examples of the calculation of standing time and cycle length are shown in this manual and depend on the litre water per crop principle. **Chapter 3: Planning and evaluation of an irrigation design** shows the same calculations in mm.

This chapter contains information regarding scheduling techniques obtained from **"Class notes and Water management course"** of the University of Stellenbosch, as edited by Dr. J.E. Hoffman. The information describes scheduling techniques applied in practice, namely, a) the monitoring of the soil water content and/or soil water stress, or b) by calculating evapotranspiration by means of monitoring the climate. Information regarding the climate, crops and evapotranspiration is obtainable from the **Irrigation Design Manual** of the ARC-Institute for Agricultural Engineering.

2 Climate

Climate is influenced by the following:

2.1 Rainfall

Rainfall is the depth of rain measured in a correctly set up rain gauge for a specific period.

2.1.1 Rainfall parameters

The rainfall for an area is often characterised by the average of the total annual rainfall measured over a long period. Usually the results of at least 30 years are used to determine an acceptable average. As extreme values strongly influence the average, a tendency to express rainfall for an area in terms of a median value has arisen. The median is the middle value obtained when yearly values are arranged in ascending order.

The average annual rainfall is used in the planning of dam capacities and also in irrigation water balance calculations. The shorter the period for which averages are determined, the less reliable the results are.

2.1.2 Effective rainfall

All rain that falls is not available to plant roots because of interception, evaporation, run-off and seepage. Rainfall figures are often used as if all rainfall reaches the soil surface. This is not the case as dense foliage needs more water to wet the leaf cover to such an extent that water will move between the leaves to wet the soil. The part of rainfall which remains on branches and leaves of plants is known as intercepted water, which is considered only as water being lost by evaporation and not water which may eventually trickle down the stalk.

A relatively large quantity of water is therefore subtracted from the measured rainfall as evaporation losses and depends mainly on the following:

- Density of foliage: Trees and shrubs intercept more water for the same area than strawberries or onions.
- Leaf area: Leafy crops intercept more water than stalky crops, e.g. potatoes as opposed to wheat.
- Rainfall duration: A short shower will have a higher percentage of interception than a long shower.
- Rainfall intensity: High intensity showers have a lower percentage of interception and vice versa, for the same time.

Statistics obtained from South African weather experts indicate that interception by plants makes up no more than 10 - 15% of annual rainfall. With forests, however, the loss may be as high as 25% of total annual rainfall. There are varied opinions on the hydrological significance of interception, but not in a plant physiological sense. Regarding plant physiologically, intercepted rain is not a loss, as the water on the leaves help to cool the plant, thereby saving an equal amount of groundwater.

In view hereof, interception losses should be seen as an alternative and not as additional to transpiration.

The monthly effective rainfall is determined as follows, using long-term average rainfall figures:

$$R_e = \frac{R_{aver} - 20}{2} \qquad (12.1)$$

where R_e = effective rainfall [mm/month]
R_{aver} = long-term average monthly rainfall [mm/month]

Daily effective rainfall may be determined, amongst others, by the following equation:

$$R_e = R - 1{,}5 E_o \qquad (12.2)$$

where R_e = effective rainfall [mm/day]
R = rainfall [mm/day]
E_o = A-pan evaporation [mm/day]

Effective rainfall is zero if a negative value is obtained.

SAPWAT (Crosby, 1996) may also be consulted for determination of effective rainfall.

2.2 Evaporation

Water evaporation rate depends on humidity, temperature, radiation, air movement and attitude above sea level.

2.2.1 Evaporation measurement

Evaporation is measured by exposing free water to the atmosphere and then determining the loss through evaporation. Therefore evaporation is not really a weather parameter but may be seen as a combination of different influences. The South African Weather Bureau and the Department of Agriculture make use of the American Class A evaporation pan to measure evaporation. The pan is circular, 1,22 m in diameter and 250 mm deep. The water surface height is read off from a scale located diagonally in the water.

As with a rain gauge the evaporation pan must be placed away from obstructions and in such a way that sun and wind can move around it freely. Only direct rain must fall in the pan but it must also not be screened off. The pan must never be in the shadow. The Symonds pan is not recommended for measuring evaporation for irrigation.

2.2.1.1 Erection

The evaporation pan rests on a framework approximately 200 mm high, which is placed level on the ground. The openings between the lower beams of the framework may be filled up but those between the upper beams must be kept clean to promote ventilation and ease leak detection. Grass and weeds around the pan must be kept short.

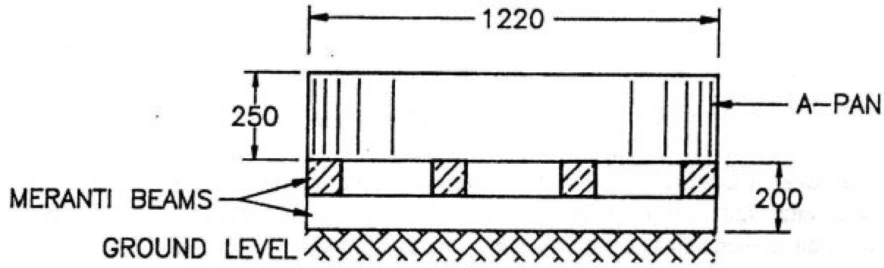


Figure 12.1: Erection of a Class A Evaporation pan

2.2.1.2 Calibrating the scale

A stilling basin which is connected to the main pan by a hole, is provided around the scale. When water is added to the pan, it takes about a minute for the water in the stilling basin to reach the same level, therefore wait a few minutes before taking a reading.

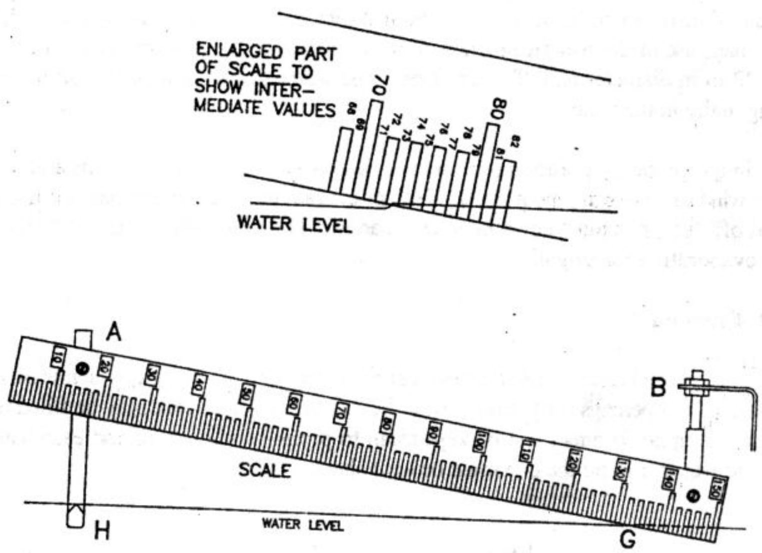


Figure 12.2: The Class A Evaporation Pan scale

The scale is calibrated as follows: Once the pan has been positioned on the framework, it is filled with water until the metal pointer at H (see Figure 12.2) is just submerged. The right hand side of the scale is then adjusted with the nuts at B until the water surface at G gives a scale reading of 138, and locked in position. Then the pan is filled until the scale reading is approximately 50, this reading being recorded in column 4 (see Table 12.1). This process is repeated whenever the pan is cleaned or moved.

Evaporation pan readings may be recorded on a form (see Table 12.1) which makes provision for the date (column 1), rainfall (column 2), water level before regulation (column 3), water level after regulation (column 4) and evaporation (column 5).

2.2.1.3 Reading the scale

As with all weather readings, the evaporation is measured at 08:00. The position where the scale cuts the water surface is wetted by finger before reading the scale. The reading at the contact point is then taken. Note that the white lines on the scale indicate EVEN values (e.g. 70, 72, 74, 76, 78) while the blue lines indicate UNEVEN values (e.g. 71, 73, 75, 77, 79). The value to be recorded from the enlarged part of Figure 12.2 is 73. Regularly make sure that the connecting hole between the pan and stilling basin is not blocked.

The evaporation for a specific day is determined by subtracting the reading for that day from the value in column 4 from the previous day, dividing the difference by two and adding it to the rainfall for the day. The unit is millimetre. Evaporation pan readings are divided by two to allow for the enlarged scale used in the Class A Evaporation Pan. NB: When the water level is higher than 50 mm due to rain, water is removed until approximately the 50 level and the value recorded in column 4. When the water level is lower than 100 due to evaporation, water is added up to approximately 50 and the value recorded in column 4.

Example 12.1:

(See Table 4.1) Reading procedure for Class A Evaporation Pan

- *Day 1: Start with a reading of 50 and record it in column 4.*
- *Day 2: Read the water level, record the value, e.g. 72 in column 3 as well as column 4, determine the A-pan evaporation for day 1 as indicated and record it in column 5.*
- *Day 3: The same as for day 2.*
- *Day 4: Read the water level, record the value, e.g. 112 in column 3 and regulate to ± 50 by adding water.*
  Water level after regulating: In this case it is 48 which is recorded in column 4, the A-pan evaporation is determined as indicated and recorded in column 5.
- *Day 5: The same as for day 2 and 3.*
- *Day 6: Record the rainfall for day 5 in column 2. Record the water level reading in column 3 and 4, determine the evaporation as indicated and record in column 5.*

Table 12.1:An example of recording A-pan evaporation reading

1	2	3	4	5	
Date	**Rainfall [mm]**	**Water level before regulating [mm]**	**Water level after regulating [mm]**	**Evaporation [mm]**	**Calculations**
1			50		
2		72	72	11	$\frac{72 - 50}{2} = 11$
3		97	97	12,5	$\frac{97 - 72}{2} = 12,5$
4		112	48*	7,5	$\frac{112 - 97}{2} = 7,5$
5		72	72	12	$\frac{72 - 48}{2} = 12$
6	12	62	62	7	$\frac{62 - 72}{2} + 12 = 7$

* *Water added to A-pan*

2.2.1.4 Maintenance

It is imperative that the pan regularly be cleaned once per month. The following procedure is followed:

- Record the scale reading.

- Invert the pan and remove all accretions, silt, duckweed, etc. Ensure that the connecting hole between the pan and stilling basin is open. Rinse the whole pan thoroughly.

- Inspect the pan, especially the base and seams for possible leakages and rust spots. When rusting becomes severe, the A-pan must be painted with aluminium bituminous paint.

- Always clean the openings between the upper beams to ensure good ventilation

- Re-erect the pan level as close as possible to the previous position on the frame. Fill with water and calibrate the scale as indicted in Section 2.2.1.2.

- Fill the pan to the starting reading prior to cleaning.

2.3 Radiation

All daily, seasonal and cyclic climate changes can be traced back to the energy that reaches the earth in the form of electromagnetic radiation from the sun.

Radiation intensity is expressed in terms of watt per square metre [W/m^2]. The intensity relates to the rate at which energy is received. At times it may be necessary to indicate a quantity of energy. The unit of energy is the joule [J]. An intensity of 1 W/m^2 is equal to 1 J/s per m^2. The intensity of full summer sunlight is in the order of 1 000 W/m^2.

It is often referred to as light intensity when radiation relates to photosynthesis. Light is the radiation to which the human eye is sensitive. Plants, however, do not react to radiation in the same way as the human eye. It is therefore incorrect to compare light, as observed by eye, to photosynthesis. The unit of light intensity is the lux [l×] (1 $W/m^2 \approx$ 680 lx).

Radiation measurement is usually done by measuring the temperature relationship which occurs when the sun shines on a blackened surface. Radiometers must be handled with great care.

2.4 Sunshine duration

In reality sunshine duration (when the sun shines) should be considered as the period between which the sun just begins to appear above the horizon until it just disappears below the horizon. Weather experts consider sunshine duration as the period of "full" sunshine. According to this definition full sunshine occurs when the sun burns a visible mark on special paper through a glass sphere of specific dimensions. (There are also other so-called sunshine meters, so full sunshine will depend on which one is used.) Electronic sunshine meters are available but not widely used due to high costs. In South Africa, the sunshine duration is measured with the Campbell-Stokes sunshine meter.

2.5 Temperature

The measuring unit for temperature is Kelvin [K]. In South Africa air temperature is indicated in degrees Celsius [ºC]. It is, however, acceptable to use ºC as the unit for temperature (K = ºC + 273).

In measuring temperature, special care must be taken to eliminate the effect of sun radiation or radiation from the earth's surface. Temperature is measured with suitable thermometers in a Stevenson shield. The Stevenson shield is used to house measuring instruments and is designed to shield as many of the sun's rays and reflections from the earth's surface as possible from the instruments, while allowing unrestricted air-flow over them. The purpose is to measure air temperature without the influence of radiation.

The Stevenson shield is erected on a metal frame so that the instruments therein are 1,2 m above the ground. The shield must open southwards so that the sun does not shine on the instruments when readings are taken.

A Stevenson shield usually contains a maximum, minimum and standard or dry bulb thermometer. The maximum and minimum thermometers are mostly only read twice per day and indicate the highest and lowest temperatures respectively, since the previous readings. The standard thermometer indicates the temperature at the time of reading. At times a continuous record of the temperatures is required, which can be measured with a thermograph. Thermograph readings must always be corrected by comparing them to the maximum and minimum thermometers.

Both extremely high and low temperatures can have an adverse effect on a crop. Cooling as well as frost combating can be executed by application of water during critical periods and it will have an influence on the total water requirement of the crop. It may also be necessary to install an additional irrigation system to meet these requirements. Provision for the additional required water must therefore be made during planning, as well as for as the costs it may implicate.

2.6 Water vapour

The relationship between the different gases comprising the atmosphere is exceptionally constant, the only exception being water vapour which can change from one minute to the next. The atmosphere is saturated when the maximum water vapour is present. When saturated air is cooled, excess water vapour will condense in the form of clouds, mist, dew or frost. Alternatively the air will become unsaturated with an increase in temperature. Such air can become very "dry" without losing any water vapour, depending on the temperature increase.

Relative humidity is usually measured with a hygrograph placed in a Stevenson sun shield, the measuring element being human hair which stretches as it becomes moist. Water vapour can also be measured with two thermometers, the bulb of one being covered with a moist cloth. The dryer it becomes, the quicker water evaporates from the moist cloth, cooling the bulb down (like a canvas water bag). The relative moisture can be obtained from tables (see Table 12.2) by making use of the temperature difference between the dry and wet bulb thermometers. The cloth on the wet bulb thermometer should ideally be moistened with distilled water.

A measure of the actual amount of moisture present in the air is the dew point. The dew point is the temperature at which air will be saturated with water vapour provided that it is cooled down at a constant pressure. Dew point is not dependant on temperature like relative humidity and it is also measured in K or ºC.

Table 12.2: Percentage relative humidity, only applicable for heights from the sea level to 450 m above sea level and wind speeds < 1,5 m/s.

