



**DEVELOPMENT OF IRRIGATION GUIDELINES FOR CITRUS UNDER DRIP
IRRIGATION IN ZIMBABWE**

By

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Abstract

This study was carried out to develop drip irrigation guidelines for citrus in Zimbabwe. In order to achieve this, the average ET_0 values for the study site were derived from climatic data. The study, which was carried out at Mazowe Citrus Estate, also involved the determination of the class A evaporation pan coefficient, K_{pan} to enable local estimations of ET_0 from the class A evaporation pan. The whole season crop coefficient, K_c , curve for citrus was developed for the estimation of crop water requirements. The ET_0 trend for the study site was established from the FAO Penman Monteith equation using observed and historical climatic data. K_{pan} was determined using two methods. The first method was empirical and K_{pan} was estimated from the mean relative humidity, mean wind speed at 2 m height and the fetch conditions. In the second method, K_{pan} was determined as the slope of the plot of the FAO Penman Monteith ET_0 against the pan evaporation, E_{pan} . The K_c curve was developed after the empirical determination of K_c during the initial growth stage, the mid season stage and at the end of fruit development. The K_c value of the initial growth stage that was developed for the sub humid climates was adjusted to reflect the wetting frequency of the soil. The mid season K_c value developed for the sub humid climate was adjusted to the local climatic conditions using wind speed at 2 m height, the minimum relative humidity and the average tree height. During the crop development and the late season stages, K_c was estimated by considering that K_c varies linearly between the value at the end of the previous stage and that at the beginning of the next stage. Transpiration rate was monitored using a Stem Heat Balance sap flow gauge that was installed on a branch of the tree. The leaf area was used as the scaling up factor for the sap flow from the branch to the whole hectare. This was done to compare the crop water requirement to the irrigation depth prescribed by the developed irrigation guidelines. BUDGET (version 6.2), a soil water balance model was used to develop irrigation calendars using a fixed irrigation interval of one day. The model was also used to simulate the soil water status after using the irrigation guidelines. Four treatments were established to assess the effect of different irrigation strategies on fruit growth and abscission. These were the control (use of ET_0 data for irrigation scheduling), well watered (where both sides of the tree were irrigated but each side receiving half the amount of water as the control), the grower's scheduling practice and the last one was a PRD 50 where one side of the tree was irrigated whilst the other one was drying out. The switching of the drip lines was done on a 10 day interval. The effects of the different irrigation strategies were evaluated in terms of fruit growth rate and fruit abscission during the fruit drop period. ET_0 was approximately 4 mm day⁻¹ from January to April, lowest in winter (almost 3 mm day⁻¹) and was highest in October (slightly above 5 mm day⁻¹). The green fetch K_{pan} was high from January to April (almost 0.8). The value fell from May and the lowest K_{pan} value of 0.72 was established in October. Using the second method, a K_{pan} value of 0.78 was determined for October to March. The initial K_c value was 0.47 but it rose sharply during the crop development stage. K_c values for the mid season and at the end of the season were 0.84 and 0.76 respectively. There is a possibility that the grower was over irrigating based on simulated soil moisture conditions usually above the field capacity. High drainage losses of up to 1964 mm for the whole season were simulated compared to 381 mm for the irrigation scheduling guidelines. No significant differences ($p < 0.05$) were observed on fruit growth rates although the control treatment had larger fruit diameters than the other treatments. Fruit abscission was generally low for all treatments. A single K_{pan} value

can not be used throughout the season and the variations along the season should be taken into account for better estimations of ET_0 using the evaporation pan. K_c fluctuations during the crop development stage should be noted to reduce errors in the estimation of citrus crop water requirements. Taking into account the atmosphere's evaporative demand is an effective way of irrigation scheduling. Irrigating both sides of the tree at the same time is not effective if the irrigation depth is low. PRD 50 showed great potential in balancing fruit growth and water conservation. Zimbabwean citrus farmers are encouraged to adopt the developed irrigation guidelines as well as the K_{pan} and K_c values. PRD, if well timed, proves to be a better irrigation strategy.