Dry bulb [ºC]	**Difference between wet and dry bulb thermometer reading [ºC]**																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
50	95	89	84	80	75	71	66	62	58	54	51	47	44	41	37	34	32	29
49	95	89	84	79	75	70	66	62	58	54	50	47	43	40	37	34	31	28
48	94	89	84	79	74	70	66	61	57	53	50	46	43	39	36	33	30	27
47	94	89	84	79	74	70	65	61	57	53	49	45	42	39	35	32	29	26
46	94	89	83	79	74	69	65	60	56	52	48	45	41	38	35	31	28	26
45	94	89	83	78	73	69	64	60	56	52	48	44	41	37	34	31	28	25
44	94	89	83	78	73	68	64	59	55	51	47	43	40	36	33	30	27	24
43	94	88	83	78	73	68	63	59	55	51	47	43	39	36	32	29	26	23
42	94	88	83	78	72	68	63	58	54	50	46	42	38	35	31	28	25	22
41	94	88	83	77	72	67	62	58	53	49	45	41	37	34	30	27	24	21
40	94	88	82	77	72	67	62	57	53	48	44	40	37	33	29	26	23	20
39	94	88	82	77	71	66	61	57	52	48	44	40	36	32	28	25	22	18
38	94	88	82	76	71	66	61	56	51	47	43	39	35	31	27	24	20	17
37	94	87	82	76	70	65	60	55	51	46	42	38	34	30	26	23	19	16
36	94	87	81	76	70	65	60	55	50	45	41	37	33	29	25	21	18	15
35	93	87	81	75	70	64	59	54	49	44	40	36	32	28	24	20	17	13
34	93	87	81	75	69	64	58	53	48	44	39	35	30	26	23	19	15	12
33	93	87	80	74	69	63	58	52	47	43	38	34	29	25	21	17	14	10

Table 12.2:(continued)

Dry bulb [ºC]	Difference between wet and dry bulb thermometer reading [ºC]																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
32	93	86	80	74	68	62	57	52	46	42	37	32	28	24	20	16	12	8
31	93	86	80	73	67	62	56	51	45	41	36	31	27	22	18	14	10	7
30	93	86	79	73	67	61	55	50	44	39	34	30	25	21	17	13	9	5
29	93	86	79	72	66	60	54	49	43	38	33	28	24	19	15	11	7	3
28	93	85	79	72	65	59	53	48	42	37	32	27	22	18	13	9	5	1
27	92	85	78	71	65	59	52	47	41	36	30	25	21	16	11	7	3	-
26	92	85	78	71	64	58	51	46	40	34	29	24	19	14	9	5	-	-
25	92	84	77	70	63	57	50	44	38	33	27	22	17	12	7	3	-	-
24	92	84	77	69	62	56	49	43	37	31	26	21	15	10	5	-	-	-
23	92	84	76	69	62	55	48	42	36	30	24	18	13	8	3	-	-	-
22	92	83	76	68	61	54	47	40	34	28	22	16	11	5	-	-	-	-
21	91	83	75	67	60	52	46	39	32	26	20	14	8	3	-	-	-	-
20	91	83	74	66	59	51	44	37	30	24	18	12	6	-	-	-	-	-
19	91	82	74	65	58	50	43	35	29	22	15	9	3	-	-	-	-	-
18	91	82	73	65	56	49	41	34	27	20	13	7	-	-	-	-	-	-
17	90	81	72	64	55	47	39	32	24	17	10	4	-	-	-	-	-	-
16	90	81	71	62	54	46	37	30	22	15	8	1	-	-	-	-	-	-
15	90	80	71	61	52	44	36	27	20	12	5	-	-	-	-	-	-	-

Table 12.2: (continued)

Dry bulb [ºC]	Difference between wet and dry bulb thermometer reading [ºC]																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
14	90	79	70	60	51	42	33	25	17	9	2	-	-	-	-	-	-	-
13	89	79	69	59	49	40	31	23	14	6	-	-	-	-	-	-	-	-
12	89	78	68	57	48	38	29	20	11	3	-	-	-	-	-	-	-	-
11	88	77	66	56	46	36	26	17	8	-	-	-	-	-	-	-	-	-
10	88	77	65	54	44	34	24	14	5	-								
9	88	76	64	53	42	31	21	11	1									
8	87	75	63	51	40	29	18	7	-									
7	87	74	61	49	37	26	14	-	-									
6	86	73	60	47	35	23	-	-	-									
5	86	72	58	45	32	-	-	-	-									
4	85	70	56	42	-	-	-	-	-									
3	84	69	54	-	-	-	-	-	-									
2	84	68	-	-	-	-	-	-	-									
1	83	-	-	-	-	-	-	-	-									

2.7 Wind

Wind originates due to differences in air pressure. Air moves from an area of high pressure to one of low pressure. These pressure differences may occur locally or could originate in pressure systems spanning thousands of kilometres.

Wind measurement consists of two components, namely direction and speed. At most weather stations only speed is measured by means of an anemometer, which has three circular cups mounted on a vertical axis. The speed with which the cups rotate is proportional to the wind speed. The axis about which the cups rotate is connected to a mechanical counter which is read at a fixed time (always 08:00). The "distance" that the wind has moved during a period of time is measured by determining the difference between two consecutive readings. The "distance" usually describes the wind run and may be interpreted as the average wind speed for the particular period.

For most purposes the average wind speed, over a long period as measured with ordinary anemometers, is of little value. The average speed and direction is usually required for a shorter period, like an hour. In many cases, instant peak values are also important. There are various types of wind meters using different techniques to continually measure and register wind speed and velocity.

Wind meters are erected so that air movement at a height of 2 m or 10 m is measured. It is important to keep the area of exposure free from obstructions as wind measurement is strongly influenced by local conditions. The recognised unit for wind speed is metres per second [m/s], although it is often indicated in km/hour (1 m/s = 3,6 km/hour). Seafarers use knots, one knot being equal to 0,514 m/s.

With certain instruments air movement is measured over long periods of 6 hours or 24 hours, normally referred to as wind run. Wind run is measured in kilometres and is equivalent to the distance travelled by an air particle during the particular period at the average wind speed. Wind direction is given as the compass direction that the wind is blowing from.

3 Crops

Crop water requirements depend on the relationship between water absorption and transpiration.

3.1 The role played by water in plants

More than half of all living fibre, as well as more than 90% of all plant fibre, consists of water, therefore water is by far the largest plant component. Water influences the metabolism, physiological activity and growth of plants, also functioning as a solvent in plants in which gases, minerals and organic solutions are transported from one part to another. Water plays an important role within the plant, with photosynthesis and many hydrological processes as well as maintaining turgor which is imperative to cell enlargement and produces plant growth.

More than 90% of the water absorbed by a plant's roots is released in the atmosphere as water vapour. The process is known as transpiration and is defined as the loss in water to the atmosphere from a growing plant, which is regulated by physical and physiological processes in the plant.

Why do plants then lose such large quantities of water through transpiration? The answer lies in the composition of a leaf. The main function of a leaf is photosynthesis, which manufactures food for the entire plant, the required energy being obtained from sunlight. The plant must therefore expose the largest possible transpiration area to sunlight. Sunlight is, however, only one of the requirements of photosynthesis, as the chlorophyll also requires carbon dioxide. Carbon dioxide is normally readily available in the air surrounding the plant, but before it can reach the plant cells by diffusion, it must be dissolved. Carbon dioxide in the air must come into contact with a moist cell surface because the cell walls cannot readily absorb it in a gaseous form. Evaporation occurs wherever water is exposed to air. The evaporation of water from the leaf surface has a two-fold function, namely the absorption of carbon dioxide as described above and plant cooling.

Plants have developed a number of special methods to limit evaporation which in turn limits carbon dioxide absorption. Photosynthesis and loss of water through transpiration are therefore firmly bound in the life of green plants.

3.2 Plant roots

Plant activity is normally proportional to soil water availability and therefore also the rate of water absorption by the root system. While small quantities of water may be absorbed by external plant components under certain conditions, the root system is usually the organ of absorption for virtually all the water required by upper plant sections. Therefore the root system depth of each crop determines the soil water reservoir size or the total available water in normal and deep soils. The water withdrawal pattern is then determined by the lateral distribution and specific properties of the roots.

Absorption of water and food substances takes place through the root hairs. Older root sections suberise and transmit less water and dissolve food substances.

Plant roots make contact with water in two ways:

- capillary movement of water to the roots and/or
- root growth from dry to moist areas.

Osmosis is the process by which root hairs absorb water - it is the movement of water through a selectively permeable membrane from a higher water potential to a lower water potential. When roots absorb water, the soil water content reduces at that point, causing an increase in the soil water tension, binding the remaining water. The soil water tension will be at its highest when the soil moisture content has dropped close to wilting point, in other words, the attracting or suction force of the water in the soil is at its highest. However, rapid root growth during active growth periods maintains sufficient water contact even though the soil water profile is decreasing as a whole and no capillary addition occurs. In any case, root growth is more rapid than capillary water movement during active root growth. It may eventually happen that the roots are unable to supply water to the plant fast enough -this is called temporary wilting and if it continues too long, the plant may wilt permanently.

3.2.1 Root systems

The nature of the root system which a plant can develop under optimal soil and climatic conditions is predetermined by its genetic code (see Table 4.3 and Figure 4.3). Therefore each plant species has its own characteristic, natural root growth pattern. Some plants have a tap root which tends to penetrate rapidly, deep into the subsurface layers while others have slowly growing roots which develop a shallow, primary system with many lateral, secondary and tertiary roots. The natural lateral root distribution of trees is normally as wide as the drip area of the tree.

Table 12.3: Natural root depth

Crop	Natural root depth [mm]
Almonds	900+
Apricots	500+
Avocados	900
Bananas	500
Beans	600
Brassicas	500
Citrus	900+
Clover	300
Grapes	900
Green peas	450
Lucern	900+
Macadamia	900
Maize	600+
Mangos	600+
Olives	900
Onions (transplanted)	450
Onions (seed)	600
Pecan nuts	900
Pineapple	450
Potatoes	350
Tomatoes	600
Wheat	900+

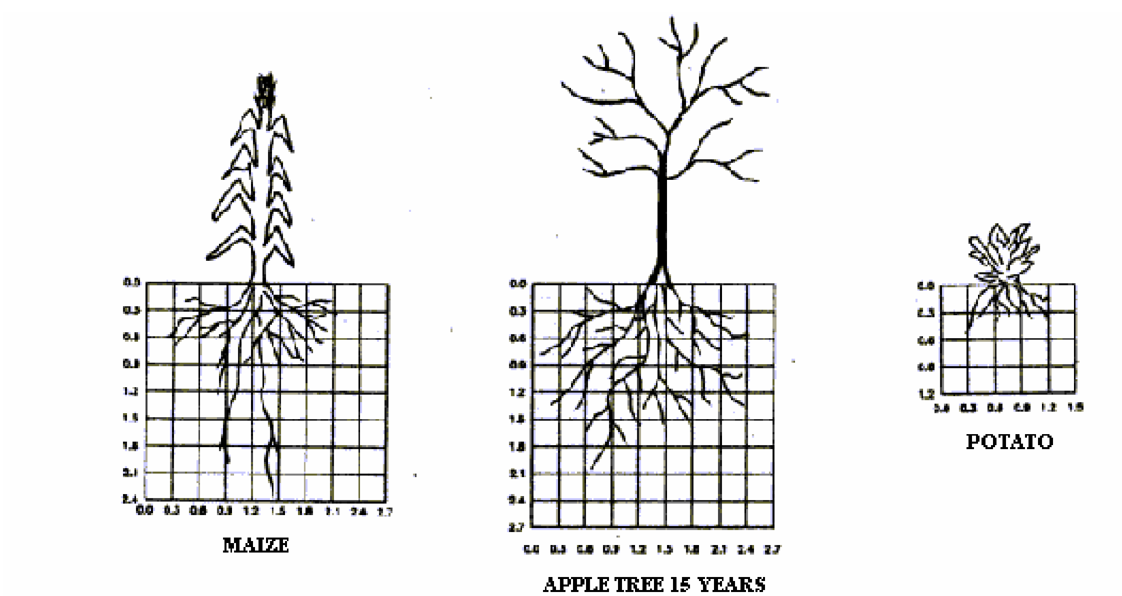


Figure 12.3: Natural root depth and distribution

3.2.2 Factors influencing root development

Root penetration is seriously deterred by dense subsurface ground layers and the root depth in many South African soils is limited to the upper 250 mm of the profile by a plough sole. Roots cannot penetrate a hard layer unless cracks occur and find it difficult or impossible to grow from one to another soil layer where the texture differs drastically. A factor limiting root growth may also be a shortage of plant food substances or an underground chemical imbalance. Root growth is limited by a high water profile.

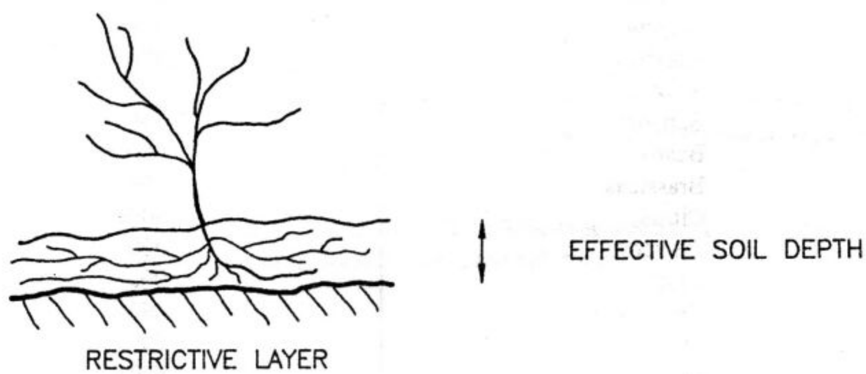


Figure 12.4: Root development due to physical and chemical soil limitations

Most roots will occur in the wetted area when soil is only partially irrigated, e.g. with drip irrigation. Root depths will also be influenced by irrigation practices, e.g. with a too short cycle length and standing time, most plants will tend to develop a shallow root system to adapt to the shallow wetted depth.

3.3 Groundwater withdrawal patterns

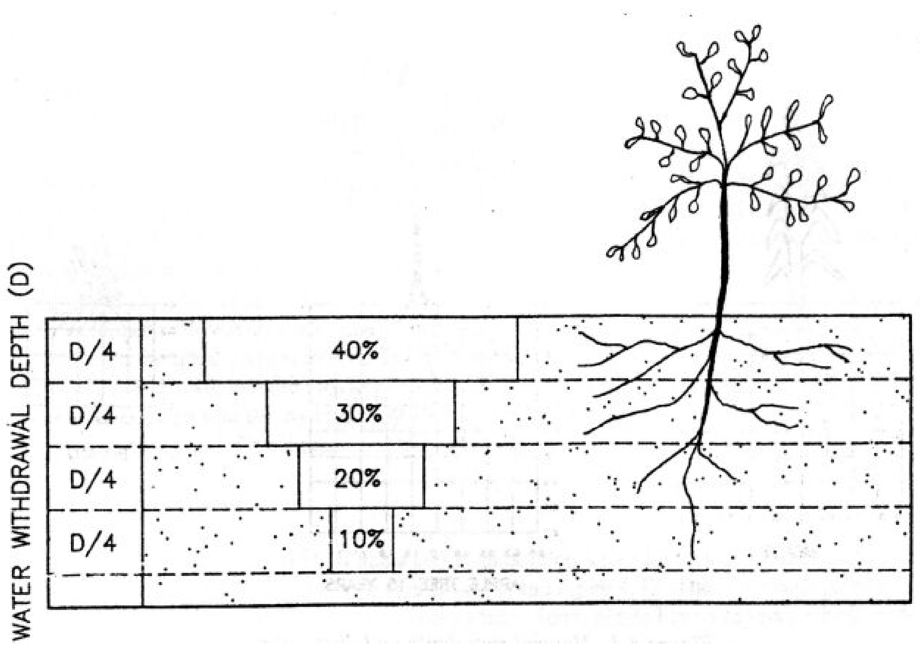


Figure 12.5: Typical plant water withdrawal pattern

With most plants the active roots are mainly concentrated in the upper part of the root zone (see Figure 12.5). Therefore the most rapid water withdrawal occurs in the area of highest root concentration under favourable temperature and aerating conditions.

The reduction of groundwater also takes place more rapidly in the upper soil layer as groundwater evaporates directly from it. With the reduction in available water in that part of the root zone, the soil water tension binding the remaining water increases. Plants then withdraw water at a deeper level where it is bound with less energy.

3.4 Evapotranspiration

The combined loss of water from a given surface during a specific time by evaporation from the ground surface and through plant transpiration is known as evapotranspiration.

Only a small part of the water which a plant absorbs from the soil is taken up by the plant cells. By far the largest part of the water is released through the stoma to the atmosphere by transpiration. A plant's water consumption varies during the season and with a crop increase, the water requirement also increases to a point. Plant water absorption is also higher with a high groundwater level.

3.4.1 Daily and seasonal evapotranspiration

Evapotranspiration is at its highest during the middle of the day and lowest during the night. Seasonal evapotranspiration is used to determine the amount of water required for irrigation during one season.

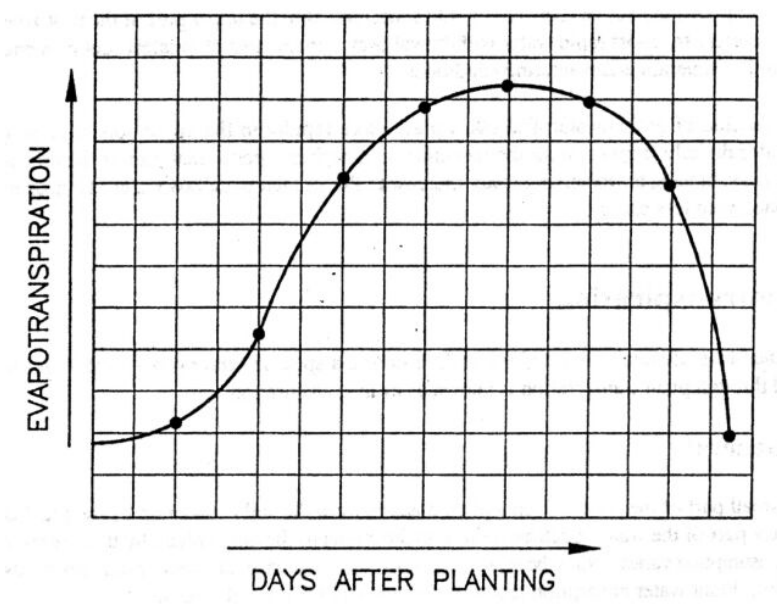


Figure 12.6: Typical seasonal evapotranspiration

3.4.2 Peak periods of evapotranspiration

The peak period is the plant's growth stage with the highest average evapotranspiration. An irrigation system must be designed to supply sufficient water during the plants' peak period of evapotranspiration. This peak consumption period usually occurs when plants start to produce their crops.

3.4.3 Factors influencing evapotranspiration

The rate of groundwater withdrawal by the evapotranspiration process is mainly determined by:

- climate
- groundwater storage
- irrigation practice
- soil texture
- tilling practice
- type of natural plant or crop being cultivated
- salinity of soil or irrigation water

Of the above, climate is the factor which has the highest influence on evapotranspiration

The use of mulch also has an effect on evapotranspiration. The mulch may consist of organic material (such as hay) or a permanent green crop (such as clover). In the case of dry material, the mulch can aid in limiting evaporation from the soil and thereby reduce the evapotranspiration. The irrigation requirement is therefore reduced. There is however a danger that the organic material may prevent the crop from absorbing the chemicals applied to the surface. In the case of green mulch, the evapotranspiration will increase as a result of the water utilised by the mulch crop. Provision must therefore be made for the additional irrigation water required during system planning.

3.4.4 Effect of groundwater levels on crop growth and harvests

Most plants absorb water easily at a high minimum water level (low soil water depletion level) provided that sufficient air is present in the soil. As the groundwater level reduces, the plant must use more energy to withdraw water from the soil. Crop damage may occur if the groundwater level drops too low and plants may wilt temporarily or even permanently if the condition continues too long.

3.4.5 Critical periods

Most plants have a critical period during the growth season when a high groundwater level must be maintained for optimal production. If enough water is available for germination as well as the development of a sufficient growth density with yearly crops, the critical period will generally occur during the latter part of the growing season. This is during the period of flowering to fruit ripening.

Table 12.4: The critical periods of crops

Crop	Critical period
Almonds	Blossoming, shoot growth, cell division, fruit growth
Avocados	Flowering, cell division, fruit growth
Bananas	Flowering, cell division, fruit growth
Beans	Blossoming until fruit growth
Brassicas	Remaining 50 days before harvesting
Citrus	Blossoming, cell division, fruit growth
Clover	Continually
Deciduous fruit	Blossoming, shoot growth, cell division, fruit growth
Grapes	Budding, flowering, cell division, fruit growth
Macadamia	Flowering, cell division, fruit growth
Maize	Plum forming until beard forming
Mangos	Flowering, cell division, fruit growth
Olives	Blossoming, cell division, fruit growth
Onions	Bulb formation until harvesting
Peas, green	Blossoming until fruit growth
Pecan nuts	Flowering, cell division, fruit growth
Pineapple	Vegetative growth stage
Potatoes	Blossoming until harvesting
Tomatoes	Flowering until harvesting
Wheat	Ear appearance until ear completion

3.4.6 Determination of crop-evapotranspiration

Determination of crop-evapotranspiration is the first step in project planning and the design of irrigation systems.

Various methods are used worldwide to determine crop-evapotranspiration, but only those used in South Africa will be treated in this section.

3.4.6.1 A-pan evaporation with crop factors

This method assumes that, for a given period, crop-evapotranspiration (ET_c) is directly proportional to the A-pan evaporation (E_o).

The standard method currently in use in South Africa is based on the average monthly A-pan evaporation and crop factors. The place and vicinity where the A-pan is erected is important in obtaining a true reflection of the evaporation. Different crops have different crop factors which vary during the growth season and should be adapted to suit the area as shown in Appendix A.

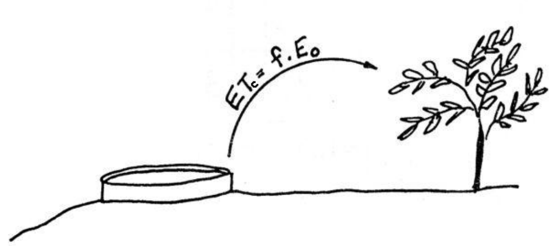


Figure 12.7: Direct determination of crop-evapotranspiration by using A-pan evaporation and crop factors

The equation to determine crop-evapotranspiration (ET_c) directly from A-pan evaporation is as follows:

$$ET_c = f\ E_o \qquad (12.3)$$

where ET_c = crop-evapotranspiration [mm/period]
f = crop factor for direct use with A-pan evaporation [fraction]
E_o = A-pan evaporation [mm/period]

3.4.6.2 Penman-Monteith method (short grass reference)

The alternative method for the calculation of crop-evapotranspiration depends on the use of climate data from weather stations and the amended Penman-Monteith equation. Crop-evapotranspiration can be calculated by means of the following equation:

$$ET_c = k_c\ ET_o \qquad (12.4)$$

where ET_c = crop-evapotranspiration [mm/period]
k_c = crop coefficient [fraction]
ET_o = reference evapotranspiration [mm/period]

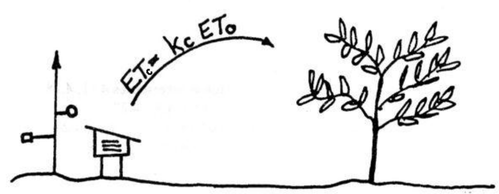


Figure 12.8: The calculation of crop-evapotranspiration with the aid of a weather station

The computer program, SAPWAT, uses crop coefficients for the estimation of crop-evapotranspiration for all crops irrigated in South Africa. The program is available on the Internet on http://sapwat.org.za (please note; no www address) and can be used to examine different irrigation approaches. Training is however essential.

The reference evapotranspiration is shown in SAPWAT as average daily values per month for the different weather stations. Figure 12.9 is an example of the screen on SAPWAT where the reference evapotranspiration is shown for a specific weather station (Kakamas). The bottom curve on the graph is the Penman-Monteith reference evapotranspiration (ET_o) and the top curve is the A-pan evaporation values at the same station.

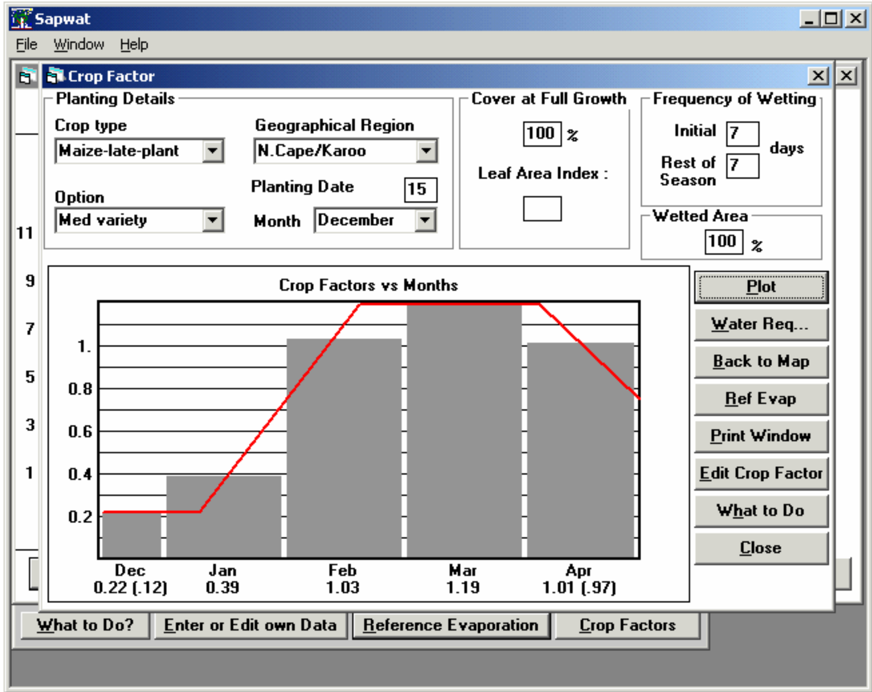


Figure 12.9: Crop coefficients screen in SAPWAT

3.5 Calculation of the nett irrigation requirement

The nett irrigation requirement (NIR) is the amount of water required by the crop to comply with the crop evapotranspiration in a specific growth phase and during a specific period. It can be calculated as follows:

$$NIR = (f\ E_o - R_e) \times L_g \times L_r \qquad (12.5)$$

where NIR = Nett Irrigation Requirement [ℓ/period]
f = crop factors for direct use with A-pan evaporation [fraction]
E_o = A-pan evaporation [mm/period]
L_g = crop spacing [m]
L_r = row spacing [m]

4 Soil

In this section, the factors influencing the size of the soil water reservoir are dealt with briefly. For further information, **Chapter 4: Soil** of this manual, can be consulted. The definitions relating to irrigation scheduling are the following:

- Field capacity (FC) [mm/m]: the depth of water per metre soil depth after all free water has drained from the saturated soil under gravity. A soil water tension of approximately -10 kPa is considered as field capacity. This value is considered the full point of the soil water reservoir.
- Permanent wilting point (PWP) [mm/m]: the depth of water per metre soil depth when the majority of plants of a crop will permanently wilt. A soil water tension of approximately -1 500 kPa is considered as PWP. At this point the water reservoir is empty.
- Soil water capacity (SWC) [mm/m]: the total depth of water per metre soil depth between the FC and the PWP for a specific crop. It is important to know exactly between which soil water tension

limit the soil water capacity is determined, because it influences the size of the soil water reservoir.

- Total available water (TAW) [mm]: it is the total depth of water available to the crop within the effective root depth between FC and PWP.

Figure 12.10 shows a generalisation of the total available water for different soil texture classes.

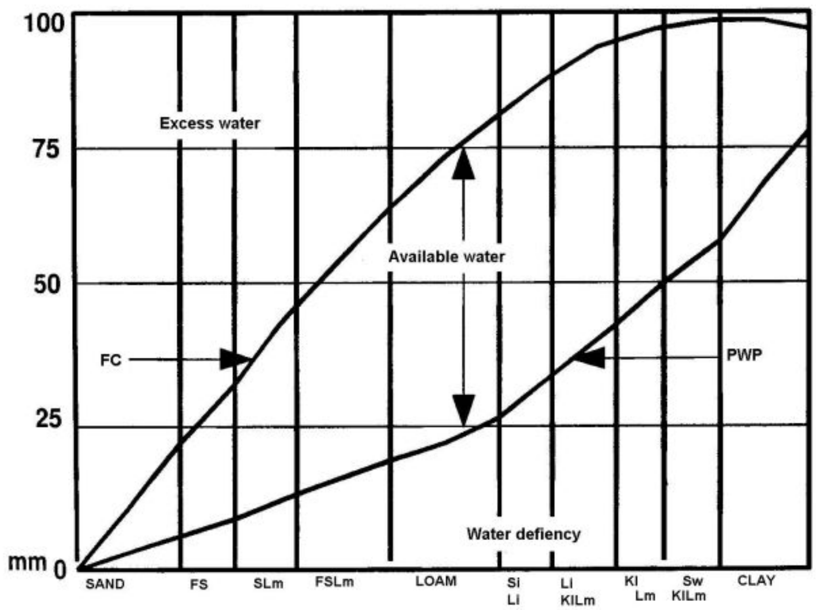


Figure 12.10: Generalised available soil water content as a function of texture.
The soil water content are given as mm water per 300 mm soil

- Percentage allowable water depletion (α) [%]: the maximum percentage of the available water (AW) that may be extracted from the root zone under given soil and climatic conditions and unlimited evapotranspiration (ET) still taking place.
- The combination of allowable water depletion (α) and the soil water capacity of the soil (SWC) is approached in practice according to two different methods:
  - On the one hand, (and probably the popular method) laboratory determined soil water capacity between -10 kPa and -100 kPa (SWC_{100}) and a determined, adapted set of values of α for the specific crop is used.
  - On the other hand, the soil water capacity between -10 kPa and -1 500 kPa (SWC 1500) is used with a different set of values for α, with reference to the same crop.

Note that, although both methods give almost the same results, care must be taken with the values of α and SWC, so that applicable values can be used for the specific calculation.

- Minimum soil water level (100-α) [%]: the minimum percentage of the available water (AW) that must always be retained in the root zone for unimpeded evapotranspiration (ET) and crop growth under given climatic conditions. This value indicates the replenishment point of the soil water reservoir.
- Readily available water (RAW) [mm]: the depth of water available to a certain crop in the effective root depth and unlimited evapotranspiration (ET) and allows crop growth under certain climatic and soil conditions. The term also takes into consideration the allowable water depletion.

The readily available water in the root zone can be calculated as follows:

$$RAW = SWC\ \ ERD\frac{\alpha}{100} \qquad (12.6)$$

where RAW = readily available water in root zone [mm]
SWC = soil water capacity of the soil [mm/m]
ERD = effective root depth [m]
α = allowable water depletion in the root zone [%]

- Soil water tension or matrix potential [kPa]: the suction power that the roots of a crop must exercise to extract the soil water.

The term soil water level and soil water tension are both used to refer to a certain condition, which must be created and maintained in the soil by means of organised irrigation. The term soil water level refers to the lowest soil water content in the root horizon, or in a certain layer of the design root depth in the soil profile, to which the available water (AW) is allowed to drop before irrigation must be applied. It is shown as a percentage of the AW that should remain in the soil layer after a portion thereof has been consumed. With a e.g. 15% soil water level is meant that 85% of the AW can be consumed, but that 15% of the AW must remain in the soil to prevent the entire soil profile from drying out to the PWP.

The term soil water tension is used exactly as the soil water level, i.e. it refers to a certain water content to be maintained in the soil. It is however also sometimes used to refer to the minimum matric potential that must not be exceeded in the root zone of plants. When talking about a -50 kPa soil water tension, it means that the matric potential in the root zone must not drop lower than -50 kPa. Each time the matric potential drop to this value, irrigation water must be applied. Both terms are usually used interchangeable and refers to the amount of water to be maintained in the soil. For further information see **Chapter 4: Soil** of this manual. A typical example of the relation between the allowable water depletion and the water tension is shown in Table 12.5.