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List of Acronyms and symbols

AWC	Available Water Capacity
AWS	Automatic Weather Station
BUDGET	A soil water and salt balance model
CWR	Crop Water Requirements
DOY	Day of year (in Julian days)
E_{pan}	Pan Evaporation
ET_c	Crop Evapotranspiration
ET_o	Reference evapotranspiration
FAO	Food and Agriculture Organisation
FC	Field Capacity
FET	Fetch i.e. the distance of the identified surface type upwind of the evaporation pan
f_w	The fraction of the surface wetted by irrigation or rain
K_{pan}	Pan Coefficient
K_c	Crop Coefficient
$K_{c \text{ end}}$	Crop Coefficient value that corresponds to the end of the season
$K_{c \text{ ini}}$	Crop Coefficient value for the initial crop growth stage
$K_{c \text{ mid}}$	Crop Coefficient value for the mid season stage of crop development
$K_{c \text{ next}}$	Crop Coefficient value for the next crop growth stage
$K_{c \text{ prev}}$	Crop Coefficient value for the previous crop growth stage
K_{sh}	Thermal conductance constant for a particular gauge installation
K_{st}	Thermal conductivity of the stem
MCE	Mazowe Citrus Estate
MDS	Maximum Daily Trunk Shrinkage
PI	Pulsed Irrigation

PRD	Partial Root zone Drying
PRD 50	Partial Root zone Drying applying half the amount as the control
RAM	Readily Available Moisture
RDI	Regulated Deficit Irrigation
RH	Relative Humidity
$RH_{\min}$	Minimum Relative Humidity
RZ	Root Zone
SHB	Stem Heat Balance
TAM	Total Available Moisture
TDP	Thermal Dissipation Probe
U_2	Wind speed at 2 m height
WMO	World Meteorological Organisation

CHAPTER 1

INTRODUCTION

1.1 Background

The recent uncertainties in the rainfall patterns of Southern Africa and the prevalence of drought in the region are the major driving factors that call for the efficient utilization of water resources. Climatic variability and change that result in increased evaporation rates coupled with reduced capacities of reservoirs in Zimbabwe due to siltation has recently led to increased pressure on the limited and diminishing water resources. Agriculture is the largest consumer of water in all regions of the world except Europe and North America and up to 70 % of water abstracted from rivers and ground water goes to irrigation (FAO, 2002a; Lenntech, 2003).

Water can be utilized efficiently in agriculture through properly designed irrigation schedules. Irrigation scheduling is an important aspect of management that determines when to irrigate and how much water to apply. Water applied at the proper time and quantity can influence fruit yield and quality. Crops require water in the root zone and any water applied should be equal to the water lost through evapotranspiration. The type of irrigation rather than scheduling mainly governs irrigation efficiency. Drip irrigation is more efficient than sprinkler irrigation and flood irrigation is the least efficient. All these irrigation types are in use in Zimbabwe but resources permitting, farmers should move to drip irrigation because of its high efficiency.

Recent studies have shown that the drip irrigation system can be modified to increase application efficiency. Some of the strategies to be used in drip irrigation are the Partial Root zone Drying (PRD), Regulated Deficit Irrigation (RDI) and the Pulsed Irrigation (PI) techniques. PRD is a water application technique that involves alternately wetting each half

of the root zone during successive irrigation events. RDI is an irrigation strategy in which water is either withheld or reduced during specific periods of crop (fruit) growth (Dzikiti, 2007). A certain level of drought stress is maintained in the root zone and the objective in tree crops is to control the canopy size and to limit the applied water. A fraction of crop evapotranspiration is replaced during each irrigation event rather than applying full irrigation (100 % ET_c). The applied amount of water, however, must not affect production (yield and quality of the crop).

PI is the application of small amounts of water at intervals across the day rather than applying the required amount of water at once. This is beneficial in that all water applied will be used by the plant reducing deep percolation losses. PRD and RDI have been found to have high water use efficiencies in citrus production and improve yield with no negative effects on fruit quality (Chalmers et al., 1981; Cohen et al., 1985; Dry et al., 1996; Dzikiti et al., 2008).