Table 12.5: Typical example of the relation between the allowable water depletion and the water tension for table grapes (Scheepers, et. al., 1991)

Month	**Allowable water depletion (α) (%)**		**Maximum tensionmeter reading within root zone [kPa]**	
	SWC [mm/m]		**SWC [mm/m]**	
	<50	**>50**	**<50**	**>50**
Winter	70	100	50	70
August	70	100	50	70
September	50	70	30	50
October	50	70	30	50
November	50	70	30	50
December	50	70	30	50
January	50	70	30	50
February	50	70	30	50
March	50	70	30	50
April	70	100	50	70

Please note: Similar information for other crops can be obtained by contacting your local crop specialists. The soil water capacity (SWC) in this case is considered between a soil water tension -10 kPa and -100 kPa. From the above table it seems clearly that a smaller water extraction and smaller maximum tensiometer reading for soils with a low (< 50 mm/m) SWC must be maintained than for a high SWC. It reduces the risk that if an area experiences a heat wave, crop growth could be inhibited.

Figure 12.11 indicates the relation of soil water tension and percentage extraction of the total available water.

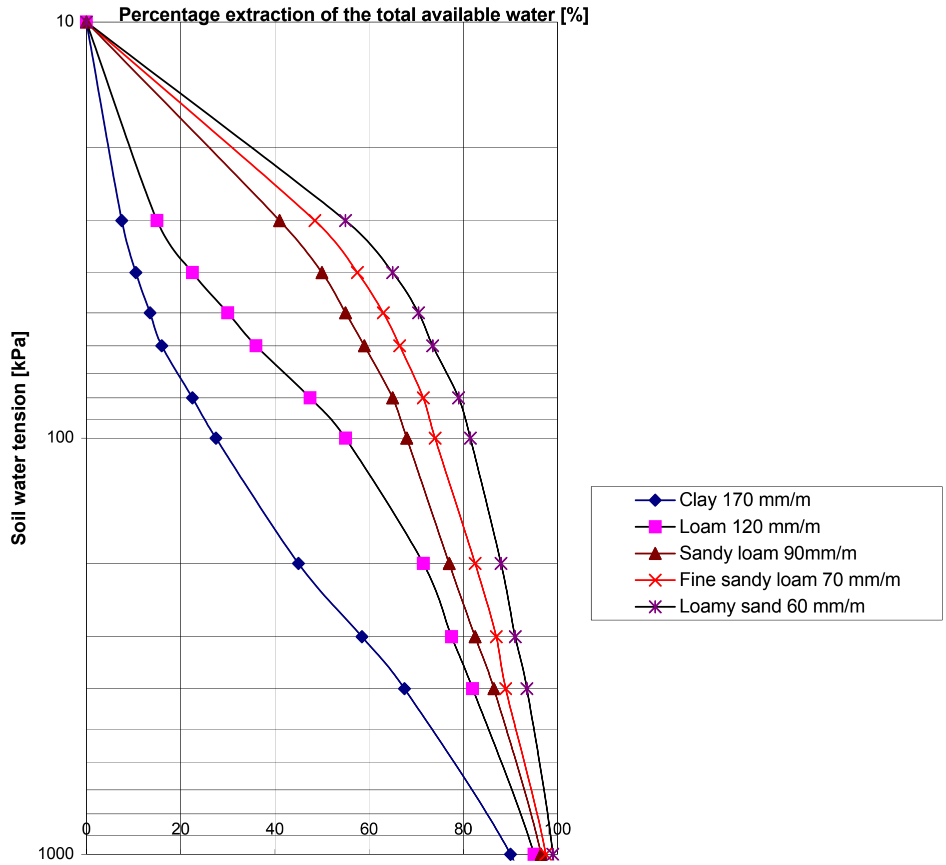


Figure 12.11: Relation between soil water tension and the total available water

It is clear from the above figure that for clay soils, the water extraction at a 50 kPa soil water tension is only 15%, while for loamy sand the extraction is already 72% of the TAW.

With the above information available, the soil water reservoir per tree/plant can be calculated.:

$$\text{GWR} = \text{RAW}\, L_g\, \text{B} \qquad (12.7)$$

where SWR = soil water reservoir per tree/plant [ℓ]
RAW = readily available water in the root zone [mm]
L_g = crop spacing [m]
W = wetted strip width of the emitter [m]

The management of the crop water reservoir is extremely important to make effective irrigation possible. More irrigation than what the soil water reservoir can hold must not be applied, as it can lead to wastage of water and nutrients. Cash crops can be planted when the soil water reservoir is full and in this way less water have to be irrigated over the season.

5 Irrigation system

The irrigation system must be operated in such a way that the producer's available water resources can be utilized to its maximum. The question often arises when to irrigate. According to the design norms, it is recommended that the micro-irrigation system is designed for 144 per week's irrigation. Night irrigation is however more efficient than day irrigation, as the evapotranspiration is lower during the night. Another advantage is that the energy cost outside peak times is lower. There are unfortunately disadvantages to night time irrigation, such as blockages/leakages that can occur because there is no supervision. Open hydroponics systems (OHS) require water application daily during the active transpiration period of the crop. The OHS approach is discussed in **Chapter 8: Micro-irrigation systems**. It must always be kept in mind that with conventional irrigation systems, a continuous strip in die crop row is irrigated. With the OHS approach pots are irrigated, which leads to a smaller soil water reservoir.

The theoretical cycle length and maximum standing time is calculated as follows and adapted according to the producer's requirements.

$$t_c = \frac{SWR}{NIR} \qquad (12.8)$$

where t_c = theoretical cycle length [days]
SWR = soil water reservoir available per tree/plant [ℓ]
NIR = nett irrigation requirements per tree/plant [ℓ/day]

Most producers prefer to follow a fixed irrigation cycle length and adapting the standing time according to the season. If the soil water reservoir is such that 6 hours of irrigation per day is needed in the peak month, but only 3 hours per day irrigation may be necessary outside peak time.

$$t_s = \frac{SWR\ L_e}{q_e\ L_g\ \eta_t} \qquad (12.9)$$

Where t_s = the maximum standing time of irrigation [hours]
L_e = emitter spacing [m]
q_e = emitter delivery [ℓ/h]
L_g = crop spacing [m]
η_t = application efficiency [decimal]

The norm for the application efficiency of the different systems is as follows:

Table 12.6: Application efficiency for the different systems (Koegelenberg, 2002)

Type of system	**Application efficiency [%]**
Drip systems	90
Micro sprayer systems	80
Permanent sprinkler systems	75
Moving systems	80
Portable quick-couple sprinkler systems	70
Travelling guns and other portable sprinkler systems	65
Flood irrigation (with pipe supply system)	80
Flood irrigation (with earth channel supply systems)	60

The efficiency of any irrigation system depends mainly on how the system is operated and maintained. The following factors negatively influence, among others, the efficiency of the system:

- a great pressure difference (>20%) through the system;
- the use of different types of emitters;
- low infiltration that leads to runoff;
- too high applications;
- poor soil preparation;
- poor management;
- blockages, and;
- leakages

It is therefore important that the irrigation system should be evaluated on a continuous basis to ensure even water application through the system. If it is not done, it can lead to over-irrigation to provide for portions of the system receiving too little water. Modern irrigation systems are not always more efficient, because problems can occur without the correct management. Thus, the efficiency of flood irrigation systems can be improved by techniques such as laser-levelling, while modern irrigation system such as drip irrigation can be insufficient if incorrectly applied and managed. The importance of the use of applicable scheduling techniques is therefore of the utmost importance.

Example 12.2:

A producer wants to irrigate 35 hectare of pears at Wolseley with a micro-irrigation system. He wants to irrigate only 5 out of 7 days and 10 hours per day. From the long-term climatic statistics of the Winter Rainfall Region, the following:

Peak irrigation month:	*January*
Crop factor:	*0,55*
Average monthly A-pan evaporation:	*323 mm*
Average monthly rainfall figure:	*12 mm*

Use the equations as described in Chapter 3 of this manual. Determine the gross irrigation requirement (GIR) if the application efficiency is 80%.

Solution:

Effective rainfall $= \dfrac{\text{Rainfall (mm/month)} - 20}{2}$

$= \dfrac{12 - 20}{2} = 0 \text{ mm}$

Evapotranspiration = *Monthly A-pan evaporation (mm/month) × crop factor*
= *323 × 0,55 mm/month*
= *178 mm/month*

Nett irrigation requirement = *Evapotranspiration (mm/month) – effective rainfall (mm/month)*
= *178 mm/month*
= *1 780 m³/month*
= *57,42 m³/ha per day for a 7 day working week*
= *80,38 m³/ha per hour for a 10 hour working day*

Gross irrigation requirement = NIR / η_a
= *281,35 / 0,8 m³/ha*
= *351,7 m³/ha*

6 Scheduling techniques

There is a variety of ways in which irrigation scheduling can be applied, i.e. with which to determine when to irrigate. The decision of which irrigation scheduling technique should be used depends on the producer’s choice. The factors influencing the system choice as discussed in **Chapter 2: Guidelines for irrigation system choices**, also influence which scheduling technique the producer will use. Scheduling aids will only be to the producer’s benefit if at least two readings can be taken per irrigation cycle. It is recommended that the readings be obtained from the different scheduling aids and plotted on graphs to identify tendencies in water consumption and possible problems with the irrigation management in time. The most practical method is to follow a program calculated by means of the historic evapotranspiration and adapted by soil water measuring at strategic points in an irrigation block. The calculation of evapotranspiration can be simplified by the use of the models as suggested in Section 7. Continuous soil water measuring is recommended for especially open hydroponics systems where irrigation is applied daily. The amount of water to be applied depends on how empty the SWR is at that specific stage. The techniques can be divided broadly into four groups, namely:

a) monitoring of the soil water content;
b) monitoring of the matrix potential;
c) scheduling regarding the set-up of a water balance sheet by means of the calculation of the crop evapotranspiration; and
d) monitoring of the plant’s reaction.

The first three methods are discussed in this manual. Most of the methods that measure the plant’s water status are only used in tests and contains slow readings and processing with expensive apparatus. At this stage it is therefore not recommended to producers on a commercial basis. Techniques that determine the water status of plants include infrared thermometers, pressure chambers, dendrograph, that reads the expansion of the plant stem and equipment that measures certain physiological processes.

6.1 Feel method

Determining soil water by means of feeling and observation is one of the oldest methods used for determining the soil water status. This is a simple method, but practice and experience is necessary to determine this exactly. Soil samples taken at different depths in the root zone is collected with a soil auger, after which it is thoroughly studied and feeled. The soil is classed on the basis of the observation and the soil water can be determined with the aid of tables. The soil water can be determined within 10 - 15% accuracy with a little practice. Table 12.7 shows the relation between soil water and soil appearance. This method of scheduling is not recommended.

Figure 12.12: Water determination by means of feel and observation

Table 12.7: Feel method – relation between soil water and soil appearance (Jordaan, 2001)

Total available water	Coarse (sand, loam-sand)	Slightly coarse (sand-loam, fine sand-loam)	Medium (loam)	Fine (silt-loam, clay-loam)
100% Field capacity	Leaves a wet pattern on the hand when squeezed (0 mm/m)	Appears very dark, leaves a wet pattern on the hand when squeezed, forms a short sausage (0 mm/m)	Appears very dark, leaves a wet pattern on the hand when squeezed, forms a sausage of about 25 mm (0 mm/m)	Appears very dark. Leaves slight wet pattern on the hand when squeezed, forms a sausage of about 50 mm (0 mm/m)
70% - 80%	Appears wet, forms a weak ball (17 – 25 mm/m)	Dark in colour, forms a hard ball (25 – 33 mm/m)	Dark in colour, forms a plastic ball, gets a smooth finish when rubbed, forms a sausage of 10mm (33 – 50 mm/m)	Dark in colour, forms a plastic ball, easily forms a sausage with a smooth finish (42 – 58 mm/m)
60% - 65%	Appears slightly wet, forms weak brittle ball (33 mm/m)	Dark in colour, forms a good ball (50 mm/m)	Dark in colour, forms a hard ball, forms a weak sausage (67 mm/m)	Dark in colour, forms a hard ball, forms a sausage of 5 – 10 mm, gets smooth finish when rubbed (75 mm/m)
50%	Appears dry, forms a weak ball or none at all (42 mm/m)	Slightly dark, forms a weak ball. (67 mm/m)	Dark in colour, forms a ball, slightly brittle (83 mm/m)	Will form a ball, small lumps can be pressed flat without crumbling 92-100 mm/m)
35% - 40%	Dry, does not form a ball (50 - 58 mm/m)	Slightly discoloured by water, will not form a ball (75 – 83 mm/m)	Slightly dark, forms a weak ball (100 – 108 mm/m)	Slightly dark, forms a weak ball, lumps crumble 117 – 125 mm/m)
Smaller than 20%	Very dry, loose, flows through fingers (67 – 83 mm/m)	Dry, loose, flows through fingers (108 – 133 mm/m)	Light in colour, powdery, dry (133 – 167 mm/m)	Hard, baked, cracked, light in colour (150 – 208 mm/m)

NOTE: The values in brackets indicate the estimated soil water shortage (in mm/m) to field capacity for uniform soils. Squeezing the soil hard in your hand forms a ball. Rolling the soil between the thumb and index finger forms a sausage.

6.2 Gravimetrical soil water determination

For many years, the gravimetric method was the standard technique according to which the soil water content was determined. The method contains the following steps:

(i) removal of a soil sample from its field condition;
(ii) weighing the sample in its wet condition;
(iii) drying the sample at 105°C for about 18 hours and
(iv) determining the oven-dry mass of the sample.

The mass difference between the "wet" and "dry" sample is then accepted as a percentage of the oven-dry mass. An example is discussed in detail in **Chapter 4:Soil** of this manual.

Benefits

(i) It is very accurate, at least for the relevant soil sample on which the determining is done.
(ii) It is an objective method and the personal judgement of the person doing the determining is not applicable.
(iii) It is a cheap method and a large number of samples can be handled simultaneously.
(iv) The salt content of the soil does not influence it.

Disadvantages

(i) It requires laboratory equipment e.g. a balance scale and drying oven – i.e. the determining cannot be done *in situ.*
(ii) It is time-consuming, requires 18 hours of drying time plus additional cooling time and an answer can only be obtained at least a day after the sample was taken.
(iii) The method is destructive in the sense that a sample is physically removed from the soil and a hole remains.
(iv) Since it is destructive, it is impossible to do a follow-up determination on the same spot. Measurements done over time therefore include an element of inaccuracy (because of the spatial variation present in any landscape when moving from one position to another).
(v) In order to convert the gravimetrical reading to a volumetric reading, it is also necessary to determine the bulk density. Many soils become dense during sample taking, which gives a false image of the bulk density.

Figure 12.13: Apparatus required for the gravimetric method

6.3 Determining the soil's electric resistance

The electric resistance of a volume of soil depends, among others, on the soil water content. If the electric resistance of a soil is determined, such a reading can, after calibration, be converted to soil water content. An example of a measuring instrument, which is based on this principle, is the gypsum block (Figure 12.14). The instrument consists of a porous gypsum block in which two electrodes are placed, which are connected to two electric cables. When the block is buried in the soil, the water in the gypsum block will equilibrate with the soil water. Water will move through the pores of the block until the matrix potential (soil water tension) inside and outside the block is the same. The resistance that the electric current experiences in flowing between the two electrodes, can then be determined by means of an ordinary resistance bridge. The resistance is equal to the prevailing soil water tension, but the resistance can also be calibrated against the soil water content (gravimetric or volumetric). Soil water tension can also be directly determined, while the absolute soil water content can be read indirectly from a soil water characteristic. The two electrodes can also be placed in porous nylon or fibreglass blocks.