The citrus species are perennial in growth habit. The most common species are *Citrus sinensis* (sweet orange), *Citrus aurantium* (sour orange), *Citrus aurantifolia* (lime), *Citrus limon* (lemon) and *Citrus paradisi* (grape fruit). In 2001, the world production of citrus was around 98.7 million tonnes of fresh fruit, 62 % of which were oranges (FAO, 2002a). The production levels of citrus reflect that citrus production is one of the major agricultural activities contributing to the irrigation water demand.

In citrus production, there should be a well-defined irrigation calendar that is derived from the evaporative demand of the atmosphere, soil type as well as water application strategies that are effective. The vegetative and fruit development phases in citrus trees consist of bud break, flowering, fruit set, fruit growth, summer flush and autumn flush. Water application

throughout the season should take into account the water requirements of these phases so as to enhance yield and fruit quality. The use of the drip irrigation strategy in Zimbabwe is expected to enhance the water use efficiency, yield and fruit quality of citrus trees, and has been applied by some growers in Zimbabwe. However, productivity under this strategy has in some cases failed to surpass, let alone match that under less precise water application methods such as flood irrigation. One of the main constraints identified is the lack of operational guidelines for system and site-specific irrigation scheduling.

1.2 Justification

About 6000 hectares are under citrus cultivation in Zimbabwe (Ministry of Foreign Affairs, 2009). More resources must be directed towards citrus production as it has potential to increase the country's revenue, since it is one of the major horticultural exports. The quality and quantity of produce can be drastically reduced when the trees are not receiving the right amount of water. Citrus production in Zimbabwe depends largely upon the availability of water for irrigation since rainfall occurs mainly during summer.

The mean monthly precipitation for Mazowe Citrus Estate (MCE) is less than the mean monthly potential evapotranspiration for eight months i.e. from April to November with an average of ninety-three rain days per year (Grieser, 2006). The climatic net primary production is precipitation limited. MCE is in natural region II of Zimbabwe and is hence even better in terms of precipitation compared to natural regions III, IV and V (Vincent and Thomas, 1960). For viable citrus production, the precipitation deficit has to be covered by irrigation since citrus are annual crops. There is need for irrigation for more than two thirds of the year. It is apparent that there is heavy reliance on irrigation and hence proper irrigation

strategies have to be implemented for higher production as well as effective water management.

The development of site-specific operational guidelines for citrus irrigation is a requirement for the local citrus growers. Irrigation must take into account the evaporative demand of the atmosphere at any given day. The use of the irrigation guidelines will aid growers to apply the required amount of water. This ensures the optimal utilisation of water resources (avoids over irrigation and under irrigation). The current blanket recommendations for citrus irrigation do not take into account the variations in the evaporative demand of the atmosphere from day to day and even from season to season.

The study promotes the effective use of simple weather stations for the estimation of potential evapotranspiration, ET_o by the growers. Since most growers do not afford and or do not have the expertise for advanced instrumentation for estimating ET_o , they can use evaporation pans and obtain reliable results. The reliable ET_o from the evaporation pans is aided by the application of a site-specific pan coefficient, K_{pan} . The K_{pan} value was obtained by the calibration of pan evaporation, E_{pan} against ET_o computed with the Penman Monteith method. The determination of the site-specific crop coefficient, K_c curve from the study allows for better estimation of crop water requirements by the growers. The growers will therefore know the optimum amount of water to apply as demanded by the trees.

1.3 Objectives

The main aim of this study was to establish irrigation guidelines for citrus trees under PRD and non-PRD drip irrigation in Zimbabwe. The specific objectives of the study were to:

1. Determine the evapotranspiration of citrus trees using the FAO Penman Monteith method.

2. Determine a site-specific crop coefficient curve, K_c for citrus.
3. Develop appropriate irrigation guidelines for citrus under PRD and non-PRD drip irrigation.
4. Evaluate the performance of these guidelines by comparison against an existing operational system (the current grower practice) at Mazowe Citrus Estate.

1.4 Expected Benefits

The benefits derived from this study are of great value to citrus farmers in Zimbabwe. This study provides comprehensive yet user friendly irrigation guidelines for all weather conditions and these guidelines can be transferred to other areas after proper adjustments. Citrus plant water use throughout the season is outlined to enable farmers to know the amount of water expected to be used through irrigation for planning purposes.

The study provides a means for farmers to estimate crop water requirements by using the mean daily ET_0 values derived from the reliable FAO Penman – Monteith equation as well as a site specific empirically determined crop coefficient curve. One of the major benefits of this study is that it transformed the complex and expensive way of estimating citrus water requirements. Farmers will be able to use the easy and cheap evaporation pan method because of the establishment of site specific pan coefficients throughout the growing season. The study also gives an illustration of the soil moisture dynamics throughout the season for all scenarios of rainfall and ET_0 . This is essential for irrigation planning and decision making. This gives a better understanding of when to irrigate and the depth of application. The understanding of soil water dynamics provides a way for timing of water harvesting in orchards during periods of excess rainfall. This reduces the amount of water that will be lost

through drainage beyond the root zone. If captured and well stored, the water can be used for other purposes.

1.5 Thesis Outline

The thesis consists of 5 chapters. In chapter 1, the thesis is introduced by giving a brief background, the justification of the study and an outline of the objectives of the research. Chapter 2 outlines the literature that is linked to the study. The study site description, treatments, materials and methods applied for the collection of the required information are described in chapter 3. The results and their subsequent discussion from different experiments of the study are displayed in chapter 4. The findings from the research work are concluded in chapter 5. The recommendations for further studies and possible ways for the improvement of citrus water management are also outlined in chapter 5. The appendices at the end of the thesis give more details on sections that could not be included in the main body.

2.0 Introduction

Water management is an important aspect for successful citrus production. Irrigation scheduling strategies are an integral part of water management. Huygen et al., (1995) outlined the following as objectives of irrigation management:

- Maximum net return
- Reduction of irrigation costs
- Rational use of the limited water supply
- Reduction of ground water pollution

Irrigation water management is principally achieved by irrigation scheduling in the form of an irrigation calendar or guidelines. There are many methods that are used for irrigation scheduling and the choice depends mainly on the availability of weather data, level of instrumentation and expertise. The three major forms of irrigation scheduling are: empirical, weather based and the tracking of crop condition. Irrigation guidelines are produced from the evaporative demand of the atmosphere, crop type and growth stage.

2.1 Crop water requirements, CWR

Water is essential for plant survival and growth and approximately 1 % of water taken up by plants is used for metabolic activities and the rest is transpired (Raes, 2007). Water is a solvent in most physiological processes, is vital for chemical reactions and is involved in photosynthesis. Evaluation of crop water requirements in irrigation scheduling is based on the estimation of crop evapotranspiration, ET_c . The CWR is expressed as depth of water in unit

time (usually a day) and is affected by weather variables, crop factors, management and environmental conditions.

The vapour pressure gradient i.e. the difference between vapour pressure at the transpiring surface and that of the surrounding air is the major force in removing water vapour from the transpiring surface (the leaf). There is need for accurate methods for measuring CWR on real time basis. This is very crucial since the reduction of irrigation needs by 10 % would free up enough water to double domestic water use world wide (Lascano et al., 1996). The determination of CWR breaks the obstacle of the evaluation of water inventories and future demands since ET_c is a basic component of the hydrological cycle (Lascano et al., 1996).

2.2 Citrus production in Zimbabwe

Citrus is an evergreen, cold sensitive plant with a geographical distribution mainly influenced by low temperatures (Gat et. al., 1997). Major citrus growing areas i.e. citrus belt, extend from 40⁰ North to 40⁰ South latitude (Gat et. al., 1997; FAO, 2002b) and an altitude of up to 1800 m in the subtropics (FAO, 2002b) thus making Zimbabwe a citrus growing region. Citrus production in Zimbabwe depends largely upon the availability of water for irrigation since rainfall occurs mainly during summer. In Zimbabwe, an estimated 6000 hectares are under citrus cultivation (Ministry of Foreign Affairs, 2009). Citrus fruits grown include grapefruits, lemons, naartijies, nectarines and oranges. Fruit bearing for citrus is usually three years after planting but economic yields are realised from the fifth year.