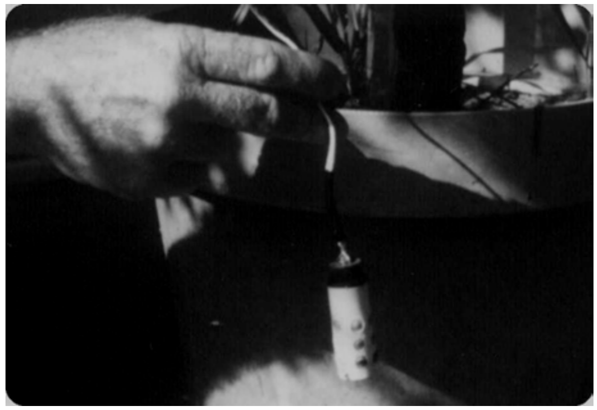


Figure 12.14: Resistance block

Benefits

i) The gypsum blocks are relatively cheap and the resistance can be determined with any commercially available resistance bridge.
ii) The blocks function over the entire soil water spectrum (i.e. from dry to wet), but the accuracy and sensitivity is better in the dry area than in the wet area of the spectrum. The sensitivity of nylon blocks in the wet area is better than that of the gypsum blocks.
iii) After installation of the blocks, the soil water content can be determined on the same spot every time. The blocks can also be buried at any soil depth.
iv) The apparatus can be connected to an automatic register.

Disadvantages

i) Each block must be calibrated individually, since even small differences in the dimensions of the blocks will cause a change in the resistance reading.
ii) The calibration curve also changes with time, especially in the case of the gypsum blocks where the use of the blocks lead to situations where high accuracy is not a requirement.
iii) Soil characteristics other than the water content also influence the resistance reading. It is especially dissolvable salts in the soil solution that plays a role here, because the more dissolvable salts there is in the soil, the better the soil will lead an electric current. The changes in resistance reading are therefore not necessarily only because of a change in the soil water content.
iv) Special set-ups (current circuits) are necessary when more than one block (at different depths in the same place) is connected to a data register.

An example of a calibration curve is shown in Figure 12.15.

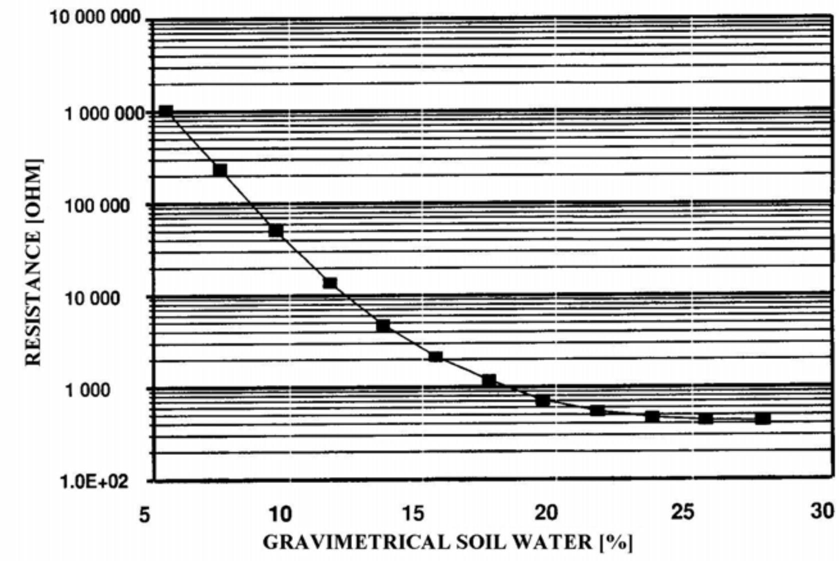


Figure 12.15: Calibration curve that indicates the relation between electrical resistance of a gypsum block and soil water content.

6.4 Neutron water meter

Since the neutron watermeter measures the absolute amount of water in volumetric units in the soil, this technique will also directly give an indication of the amount of water, in mm, to be irrigated. The method of soil water measuring by means of neutron dispersion dates back to the 1950's. It has since been accepted as an effective and reliable technique used increasingly in South Africa.

The neutron water meter consists of two main components, namely, i) a probe containing a source of high energy and fast moving neutrons, as well as a sensor which is sensitive to slow-moving neutrons, and ii) a micro processor that can register the flow of slow-moving neutrons in the soil. A schematic representation of the most important components that the instrument consists of is given in Figure 12.16.

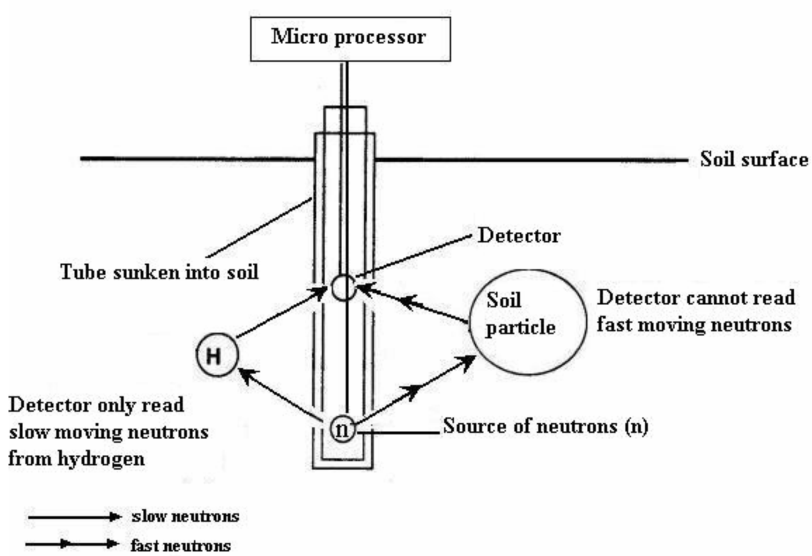


Figure 12.16: Schematic representation of the working components of a neutron water meter

The soil water content at a specific depth of a soil is measured by dropping the probe in a pipe, which was installed in the soil beforehand to a desired depth and of which the bottom is closed. A neutron count is then taken for a minimum of 16 seconds, but preferably 32 seconds. It is however important to note that the shorter the count time, the accuracy and dependability of the answer obtained reduces. The effective volume of soil of which the soil water content is measured, is determined by the radioactive strength of the neutron source and the degree of wetness of the soil. The effective volume sampled by the neutron water meter, is therefore greater in dry than in wet soil. For the generally-used sources such as Ra-Be and Am-Be, the radius of the spherical volume of soil in which the soil water content is measured, varies typically between 0,1 m for a wet and 0,25 m for a dry soil. The practical implications hereof are, strictly speaking, that a neutron water meter cannot be used to determine soil water near the soil surface (approximately 0,15 to 0,20 m).

A neutron water meter can be calibrated in the laboratory or in the field to determine the relation between the neutron counts and the volumetric soil water content. For calibration of the neutron water meter and other soil water meters, a specialist in this field must be consulted.

Benefits

(i) Measuring is very fast. A minute per reading, or even less is normally sufficient.
(ii) Measurements can be taken repeatedly on the same spot without disturbing the soil.
(iii) As many measuring points as required can be used without a significant cost increase, i.e. one instrument can be used on many different spots.
(iv) Measurements can be done at any depth, except the uppermost 150 mm, to obtain a continued profile of soil water with depth.
(v) Soil water can be determined over the entire soil water spectrum.
(vi) Soil water is measured over a large soil volume and the soil water values are given directly in volume units, which simplifies irrigation calculations.

Disadvantages

(i) Health and safety risk. Prolonged use can hold a radiation danger with accompanying problems. Because of the radioactive source it contains, the instrument is subject to certain regulations.
(ii) A large volume of soil is sampled and this can cause problems when non-uniform soil water profiles are determined, e.g. where there is a sharp transition between a wet and a dry soil layer or where there are sharp texture differences in depth, e.g. a duplex soil.
(iii) It cannot be used summarily near the soil surface. A special shield is required for this, but is not very effective.
(iv) Neutron water measurements are influenced by soil density and soil type therefore many calibrations are necessary.
(v) The cost of the instrument is high (R35 000 to R60 000 at 2001 prices)
(vi) Readings can also not be taken automatically on a continuous basis.

6.5 Tensiometry

Tensiometry is an indirect way of determining the water content of a soil. A Tensiometer indicates the matrix potential (soil water tension), which is then converted to absolute soil water content by means of a soil water characteristic. A tensiometer consists of a porous point usually made from ceramic. The porous head is connected to a mercury manometer or a vacuum meter by means of a long water-filled tube (Figure 12.17). When the tensiometer is placed in the soil (in such a way that there is close contact between the soil and the porous head) water will move through the pores of the ceramic head.

The water movement is caused by a difference in the soil water tension in and outside the porous head. If the suction tension of the soil is higher than in the pores of the tensiometer, water will move from the tensiometer to the soil. Since the tensiometer and the manometer, or vacuum meter, forms an airtight closed system, a vacuum will be created in the tensiometer, or, the air pressure in the tensiometer, which will in time come into equilibrium with the air pressure in the soil, which is lower than that of the atmospheric pressure (i.e. it is negative in relation to atmospheric pressure). These pressure differences (or vacuum amounts) are then registered on the manometer or vacuum meter. Electronic tensiometers that can register automatically have an electronic vacuum sensor and are then connected to data loggers to store the data. If the soil is wetted again, as during a rain shower or by irrigation and the soil water tension in the soil reduces to below that of the tensiometer, the tensiometer will indicate a zero reading when the soil is fully saturated. The fluctuations in the tensiometer reading therefore indicates how the soil water tension reduces (during irrigation) or rises (during drying). A graph showing such fluctuations during an irrigation season is shown in Figure 12.18.

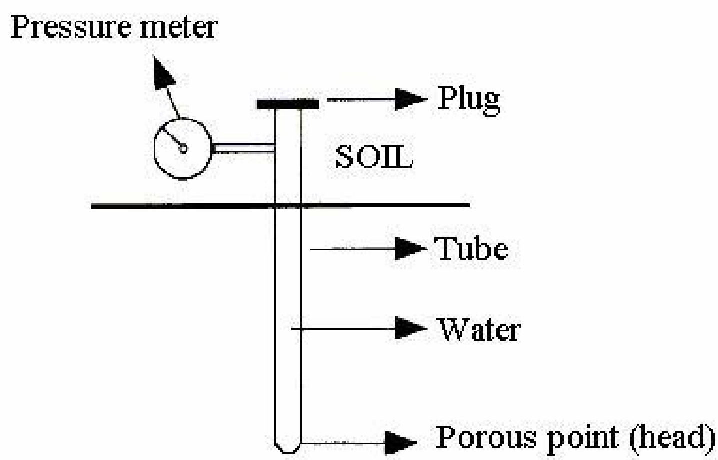
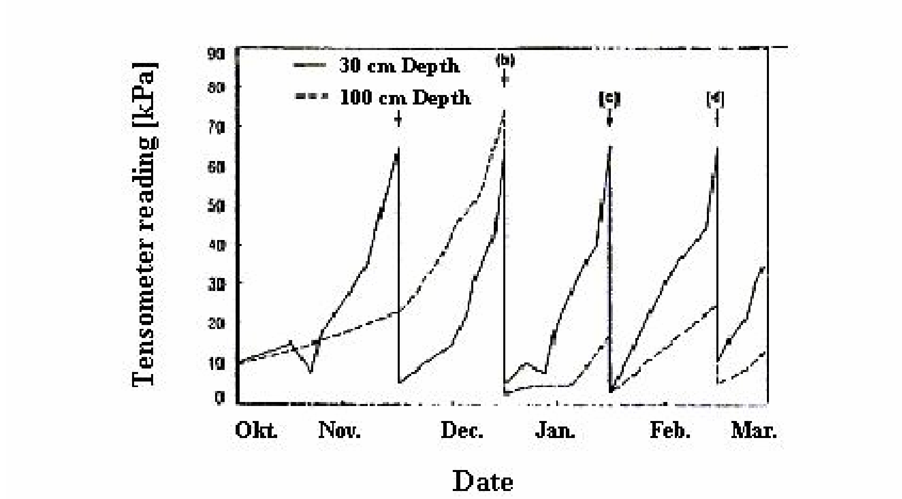


Figure 12.17: Schematic presentation of a tensiometer with a vacuum meter

The installation and maintenance of tensiometers require considerable knowledge and attention. New tensiometers must first be examined for possible leakages, all the air must be removed and it must then be set at a zero reading. Directives in this regard are supplied by Piaget (1991). The mercury manometer type tensiometer is more sensitive and accurate than the vacuum meter type, especially in the low water tension area. It is however more breakable than the vacuum meter type. Mercury manometer-tensiometers are therefore mostly used as research instruments, while the vacuum meter type is better suited for practical application by producers.

The effective and rational use of tensiometers in irrigation agriculture requires that they should be placed correctly. At least two tensiometers are required for deep-rooted crops. The shallower tensiometer will indicate when irrigated should be started, while the deeper placed tensiometer is used to indicate whether irrigation is done correctly (i.e. that the matrix potential at that depth will not rise substantially higher than approximately -5 kPa, field capacity). For shallow-rooted crops, only one tensiometer is necessary. Note that, with this method, only the matrix potential is monitored. To calculate the soil water content and consequentially the irrigation amount, the soil water characteristics curve of the specific soil must be known.



Changes in the tensiometer readings under the influence of soil water comsumption and irrigation a) did not wet the soil deep enough and the deeper tensiometer's readings kept rising. Irrigation b) was slightly too heavy and the tensiometer indicated a water saturated condition for too long (readings smaller than 19 kPa). Irrigations c) and d) was given at the right time and the correct amount of water was applied.

Figure 12.18: An example of the changes in the tensiometer reading at two depths as a function of water consumption and irrigation (van Zyl, 1981)

Benefits

i) The tensiometer readings are a direct indication of the amount of energy that a plant must apply to take up water from the soil.
ii) After installation, the soil water content is determined on the same spot each time.
iii) Changes in the soil matrix potential can continuously be captured with a data logger.
iv) The soil water characteristics can be determined *in situ* in the soil with the aid of the apparatus.

Disadvantages

(i) The apparatus is quite fragile – a single crack in the porous head is enough to render the tensiometer useless.
(ii) The tensiometer functions only in a relatively wet area of the soil water spectrum – between 0 and 80 kPa. If the tension rises above 80 kPa, the meniscuses in the pores of the ceramic head breaks and air invades the tensiometer freely. The fact that the tensiometer will only indicate soil water contents which are bound with tensions lower than 80 kPa, is not a substantial problem on coarsely structured soils. At such soils, most of the plant's available water is in any case bound in the tension area 0 to 80 kPa. In finer textured soils however, a significant amount of the plant's available soil water can fall outside the mentioned tension area.
(iii) The apparatus must be services regularly. It must be filled with de-aerated water weekly and a vacuum must be created again. This is done with a hand vacuum pump.
(iv) A time delay of up to ten minutes occurs in registering of the change in matric potential readings. It is detrimental for continuous data capturing.

6.6 Pulse delay measurements by means of Time Domain Reflectometry (TDR)

This method, as well as the frequency delay method, is vested in the principle of measuring of the dielectrical constant of materials. The dielectrical constant of a material is the measuring of the capacity (electrical permissiveness) of a non-conductive material to conduct high frequency electromagnetic waves or pulses. The dielectrical constant of a dry soil varies between two and five, while that of water is 80 at frequencies of between 30 MHz and 1 GHz. Research results have shown that the measuring of a soil water medium's dielectrical constant reflects an accurate measurement of the soil's water content. Relative small differences in a soil's water content results in large differences in the electromagnetic characteristics of the soil water medium. The soil water content of a soil can therefore be determined solely by determining the dielectrical constant of a soil.