2.2.1 Development of citrus at MCE

The phenological stage lengths for citrus at MCE are outlined in Table 2.1. The citrus growth cycle is divided into four growth stages. The initial stage is during spring where there is

maximum shoot initiation. These shoots form the sites on which flowers develop. The initial stage is approximately 70 days and begins from August to almost the first decade of October. Part of the initial stage involves the first flower opening and flowering.

Table 2.1: Typical growth cycle of citrus fruit at Mazowe Citrus Estate in Northern Zimbabwe (Dzikiti, 2007).

	Spring			Summer					Autumn	Winter			
	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
Bud break (spring flush)													
End of shoot elongation													
First flower opening													
Flowering													
Fruit-let drop (fruitset)													
Fruit growth			CELL DIVISION			CELL EXPANSION				MATURATION			
Summer flush													
Autumn flush													

The second stage (crop development) initiates from the second decade of October and stretches to end of December. The crop development stage is approximately 81 days. During this stage, there will be flowering up to end of October; fruit set up to end of December and the fruit growth consists of cell division. The mid season stage is characterised by cell expansion i.e. fruit growth. Cell expansion starts from end of December to the end of March. The mid season stage is approximately 120 days. The late season stage for citrus in Zimbabwe is about 94 days long. The fruit development and maturation stages are however not clearly distinguishable and they overlap considerably.

2.3 Irrigation strategies of citrus trees

Irrigation is one of the critical factors for the production of high value citrus fruits (Ramsey, 2007). Real time irrigation scheduling systems are usually used for high value crops e.g. citrus. Full season irrigation schedules for citrus can also be developed from historical meteorological data based on long term average data (De Jager and Kennedy, 1996). Water application for citrus should be aimed in the effective root zone i.e. 30 to 40 cm, depending on soil type (Ramsey, 2007). The prime objective is to reduce water losses and leaching through deep percolation. There are a number of drip irrigation strategies for citrus that are in use in Zimbabwe. The most common are the Partial Root zone Drying (PRD), Regulated Deficit Irrigation (RDI) and Pulsed Irrigation (PI). All these strategies have been developed with the main objectives of enhancing the water use efficiency of citrus and maintaining or even increasing fruit quality and yield.

2.3.1 Partial Root – zone Drying (PRD)

PRD is a water application technique that involves alternately wetting each half of the root zone during successive irrigation events. PRD also involves the gradual drying out of part of the root system while keeping the other part wet by scheduled irrigation (Chalmers et al., 2004). This is done for a pre-determined period before the irrigation is swapped to the dry side, allowing the wet side to start drying out. The PRD strategy seeks to reduce, artificially, stomatal conductance while maintaining the plant water status (Dzikiti et al., 2006). This irrigation strategy is designed to increase water use efficiency in citrus thereby decreasing production costs (Lovatt and Faber, undated).

The increased water use efficiency is linked to stomatal control of transpiration and favourable plant water status. This is enhanced by a chemical signal, Abscissic Acid (ABA)

i.e. a plant growth regulator produced in drying roots that is transported to leaves after night time rehydration of the roots in the dry soil (During *et al.*, 1996; O'Connell *et al.*, 2004). This results in a non-hydraulic effect by causing partial closing of leaf stomata (During *et al.*, 1996). PRD was reported to increase water use efficiency, reduce vegetative growth and maintain fruit yield and quality in grape vines (Dry and Loveys, 1999). PRD is tipped to increase yields in orchards where reduced internal shading result in increased flower initiation, fruit set, fruit size and fruit colour (O'Connell and Goodwin, 2004).