The time domain reflectometry technology for soil water content determination is vested in cable testers such as the Tektronix 1 502B. This equipment was originally used for testing the breaks and joints in subsurface cables. Various manufacturers therefore use the apparatus to conduct a high frequency transversal electromagnetic wave next to a cable, which is connected to parallel conductive probe. The parallel conduction probes (two or three) are inserted into the soil and serve as wave conductors. The wave conductors reflects the transversal electromagnetic wave back to the cable tester where it is reflected on an oscilloscope. The time taken for the signal to be reflected (time delay) is measured accurately by the cable tester. With the length of the cable and wave conductors known, the reproductive speed of the transversal electromagnetic wave can be calculated. The dielectric constant is inversely related to the reproductive speed of the electromagnetic wave, i.e. a faster reproductive speed delivers a lower dielectrical constant and therefore a lower soil water content. A higher dielectric constant will therefore be an indication of a higher water content in the soil.

Wave conductors inserted into the soil consist of two or three parallel stainless steel probes arranged approximately 50 mm apart. The wave conductors are usually inserted vertically, horizontally or at an angle of 45° into the soil. Some manufacturers use a wave conductor with three probes. A screened-off parallel connector cable conducts the electromagnetic volumetric wave between the wave conductors and the cable tester. The TDR instrument measure the average volumetric water content (%) over the length of the wave conductors. The sphere of influence of an instrument around the wave conductors (measuring point) has a diameter of approximately 1,5 times the spacing of the parallel probes.

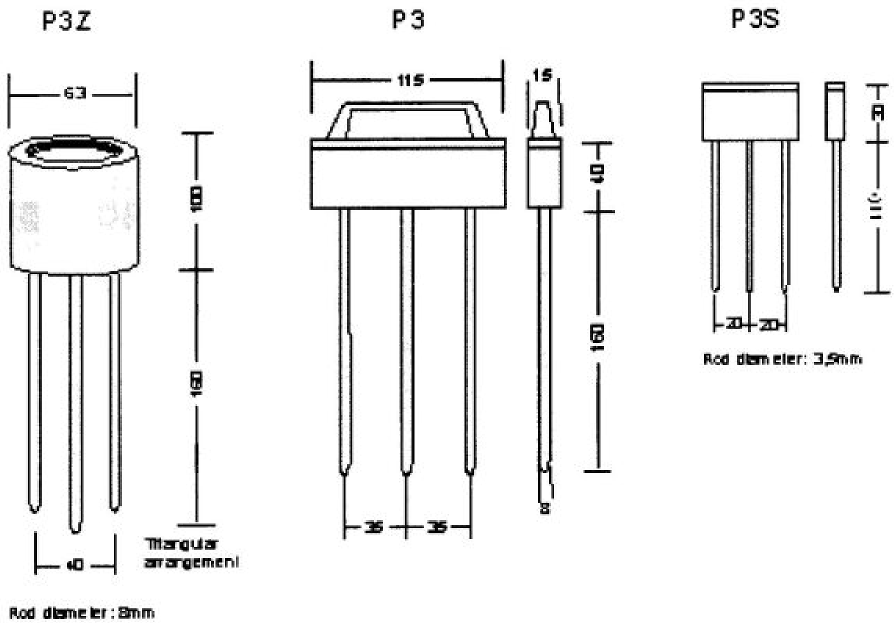


Figure 12.19: Presentation of TDR wave conductors with three probes.

The wave conductors are permanently installed on the side of a profile hole with conductors, which lie on top of the soil surface. Care must be taken to disturb the soil as little as possible. It is the only method to obtain readings at different depths in one position with the aid of the TDR. Horizontally installed wave conductors give a depth specific reading while wave conductors installed at an angle of 45°, give an integrated larger volume reading, both in the horizontal and vertical directions. Hand TDR meters consisting of a wave conductor probe, can be used like a neutron water meter to determine the water content with the aid of access tubes in the top 45 to 60 cm of soil.

The following TDR equipment is currently available (in no specific order of preference):
Aquaflex SE 200 soil water meter; Campbell Scientific's CS615-L hand feel pin wave conductor; Hydrosense from Degacon; Trime from IMKO; Tektronix TDR; Gro point & Moisture point from ESI Environmental Sensors.

Benefits

(i) Measurements are determined fast. Soil water content can be determined at different depths simultaneously. Readings are taken within one minute.
(ii) The TDR measuring technique is very accurate, if the apparatus is properly installed and calibrated.
(iii) Accurate and dependable readings can be taken near the soil surface. Measurements as shallow as 100 mm to a depth of 5 m is possible.
(iv) Research results show that the dielectrical constant is independent of the gross density of the soil.
(v) Continuous readings and data storage with the aid of data loggers are possible.

Disadvantages

(i) The wave conductors should be installed very carefully to ensure contact along the entire length of the probes. Vacuum along the probes cause faulty readings. The probes must also remain parallel, else the wave conductors do not function correctly.

(ii) Wave conductors cannot readily be used in stony soils and special precautionary measures must be taken. The access tubes of the probe are installed with a paste of the same soil.

(iii) Cable test apparatus is essential for analyses of the wave patterns. Problems with the apparatus have not been completely solved.

(iv) Soil brackishness of the gross electric conductivity of the soil influences the attenuation of the electromagnetic pulse in the soil. The higher the salt content, the lower the accuracy of the TDR in the soil. Research is currently being done to find suitable isolating materials for the probes to make it suitable for taking readings in brackish soils.

(v) TDR equipment is very expensive because of the high cost of the cable testing apparatus. TDR soil water meters cost between R48 000 and R90 000. Individual sets of wave conductors cost between R160 and R840, depending on the length.

6.7 Frequency delay measurement by means of Capacitance

Frequency delay measurement is also based on the measurement of the dielectrical constant of soil or materials. The frequency delay measurement is also called the radio frequency (RF) capacitance technique. Capacitance technique is usually referred to as it measures the soil's capacitance. Two, three or four electrode probes are also inserted in the soil. The probes are collectively connected to a test pin and the probes of some types (Delta-T-probe) can screw in if it has to be replaced. The soil acts as dielectricum by completing the capacitance circuit, which forms part of the feedback circuit loop of the high frequency transistor-oscillator. High-frequency radio waves of between 100 and 150 Mhz are also pulsed through the capacitance circuit. A natural resonant frequency is thereby established, which is dependent on the capacitance of the soil. The soil's capacitance is related to the dielectricum constant, which is created by the geometry of the electrical field around the electrodes. A number of commercial apparatus using this technique are available, namely: Netafim Flori; SDEC's HMS 9 000, Delta-T's ThetaProbe and the Aquaterr probe.

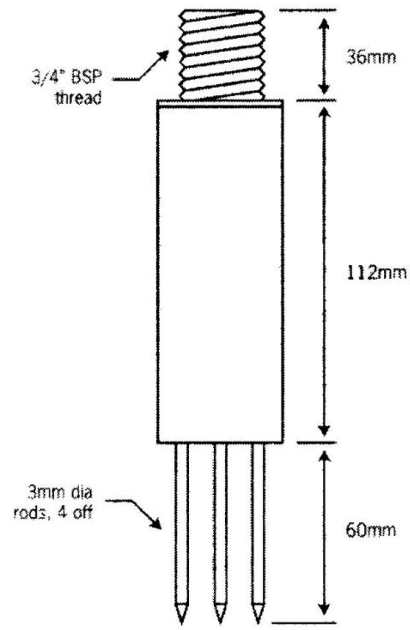


Figure 12.20: Example of a capacitance test probe (Theta-Probe)

These capacitance probes are installed in the same way as TDR wave conductors, in the side of a profile hole.

Some manufacturers arrange the electrodes around a cylindrical test probe (rod) at different distances. The test probe is then lowered into a uPVC access tube into the soil. Soil water contents are then determined at the different depths according to the electrode spacing. The depths vary in increments of 100 to 200 mm, which can be specified by the user at some types and installed during manufacturing. With other types such as the ADCON C-probe and Sentek's EnviroSCAN, the user can change the spacing.

The Troxler Sentry 200-AP apparatus and the DIVINER 2 000 (Sentek) uses an access tube similar to that of a neutron water meter to determine the soil water content at different depths. The test probe of this type of apparatus fits tightly into the access tube and takes readings while it is lowered into the soil. A natural resonant frequency or frequency movement between the radiated and received (reflected) frequency is measured by the test probe. The DIVINER apparatus measures soil water content in volumetric units at pre-programmed depths while it is lowered into the soil. The data is then shown and stored on a data logger. The data can also be downloaded onto a computer and various analyses can be executed thereon.

The access tube must be manufactured from a schedule 40 uPVC material. The size and wall thickness of a tube ensures a tight fit of the test probe in the tube. It ensures that the electromagnetic signal is radiated effectively. Installation of the access tube must be such that the tube fits tightly into the soil. In stony soils, a paste is made from the soil. The access tube is then installed in the paste in the soil, so that no vacuum exists around the access tube.

The apparatus must be calibrated for the different soils for each depth. The calibration can also be calibrated against a calibrated neutron water meter. The change of gross density with depth also requires calibration at every depth where the soil water content is to be determined. The sphere of influence of measurements (in the absence of vacuum) is not influenced by soil water content and is approximately 100 mm vertical and 250 mm horizontal in diameter. The apparatus is very accurate if it is correctly installed and calibrated.

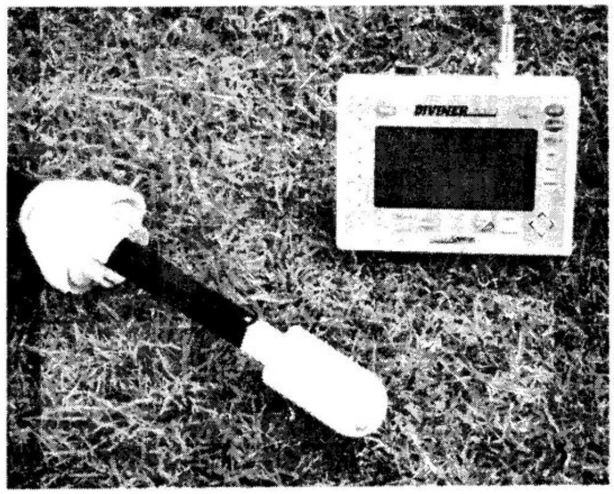


Figure 12.21: An example of a probe type capacitance sensor used exactly as a neutron watermeter
(DIVINER 2 000 from Sentek)

Benefits

(i) Readings can be taken easily and quickly. The soil water content can be determined simultaneously at different depths. A few milliseconds are necessary for the DIVINER apparatus to take the readings while the probe is sinking into the soil. The apparatus takes sixteen readings at different depths in less than two minutes.
(ii) The capacitance technique is very accurate if it is correctly installed and calibrated.
(iii) Accurate readings can be taken near the surface. Readings can be taken as shallow as 100 mm from the surface in increments of 100 to 200 mm.
(iv) The use of the apparatus is not a health hazard.
(v) Continuous data logging of the soil water content at different depths is possible. The probes can be connected to any type of data logger.

Disadvantages

(i) Probes must be placed in the soil very carefully and good contact must be ensured over the entire length of the soil. Vacuum along the rods can result in incorrect readings.
(ii) Installation procedures of access tubes are critical. Problems are experienced with vacuum around the tube in stony ground. A paste must then be made of the soil to ensure good contact.
(iii) A hand test probe must fit tightly into the access tube. Vacuum around the probe give inaccurate readings.
(iv) Systems that work at low frequencies (<20 MHz) are influenced by the soil's salt content. Frequencies of 100 MHz are therefor normally used.
(v) Capacitance probes or combination rods cost between R500 and R12 000 depending on the length.

6.8 Heat pulse measurements

Heat pulse sensors or Phene cells are made of porous blocks, in which two electrodes are implanted. These blocks are connected to an instrument that determines the water content of the soil. Heat pulse sensors are also made of stainless steel rods of 15 cm long and 10 mm in diameter. The temperature in the sensors is read before and after a small heat pulse. The size of the heat pulse transmitted by the soil is proportional to the water content that forms in the block. In the case of the stainless steel rod, the size of the reflected heat pulse is an indication of the water content of the sensor. This means that a wetter soil or medium will warm slower than a dry one. The increase in temperature (or cooling) is read with an accurate temperature sensor in the sensor. It is calibrated at soil water content for the specific soil or sensor.

Benefits

(i) The heat pulse sensors (blocks) are relatively cheap and can be read with a variety of commercial resistance meters.
(ii) The sensors work over the entire soil water spectrum (from wet to dry) but the accuracy is better in the dryer portion of the spectrum.
(iii) The soil water content can continuously be read on the same spot for different depths. The sensors can be buried at any depth.
(iv) Both temperature and soil water content can be determined by the apparatus.
(v) It can be connected to a data logger to store data.

Disadvantages

(i) Sensors have a high power requirement if readings must be taken very regularly.
(ii) Each block must be calibrated individually. A small difference in measurement and depth influence the readings.
(iii) The heat pulse sensor must have good contact with the soil, which is not always possible. Poor contact result in incorrect readings.
(iv) The thermic conduction or conductivity readings are also influenced by other soil characteristics, except by the water content thereof. Organic materials and humus content can influence the readings adversely. The higher the humus in the soil, the higher the registered water content.
(v) The sensors can also not be installed near the soil surface. A portion of the heat pulse escape above the surface and a lower reading is then obtained.

Table 12.8 shows a comparison between the above apparatus and methods.

Table 12.8: Comparative review between different scheduling techniques (Jordaan, 2001)

Apparatus or method	Measured parameter	Reaction time	Disadvantages	Benefits
Feel	Appearance and feeling	1-2 min	10-15% accurate	•Cheap •Easy
Gravimetrical	Mass of water content (% dry mass vs. wet mass)	24 hours	•Destructive test •Time consuming •Automatic control impossible •Dry mass density must be known	•Very accurate •Independent of salt content of soil
Electrical resistance method	Soil water potential by means of electrical resistance reading	2-3 hours	•Individual calibration •Varying calibration with time •Limited lifespan •Less accurate	•Relatively cheap •Non-destructive test
Tensiometer	Soil water potential (soil water tension)	2-3 hours	•Limited reading area of 0-8 bar •Needs a retention curve to convert reading to volumetric water content •Hysteresis effect on reading •Requires good maintenance	•Relatively cheap •Non-destructive test
Neutron water meter	Volume water content (% water per volume)	1-2 min	•High cost •Dependent on dry mass density and salt content •Calibration needed for different soils •Radio-active danger	•Non-destructive
Heat pulse reading	Volume water content by means of heat distribution	2-3 hours	•Fast wear in alkaline soils •Readings affected by salts in soil •Calibration needed for different soils	•Wide working range
Time domain reflectometry	Volume water content by means of a high frequency pulse	1-2 min	•Readings affected by salts in soil •Calibration needed for different soils	•Non-destructive test
Frequency domain reflectometry	Volume water content by means of retardation on oscillator	1-2 min	•Readings affected by salts in soil •Calibration needed for different soils	•Non-destructive test
Capacitance	Volume water content by means of capacity	1-2 min	•Readings affected by salts in soil •Calibration needed for different soils	•Non-destructive test •Can obtain profile of soil water content

6.9 Scheduling with crop evapotranspiration ($ET_{c)}$ and a water balance sheet

As discussed, the ET_c can be calculated by two methods, namely A-pan evaporation and crop factors and the Penman-Monteith method. The water balance method comprises the daily ET_c calculation and gives an indication of when to irrigate. Scheduling models were developed for executing these calculations automatically. (Section 7). The example discussed here, uses the A-pan method. The computer program SAPWAT can also be used for calculating similar data by means of the Penman-Monteith method.

Example 12.3:
A-pan evaporation (E_o) information is at the producer's disposal for setting up a water balance for a specific orchard. Suppose that the readily available water in the root area is 30 mm. The crop factor (f) during the period is 0,76. Use the above particulars to determine the crop evaporation-transpiration (ET_c) and the water consumption of the crop with the water balance method. Accept that the water reservoir is full at the beginning.

Solution:

Day no.	E_o	ET_c	*Cumulative water consumption [mm]*	*Soil water reservoir content [mm]*
1	4	3	3	27
2	9	7	10	20
3	9	7	17	13
4	8	6	23	7
5	7	5	28*	2
6	8	6	6	24
7	8	6	12	18
8	9	7	19	11
9	7	5	24	6
10	7	5	29*	1

After days 5 and 10*, the cumulative water consumption will exceed the readily available water in the root area and the deficit (28 mm on day 5 and 29mm on day 10) must be supplemented with irrigation. The influence on rainfall on the evaporation-transpiration calculation is shown in Example 12.1.*

7 Scheduling models

There are also other proven models that can be used for irrigation scheduling. A few of the models are discussed briefly; more information is available from the report: "*'n Ondersoek na sagteware vir besproeiingskedulering*" Jordaan, 2000. (report only available in Afrikaans).

7.2 BEWAB

BEWAB (*Besproeiingswater Bestuursprogram*/Irrigation water management program) is a water balance model that uses research data to make irrigation recommendations. The water consumption of the crop is estimated according to day-to-day irrigation requirement curves, which were fixed by historical readings.

BEWAB was developed by Prof. A.T.P Bennie, as a result of the Water Research Commission's report. "*'n Waterbalansmodel vir besproeiing gebaseer op profielwatervoorsieningstempo en gewasbehoeftes*" (Bennie *et al*, 1988)

7.2 Donkerhoek Data irrigation scheduling program

The Donderhoek Data Irrigation Scheduling Program makes use of up to date weather data, to make an irrigation recommendation on a daily basis, so that optimal irrigation can be done. The program contains a function that can control the opening and closing of valves in the field.

The program was developed by Donkerhoek Data (Pty) Ltd and Mr. T. du Preez. The total development of the program was funded by Donkerhoek Data (Pty) Ltd.

The program is used mainly by commercial farmers and consultants in the Western Cape and along the Orange river.

The program contains an option for calculating a water budget for a season or part thereof. Historical data can be used therefor.

7.3 SWB

SWB (Soil Water Balance) is an irrigation scheduling-model that uses current climatic data to simulate the salt balance and soil water balance of generic crops. With sufficient weather, soil and crop data it gives a complete description of the soil-plant-atmosphere continuum. The model contains sufficient data and equations to simulate the growth of plants mathematically.

SWB is based on the improved general crop version of NEWSWB.

The program was developed by the University of Pretoria's Department of Plant Production and Soil Science and Dr N Benade of NB Systems. The Water Research Commision, University of Pretoria, Chamber of Mines, Agricultural Research Council's Institute for Vegetable and Ornamental Plants, Potatoes South Africa and Langebaan Foods, funded the program.

SWB is mainly used for actual betimes irrigation scheduling. Researchers, commercial farmers, irrigation officers and consultants are the main users of the program.

7.4 VINET 1.1

VINET 1.1 (Estimated Vineyard Evapo-transpiration for Irrigation System Design and Scheduling) was designed to aid the producer in the decision-making process on when, how much and for how long irrigation must be applied. In the past, decision-making was made difficult because of the variation between vineyards because there were differences between foliage, soil and climatic factors. Dr PA Myburgh and Mr. C Beukes, both from the ARC-Infruitec-Nietvoorbij, developed VINET 1.1. The research was partly funded by Dried Fruit Technical Services, Deciduous Fruit Producers Trust and Winetech.

VINET 1.1 is currently used by commercial farmers, consultants, engineers and small farmers.

8 Scheduling calculations

Example 12.4:

- *Fixed cycle length of 1 day will be followed by the producer*
- *Nett irrigation requirement (NIR) = 178 mm/month*
- *Emitter spacing* ($L_r \times L_e$) = *4 m × 1 m*
- *Application efficiency* (η_a) = *85%*
- *Emitter delivery* (q_e) = *4 ℓ/h*

Solution:

Gross irrigation requirement per day

$$= \frac{10\ NIR}{31\ \eta_a}$$

$$= \frac{10 \times 178}{31 \times 0,85}\ m^3/day\ per\ ha$$

$$= 67,55\ m^3/day\ per\ ha$$

Flow rate of system per ha (Q)

$$= q_e \times number\ of\ emitters$$

$$= \frac{4}{1000} \times \frac{100^2}{4 \times 1}\ m^3/h\ per\ ha$$

$$= 10\ m^3/h\ per\ ha$$

Standing time (t_s)

$$= \frac{GIR}{Q}$$

$$= \frac{67,55}{10}\ h$$

$$= 6\ hours\ 45\ minutes$$

Example 12.5:

A micro sprayer system is used to irrigate a block of table grapes. The effective root depth is 750 mm. The soil water capacity of the soil is 65 mm/m. The allowable water depletion during the specific growth phase is 70%. The emitter delivery is 32 ℓ/h, the nozzle spacing/vine spacing is 1,8 m in the row, the row spacing is 3,5 m and the wetted strip width is 3 m. Crop factor is 0,6. Accept effective rainfall is equal to 0 and application efficiency is 80%.

The following must be determined:

a) How much evaporation must occur from the A-pan before it is irrigated again,
b) How much water must be applied, and
c) How long must irrigation be done.

Solution:

a) Readily available water in root zone

From Equation 12.5:

RAW = soil water capacity [mm/m] × effective root depth [m] × allowable depletion [dec]
= 65 × 0,75 × 0,7 mm
= 34,13 mm

Maximum soil water reservoir available per vine

From Equation 12.6:

SWR =RAW [mm] ×vine spacing [m] × wetted strip width [m]
=34,13 × 1,8 × 3 ℓ
=184 ℓ

Nett irrigation requirement per vine

From Equation 12.4:

NIR = (A-pan evaporation [mm] × crop factor – effective rainfall [mm] ×vine spacing[m] × row spacing [m]
=A-pan evaporation × 0,6 × 1,8 × 3,5
=3,78 × A-pan evaporation [mm]

The SWR must be equal to the NIR, therefore, the amount that must evaporate from the A-pan [mm]
=SWR [ℓ] (3,78)
=184/(3,78) mm
=48,75 mm

b) Amount of water to be applied
=SWR [ℓ] / (wetted strip width [m] × vine spacing [m] × application efficiency [dec])
=184 / (3 × 1,8 ×0,8) mm
=43 mm

c) Standing time

From Equation 12.8:

t_s *=SWR [ℓ] / (emitter delivery [ℓ/h] × application efficiency [dec])*
=184 / (32 × 0,8) h
=7 hours 15 minutes

9 References

1. Bennie, A. T. P., M. J. Coetzee, R. van Antwerpen and L. D. van Rensburg. 1988. *'n Waterbalansmodel vir besproeiing gebaseer op profielvoorsieningstempo en gewaswaterbehoeftes.* WRC Report nr. 144/1/88.

2. Crosby, C. T. 1996. *SAPWAT 1.0 – A computer program for estimating irrigation requirements in Southern Africa.* WRC Report No. 379/1/96.

3. Heyns, P. J., J. H. Burger, E. P. J. Kleynhans, F. H. Koegelenberg, M. T. Lategan, D. J. Mulder, H. S. Smal, C. M. Stimie, W.J. Uys, F. P. J. Van der Merwe and P. D. Viljoen. 1996. *Irrigation Design Manual*. ARC-Institute for Agricultural Engineering. RSA.

4. Hoffman. J. E. 2002. *Klasnota's opgestel vir die grond en waterbestuur kursus*. Department of Soil science. University Stellenbosch. RSA.

5. Jordaan, H. 2000. *'n Ondersoek na sagteware vir besproeiingskedulering.* ARC-Institute for Agricultural Engineering.. RSA.

6. Jordaan, H. 2001. *Grondwatersensors.* ARC-Institute for Agricultural Engineering. RSA.

7. Koegelenberg, F. H. 2002. *Norms for the design of irrigation systems*. ARC-Institute for Agricultural Engineering. RSA.

8. Piaget, J. 1991. *Tensiometers: Beskrywing, voorbereiding, opstelling en gebruik.* Elsenburg Agricultural Development Institute for the Winter Rainfall Area. RSA.

9. Scheepers, I., J. Piaget, W.A.G. Kotze and P.A. Myburgh. 1991. *Riglyne vir Besproeiingskedulering van Permanente Gewasse in die Winterreëngebied* Elsenburg Agricultural Development Institute. RSA.

10. Van Zyl, J. L. 1981. *Waterbehoefte en besproeiing.* In: (Reds. Burger, J. and Deist, J.). Viticulture in South Africa. ARC-Infruitec-Nietvoorbij, Stellenbosch. RSA.

Table 12.9: Estimated design crop factors for perennial crops in the summer rainfall areas – June 1996

Perennial crops	Description	Months of the year											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Citrus		0,55	0,60	0,65	0,70	0,65	0,60	0,45	0,45	0,45	0,45	0,45	0,5
Table grapes		0,5	0,6	0,6	0,4	0,2	0,2	0,12	0,12	0,12	0,2	0,3	0,4
Deciduous fruit	Late	0,5	0,6	0,50	0,20	0,20	0,20	0,20	0,20	0,20	0,25	0,30	0,40
	Medium	0,6	0,60	0,40	0,20	0,20	0,20	0,20	0,20	0,25	0,30	0,30	0,40
	Early	0,6	0,60	0,20	0,20	0,20	0,20	0,20	0,25	0,30	0,30	0,40	0,50
Wine grapes	Sub-intensive	0,25	0,25	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,25	0,25	0,25
	Intensive	0,50	0,50	0,30	0,20	0,20	0,20	0,20	0,20	0,2	0,3	0,4	0,50
Pastures	Rye grass	-	0,50	0,7	0,7	0,60	0,50	0,50	1,00	0,7	0,7	0,7	-
Pastures	Kikuyu	0,7	0,7	0,7	0,7	-	-	-	-	0,30	0,60	0,70	0,7
Alfalfa	Frost areas	0,7	0,7	0,70	0,50	0,40	0,30	0,30	0,40	0,50	0,70	0,80	0,7
Avocado		0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65
Coffee		0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65
Litchi		0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75	0,75
Macadamia		0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65
Pecan nuts		0,65	0,65	0,65	0,65	0,35	0,35	0,35	0,65	0,65	0,65	0,65	0,65
Bananas		0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8
Tea		0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7
Mangos		0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65

Table 12.10 : Estimated design crop factors for agronomic crops in the summer rainfall areas – June 1996

Agronomic crops	**Planting date**	**End of growth season**	**Months of the year**											
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Mealies	1 Oct	15 Feb	0,75	0,6								0,4	0,6	0,75
Mealies	15 Dec	15 Apr	0,75	0,75	0,6	0,5								0,4
Wheat	15 May	15 Sept					0,3	0,6	0,7	0,8	0,5			
Wheat	15 Jun	30 Nov						0,3	0,5	0,8	0,8	0,7	0,4	
Soya beans	1 Dec	15 Apr	0,6	0,7	0,7	0,5								0,3
Potatoes	1 Jan	30 Apr	0,3	0,5	0,8	0,8								
Potatoes	1 Mar	15 Jul			0,3	0,5	0,7	0,8	0,8					
Potatoes	1 Jun	15 Oct						0,3	0,5	0,7	0,8	0,8		
Potatoes	1 Nov	15 Mar	0,7	0,8	0,8								0,3	0,5
Tobacco	15 Oct	15 Feb	0,7	0,4								0,3	0,6	0,75
Ground-nuts	1 Oct	31 Jan	0,5									0,3	0,7	0,6
Cotton														
Area A	1 Oct	30 Apr	0,85	0,6	0,5	0,3						0,3	0,6	0,85
Area B	1 Nov	30 Apr	0,8	0,8	0,6	0,4							0,3	0,5
Area C	1 Nov	15 Apr	0,7	0,8	0,6	0,5							0,2	0,35

Area A: Limpopo, Eastern Transvaal, Lowveld and Northern Natal
Area B: Loskop, Rust-De Winter and Barberton
Area C: Vaalharts, Karoo, Eastern Cape and Transvaal middle veld

Table 12.11: Estimated design crop factors for vegetables in the summer rainfall areas – June 1996

Vegetable crops	**Portion of growing season [%]**				
	0-20	**20-40**	**40-60**	**60-80**	**80-100**
Beans	0,3	0,4	0,6	0,6	0,7
Brassicas	0,4	0,6	0,7	0,7	0,7
Cucurbits	0,3	0,4	0,6	0,7	0,7
Peas	0,3	0,3	0,4	0,7	0,6
Onions	0,3	0,4	0,7	0,7	0,7
Tomatoes	0,3	0,4	0,7	0,7	0,7

Table 12.12: Estimated design crop factors for perennial crops in the winter rainfall area – June 1990

Perennial crops	**Description**	**Months of the year**											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Citrus		0,4	0,4	0,5	0,5	0,4	0,4	0,3	0,3	0,4	0,4	0,4	0,4
Table grapes		0,5	0,6	0,6	0,3	0,2	0,2	0,2	0,2	0,2	0,3	0,4	0,5
Deciduous fruit	Late	0,55	0,55	0,55	0,35	0,2	0,2	0,2	0,25	0,3	0,4	0,45	0,5
	Medium	0,55	0,4	0,35	0,3	0,2	0,2	0,2	0,25	0,3	0,4	0,45	0,5
	Early	0,4	0,35	0,35	0,3	0,2	0,2	0,2	0,25	0,3	0,4	0,45	0,5
Wine grapes													
Sub-intensive		0,25	0,25	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,25	0,25
Intensive	Late	0,5	0,5	0,5	0,3	0,2	0,2	0,2	0,2	0,2	0,3	0,4	0,5
	Early	0,5	0,5	0,3	0,2	0,2	0,2	0,2	0,2	0,2	0,3	0,4	0,5
Pasture	Mixed	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55
Pasture	Kikuyu	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55
Alfalfa	Frost areas	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55
Guavas	Prune Aug	0,4	0,5	0,4	0,4	0,3	0,3	0,3	0,2	0,2	0,2	0,3	0,4

Table 12.13: Estimated design crop factors for agronomic crops in the winter rainfall area – June 1990

Agronomic crops	Planting date	End of growing season	Months of the year											
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Mealies	1 Oct	15 Feb	0,55	0,4								0,3	0,5	0,55
Wheat	15 May	15 Sept					0,25	0,3	0,5	0,65	0,4			
Soya beans	1 Dec	15 Apr	0,6	0,7	0,55	0,55								0,3
Potatoes	1 Jan	31 Mar	0,4	0,7	0,6									
Potatoes	1 Jun	31 Sept						0,4	0,7	0,7	0,55			
Potatoes	1 Aug	30 Nov								0,4	0,7	0,7	0,55	
Potatoes	1 Nov	31 Jan	0,6										0,4	0,7

Table 12.14: Estimated design crop factors for vegetables in the winter rainfall area – June 1990

Vegetable crops	**Portion of growing season[%]**				
	0-20	**20-40**	**40-60**	**60-80**	**80-100**
Beans	0,25	0,3	0,5	0,5	0,55
Brassicas	0,3	0,5	0,5	0,55	0,55
Cucurbits	0,25	0,3	0,4	0,4	0,4
Peas	0,25	0,3	0,3	0,55	0,5
Onions	0,25	0,3	0,5	0,5	0,5
Tomatoes	0,25	0,3	0,5	0,55	0,55