2.3.2 Regulated Deficit Irrigation (RDI)

RDI is an irrigation strategy in which water is either withheld or reduced during specific periods of crop (fruit) growth (Dzikiti, 2007). A certain level of drought stress is maintained in the root zone and the objective in tree crops is to control the canopy size and to limit the applied water. A fraction of crop evapotranspiration is replaced during each irrigation event rather than the application of full irrigation (100 % ET_c). RDI is a valuable and sustainable production strategy in dry regions (Geerts and Raes, 2009). Water application is limited for periods that correspond to drought tolerant growth stages especially the vegetative and early ripening. RDI aims at stabilising yields and obtaining maximum water productivity rather than maximising yields (Geerts and Raes, 2009).

2.3.2.1 Merits and demerits of RDI

RDI maximises water productivity and stabilises yields i.e. does not cause severe yield reductions. In areas where water is the limiting factor, maximising water productivity may be economically more profitable to the farmer than maximising yields (Geerts and Raes, 2009). Although a certain reduction in yield is observed, yield quality (sugar content, grain size)

tends to be equal or even superior (Geerts and Raes, 2009). RDI creates a less humid environment around the crop decreasing the risk of fungal diseases as well as reducing nutrient loss through leaching.

The major shortfall of RDI is that it requires precise knowledge of crop response to drought stress. All water restrictions are supposed to be linked to crop phenological stages that are less affected by water stress. There should also be unrestricted access to irrigation water during sensitive growth stages. RDI can induce salinisation and hence measures are to be taken to avoid salinisation.

2.3.3 Pulsed Irrigation (PI)

PI is the application of small amounts of water at intervals across the day rather than applying the required amount of water at once. This is beneficial in that water and nutrients are supplied at a rate that is close to plant uptake, thus enhancing growth and production (Assouline et al., 2006). PI is mainly recommended for situations where the daily water requirement exceeds the amount of water that can be held in the root zone (Ramsey, 2007).

The observed shortcomings of PI include the build up of salts in the root zone (Assouline et al., 2006). Under PI, it was noted that there is improved P mobilisation and uptake as well as higher Mn concentrations in leaves and fruits (Assouline et al., 2006). PI is essential in reducing clogging problems in drip irrigation systems.

2.4 Irrigation scheduling

Irrigation scheduling is an important aspect of management that determines when to irrigate and how much water to apply (Ramsey, 2007; Taylor and Rieger, undated). Jensen (1981) defined irrigation scheduling as “a planning and decision making activity that an operator of

an irrigated farm is involved in before and during most of the growing season for each crop that is grown.” It is important to determine the exact crop water requirements for more precise irrigation scheduling (Garcia – Orellana et al., 2007).

Itier et al., (1996) grouped irrigation scheduling criteria into two i.e. depth and time. They defined the depth criteria as back to Field Capacity, FC or a fixed depth. Three timing criteria were outlined as follows:

- Allowable daily stress or relative evapotranspiration, $ET = a$ (with $0.5 < a < 1$). This is obtained through the soil water balance or from plant water stress indicators.
- Readily Available Water Capacity (AWC) consumed or some fixed percentage of AWC consumed (obtained by a means of soil water balance).
- Critical pressure head or moisture content at sensor depth (obtained by means of a soil moisture measuring device).

Irrigation scheduling options are linked to the level of technology, expertise or data availability. Various methods for irrigation scheduling have been developed so far. These include empirical (no measurement), soil moisture based, estimates of water use from weather data and tracking crop condition i.e. crop – water stress (van Bavel et al., 1996).

2.4.1 Empirical methods

Empirical data is information that is derived from the trials and errors of experience. Empirical scheduling involves the use of known effects, through established equations. A simple correlation is developed between ET_0 and a meteorological parameter(s) using long-term data. The method is more applicable to areas where meteorological data is not readily

available. The shortcoming of this method is that it is not very accurate compared to other methods of irrigation scheduling.