Table 12.15: Penman-Monteith Crop Factors: Perennials

Assumptions:
1. Weekly irrigations
2. Cover: Mature orchards/vineyards = 75%
   Young orchards/vineyards = 40%
   Other crops = 100%
3. Wetted area: Orchards/vineyards = 50%
   Other crops = 100%

Crop	**Crop options**	**Climatic region**	k_c											
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Almonds	Mature/middle season	All areas	0,90	0,87	0,64	0,37	0,24	0,24	0,24	0,24	0,56	0,90	0,90	0,90
Almonds	Young/middle season	All areas	0,53	0,51	0,41	0,29	0,23	0,23	0,23	0,23	0,37	0,53	0,53	0,53
Apples	Mature/middle season	All areas	0,98	0,93	0,69	0,42	0,28	0,28	0,28	0,28	0,28	0,50	0,95	0,98
Apples	Young/middle season	All areas	0,57	0,55	0,43	0,30	0,23	0,23	0,23	0,23	0,23	0,34	0,55	0,57
Apricots	Mature/middle season	All areas	0,71	0,59	0,47	0,35	0,28	0,28	0,28	0,28	0,56	0,89	0,90	0,83
Apricots	Young/middle season	All areas	0,44	0,39	0,33	0,25	0,24	0,24	0,24	0,24	0,37	0,53	0,54	0,50
Asparagus		All areas	0,96	0,89	0,56	0,38	0,38	0,38	0,38	0,38	0,38	0,66	0,96	0,96
Avocado	Mature	Lowveld	0,98	0,88	0,68	0,58	0,58	0,58	0,58	0,58	0,58	0,68	0,88	0,98
Avocado	Young	Lowveld	0,57	0,51	0,37	0,31	0,31	0,31	0,31	0,31	0,31	0,37	0,50	0,57
Bananas	Ratoon	Lowveld	0,90	0,90	0,84	0,70	0,56	0,49	0,49	0,49	0,49	0,49	0,69	0,90
Brambles		Winter rain/Highveld	1,11	1,03	0,86	0,69	0,61	0,61	0,61	0,61	0,79	1,08	1,11	1,11
Cherries	Mature/middle season	Highveld	0,74	0,60	0,46	0,32	0,25	0,25	0,25	0,25	0,32	0,73	0,90	0,87
Cherries	Young/middle season	Highveld	0,46	0,40	0,34	0,28	0,24	0,24	0,24	0,24	0,27	0,46	0,53	0,52
Citrus	Mature/average production	All areas	0,63	0,63	0,63	0,62	0,61	0,61	0,61	0,62	0,63	0,63	0,63	0,63
Citrus	Young/average production	All areas	0,38	0,38	0,38	0,39	0,39	0,39	0,39	0,38	0,38	0,38	0,38	0,38
Coffee	Mature	Lowveld	0,98	0,88	0,68	0,58	0,58	0,58	0,58	0,58	0,58	0,68	0,88	0,98
Coffee	Young	Lowveld	0,57	0,51	0,37	0,31	0,31	0,31	0,31	0,31	0,31	0,37	0,50	0,57
Cut flowers		All areas	1,15	1,15	1,15	0,90	0,62	0,62	0,62	0,62	0,88	1,15	1,15	1,15
Date palm	Mature	Karoo/North Cape	0,98	0,98	0,98	0,98	0,79	0,59	0,59	0,68	0,88	0,98	0,98	0,98
Date palm	Young	Karoo/North Cape	0,57	0,57	0,57	0,57	0,45	0,32	0,32	0,38	0,51	0,57	0,57	0,57
Fescue pasture		All areas	0,80	0,80	0,80	0,80	0,76	0,72	0,72	0,74	0,78	0,80	0,80	0,80
Grapes	Table/middle season	All areas	0,66	0,57	0,45	0,37	0,26	0,26	0,26	0,26	0,34	0,63	0,67	0,67
Grapes	Wine/middle season	All areas	0,55	0,55	0,49	0,34	0,26	0,26	0,26	0,26	0,29	0,50	0,55	0,55
Guavas	Mature	Winter rainfall	0,90	0,90	0,90	0,65	0,38	0,38	0,38	0,38	0,38	0,41	0,67	0,87
Guavas	Young	Winter rainfall	0,53	0,53	0,53	0,40	0,25	0,25	0,25	0,25	0,25	0,27	0,39	0,51
Litchi	Mature	Lowveld	0,83	0,78	0,73	0,68	0,65	0,72	0,84	0,91	0,91	0,91	0,91	0,88
Litchi	Young	Lowveld	0,50	0,47	0,44	0,42	0,40	0,44	0,50	0,54	0,54	0,54	0,54	0,52
Lucerne	Semi-dormant	Areas with frost	0,86	0,86	0,78	0,62	0,47	0,38	0,38	0,46	0,62	0,78	0,86	0,86
Lucerne	Semi-dormant	Areas without frost	0,86	0,86	0,86	0,77	0,61	0,52	0,52	0,57	0,69	0,80	0,86	0,86
Macadamia	Mature	All areas	0,90	0,79	0,57	0,35	0,24	0,24	0,24	0,24	0,56	0,90	0,90	0,90
Macadamia	Young	All areas	0,53	0,48	0,38	0,28	0,23	0,23	0,23	0,23	0,37	0,53	0,53	0,53
Mangoes	Mature	Lowveld	0,72	0,67	0,62	0,56	0,51	0,53	0,53	0,78	0,83	0,83	0,82	0,78
Mangoes	Young	Lowveld	0,45	0,43	0,41	0,39	0,37	0,37	0,37	0,48	0,50	0,50	0,50	0,48
Pastures	Summer & Winter	All areas	0,85	0,85	0,85	0,85	0,85	0,85	0,86	0,86	0,86	0,86	0,86	0,85
Pastures	Summer/perennial	All areas	0,81	0,81	0,76	0,66	0,55	0,50	0,50	0,50	0,55	0,65	0,76	0,81
Pawpaws	Mature	Lowveld	0,94	0,94	0,94	0,67	0,39	0,39	0,39	0,48	0,66	0,85	0,94	0,94

Table 12.16: (continue)

Crop	**Crop options**	**Climatic region**	**k_c**											
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Pawpaws	Young	Lowveld	0,55	0,55	0,55	0,41	0,26	0,26	0,26	0,31	0,40	0,50	0,55	0,55
Peaches	Mature/middle season	All areas	0,80	0,66	0,51	0,36	0,29	0,29	0,29	0,31	0,69	0,94	0,94	0,93
Peaches	Young/middle season	All areas	0,49	0,42	0,35	0,28	0,24	0,24	0,24	0,26	0,43	0,55	0,55	0,54
Pears	Mature/middle season	All areas	0,97	0,82	0,60	0,39	0,28	0,28	0,28	0,28	0,31	0,62	0,94	0,98
Pears	Young/middle season	All areas	0,56	0,49	0,39	0,29	0,23	0,23	0,23	0,23	0,25	0,40	0,55	0,57
Pecan nuts	Mature	All areas	0,82	0,66	0,50	0,34	0,25	0,25	0,25	0,33	0,82	0,90	0,90	0,90
Pecan nuts	Young	All areas	0,50	0,43	0,36	0,29	0,25	0,25	0,25	0,28	0,49	0,53	0,53	0,53
Pistachio	Mature	All areas	0,82	0,80	0,61	0,39	0,28	0,28	0,28	0,28	0,54	0,82	0,82	0,82
Pistachio	Young	All areas	0,49	0,48	0,39	0,29	0,24	0,24	0,24	0,24	0,36	0,49	0,49	0,49
Plums	Mature/middle season	All areas	0,89	0,72	0,55	0,38	0,29	0,29	0,29	0,29	0,37	0,80	0,94	0,94
Plums	Young/middle season	All areas	0,53	0,45	0,37	0,29	0,24	0,24	0,24	0,24	0,28	0,48	0,55	0,55
Salt bush		All areas	0,31	0,31	0,31	0,31	0,29	0,26	0,26	0,26	0,29	0,31	0,31	0,31
Strawberries		All areas	0,75	0,51	0,38	0,38	0,38	0,38	0,38	0,38	0,50	0,74	0,86	0,86
Sugar	Winter harvest	KwaZulu-Natal/Lowveld	1,15	1,15	1,15	1,15	1,12	0,68	0,39	0,51	0,77	1,02	1,15	1,15
Sugar	Spring harvest	KwaZulu-Natal/Lowveld	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,12	0,67	0,44	0,88
Tea		Lowveld	0,68	0,68	0,68	0,70	0,72	0,75	0,76	0,76	0,76	0,75	0,72	0,70
Walnuts	Mature	All areas	0,90	0,90	0,58	0,23	0,23	0,23	0,23	0,23	0,23	0,56	0,90	0,90
Walnuts	Young	All areas	0,53	0,53	0,38	0,23	0,23	0,23	0,23	0,23	0,23	0,37	0,53	0,53

Table 12.17: Penman-Monteith Crop Factors: Annuals

Assumptions: 1. Weekly irrigations
2. Wetted area = 100%

Crop	Plant / Crop option	Days	Climatic region	k_c Months from plant									Remarks
				Mnth 1	Mnth 2	Mnth 3	Mnth 4	Mnth 5	Mnth 6	Mnth 7	Mnth 8	Mnth 9	
Babala	Spring/Summer	140	All areas	0,38	0,65	1,05	1,02	0,59					
Barley	Winter	140	All areas	0,64	0,82	1,12	1,11	0,66					
Beans Dry	Spring	100	All areas	0,45	1,02	1,14	0,87						
Beans Green	Spring/Summer	90	All areas	0,45	0,91	1,03							
Beetroot		90	All areas	0,46	0,94	0,98							
Brinjals	Spring	140	All areas	0,39	0,66	1,11	1,10	0,65					
Brocolli		80	All areas	0,63	0,86	0,98							
Brussels sprouts	Autumn	120	All areas	0,64	0,87	1,07	1,01						
Butternut		110	All areas	0,52	0,89	0,98	0,82						
Cabbage Early	Spring	75	All areas	0,58	0,93	0,99							
Canola	Spring	120	All areas	0,39	0,66	1,10	0,90						
Carrots	Spring/Summer	100	All areas	0,44	0,67	0,94	0,98						
Carrots	Autumn/Winter	107	All areas	0,48	0,67	0,92	1,00						
Cauliflower Main	Spring	100	All areas	0,55	0,82	0,99	0,99						
Cauliflower Main	Summer	90	All areas	0,53	0,84	0,99	0,99						
Cauliflower Main	Autumn	120	All areas	0,59	0,80	0,98	1,00						
Cauliflower Main	Winter	100	All areas	0,73	0,89	0,99	0,99						
Cereals Grazing	Autumn	190	All areas	0,48	0,60	0,88	0,90	0,90	0,80	0,50			
Chicory	Spring	195	Eastern Cape warm	0,43	0,51	0,76	0,90	0,90	0,90	0,90			
Chillies		110	All areas	0,39	0,73	1,09	0,75						
Coriander	Spring	90	All areas	0,43	0,96	0,93							
Cotton	Spring/medium grower	160	Warm areas	0,40	0,63	1,01	1,09	1,07	0,93				
Cow peas	Spring	100	All areas	0,45	0,93	1,06	0,81						
Cucumbers		105	All areas	0,45	0,93	1,09	0,75						
Cucurbits	Spring/Summer	130	All areas	0,54	0,75	0,93	0,93	0,72					

Table12.17 (continue)

Crop	Plant / Crop option	Days	Climatic region	k_c Months from plant									Remarks
				Mnth 1	Mnth 2	Mnth 3	Mnth 4	Mnth 5	Mnth 6	Mnth 7	Mnth 8	Mnth 9	
Cucurbits	Autumn/Winter	140	All areas	0,68	0,86	0,99	0,93	0,80					
Green peppers	Spring/Summer	110	All areas	0,38	0,72	1,09	0,77						
Ground nuts	Spring	150	All areas	0,39	0,61	1,04	1,14	0,79					
Hubbard squash	Spring	140	All areas	0,53	0,71	0,87	0,87	0,72					
Hubbard squash	Summer	130	All areas	0,55	0,74	0,89	0,83	0,69					
Lentils	Spring	170	All areas	0,42	0,79	1,09	1,09	0,98	0,58				
Lettuce	Spring	75	All areas	0,44	0,81	0,92							
Lettuce	Autumn	100	All areas	0,49	0,74	0,95	0,93						
Maize	Spring/medium grower	135	All areas	0,39	0,75	1,14	1,14	0,93					
Maize	Summer/short grower	120	All areas	0,36	0,79	1,14	1,03						
Oats	Winter	140	All areas	0,64	0,82	1,12	1,11	0,66					
Onions	Autumn transplant	160	All areas	0,58	0,60	0,76	0,86	0,82	0,67				
Paprika		130	All areas	0,51	0,76	0,98	1,00	1,00					
Parsley	Spring	270	All areas	0,49	1,13	1,15	1,15	1,15	1,15	1,15	1,15	0,73	Actually a bi-annual plant
Pastures	Autumn	170	All areas	0,45	0,77	0,80	0,80	0,80	0,69				
Peas	Autumn/Winter	110	All areas	0,49	0,82	1,09	1,07						
Potatoes	Spring/Summer	120	All areas	0,29	0,89	1,09	1,01						
Pumpkin	Spring/Summer	125	All areas	0,38	0,67	0,88	0,79	0,59					
Pumpkin	Autumn/Winter	150	All areas	0,39	0,63	0,86	0,87	0,70					
Radishes	Spring/Summer	45	All areas	0,72	0,86								
Ryegrass	Autumn	250	All areas	0,61	0,97	1,00	1,00	1,00	1,00	1,00	1,00	0,74	
Sorghum	Spring	170	All areas	0,45	0,77	0,80	0,80	0,80	0,69				
Soybeans	Spring/short grower	120	All areas	0,43	1,04	1,14	1,04						
Soybeans	Spring/medium grower	130	All areas	0,44	0,97	1,14	1,14	0,83					
Soybeans	Spring/long grower	140	All areas	0,43	0,87	1,14	1,14	0,99					
Sweet melon	Spring/Summer	105	All areas	0,64	0,95	0,96	0,83						

Table 12.17 (continue)

Crop	**Plant / Crop option**	**Days**	**Climatic region**	**k_c Months from plant**									**Remarks**
				Mnth 1	**Mnth 2**	**Mnth 3**	**Mnth 4**	**Mnth 5**	**Mnth 6**	**Mnth 7**	**Mnth 8**	**Mnth 9**	
Sweet melon	Autumn/Winter	120	All areas	0,66	0,91	1,00	0,90						
Spinach	Autumn	190	All areas	0,39	0,51	0,77	0,98	0,99	0,98	0,95			
Squash	Spring	105	All areas	0,53	0,79	0,89	0,82						
Sugarbeet	Spring	240	All areas	0,42	0,60	0,96	1,15	1,15	1,15	1,15	1,15		
Sunflower	Spring/Summer	100	All areas	0,40	0,92	1,14	0,86						
Sweet potatoes	Spring	150	All areas	0,42	0,82	1,09	1,09	1,03					
Sweetcorn	Spring/Summer	90	All areas	0,53	0,82	0,99							
Tobacco	Spring/Summer	120	Warmer areas	0,41	0,84	1,09	0,92						
Tomatoes	Processing	100	All areas	0,67	1,06	1,02	0,85						
Tomatoes	Table	160	All areas	0,58	0,77	0,97	1,09	1,09	1,09				
Watermelon	Early	85	All areas	0,65	0,98	0,97							
Watermelon	Late	100	All areas	0,64	0,96	0,98	0,95						
Wheat	Medium/Winter	125	All areas	0,57	0,79	1,12	1,06	1,02					
Wheat	Short/Autumn/ Spring	80	All areas	0,57	1,06	1,04							