Most empirical methods are temperature based because of the assumption that temperature is an indicator of the evaporative power of the atmosphere. Temperature is one of the major factors influencing ET_o and it is not possible to estimate ET_o without temperature data (Raes, 2007). The estimates produced are generally less reliable than those that take other climatic variables into consideration. The Blaney Criddle method, and to a lesser extend the Senami – Hargreaves and the Hargreaves methods are most sensitive to temperature change (Lee et al., 2004). The sensitivity however, varies with location and the time of the year. Table 2.2 shows some of the empirical methods that are used to estimate ET_o . Lee et al., (2004) outlined an example of the use of direct measurement of net radiation to estimate ET_o . The correlation (with a considerable accuracy i.e. $r^2 = 0.97$) was established using 30-year daily data (equation 2.1).

$$ET_o = 0.187R_s + 0.3183 \quad r^2 = 0.9733 \quad (2.1)$$

(Lee et al., 2004)

Where ET_o is potential evapotranspiration computed using the Penman – Monteith method (mm hr^{-1}) and R_s is the net global radiation ($\text{MJ m}^{-2} \text{day}^{-1}$).

Table 2.2: Examples of empirical methods used to estimate ET_o (Lee et al., (2004))

Method	Formula Applied
Hargreaves	$ET_o = 0.0038 R_a T (\partial T)^{0.5}$, $ET_o = k(T_{mean} + 17.8) \sqrt{(T_{max} - T_{min})} (0.408 R)$ $ET_o = p(0.46 T_{mean} + 8)$
Senami – Hargreaves	$ET_r = 0.00094 S_o \partial T_f T_f$
Blaney – Criddle	$ET_o = a_{BC} + b_{BC} + f$ $f = p(0.46 T + 8.13)$ $a_{BC} = 0.0043(RH_{min}) - (n/N) - 1.41$ $b_{BC} = 0.82 - 0.0041(RH_{min}) + 1.07(n/N) + 0.066(U_d) -$ $0.006(RH_{min})(n/N) - 0.0006(RH_{min})(U_d)$

Where ET_o is the reference evapotranspiration (mm day^{-1}), R_a is the extraterrestrial radiation expressed in equivalent evaporation (mm day^{-1}), T is the mean air temperature ($^{\circ}\text{C}$), ∂T is the difference between mean monthly maximum and mean monthly minimum temperatures ($^{\circ}\text{C}$), k is a coefficient and has a default value of 0.0023, T_{mean} is the mean daily air temperature ($^{\circ}\text{C}$), T_{max} is the mean daily maximum air temperature ($^{\circ}\text{C}$), T_{min} is the mean daily minimum air temperature ($^{\circ}\text{C}$), R is the extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), S_o is the water equivalent of extraterrestrial radiation (mm day^{-1}), ∂T_f is the difference between mean monthly maximum and mean monthly minimum temperatures ($^{\circ}\text{F}$), T_f is the mean temperature ($^{\circ}\text{F}$), a_{BC} , b_{BC} and f are functions, (n/N) is the ratio of actual to possible sunshine hours, RH_{min} is the minimum daily relative humidity, p is the ratio of actual daily daytime hours to annual mean daily daytime hours and U_d is the daytime wind speed at 2 m height (m s^{-1}).

2.4.1.1 Merits and demerits of empirical methods

The method usually employs simpler models with less input variables and hence can be broadly applied and not limited to data availability. Most of the empirical methods are appropriate for humid conditions where the aerodynamic term is relatively small.

Most of the methods do not consider humidity or wind factors hence they are less likely accurate in arid and semi arid conditions. Hargreaves ET_o equations were designed primarily for irrigation planning and designing rather than scheduling and the daily estimates are subject to errors caused by the fluctuation of the temperature range caused by the movement of weather fronts and by the large variations in wind speed and cloud cover (Raes, 2007). The Hargreaves methods are recommended for use with five day or larger time steps and less reliable with smaller time steps. The Thornthwaite method i.e. a temperature based method results in underestimation especially for arid conditions (Raes, 2007). Local calibration is required for satisfactory results.

2.4.2 Soil moisture based methods

The basis for irrigation scheduling is through the soil water balance in which the soil root zone, RZ is taken as a reservoir (a bank) where there is input, storage and output of water from the system. Crop evapotranspiration (ET_c) is the daily withdrawal from the bank and replenishment is through irrigation and or rainfall (Ministry of Agriculture, Food and Fisheries, 2004). The objective of the soil water balance is to predict soil water content in the RZ through a water conservation equation (equation 2.2). Soil water affects plant growth through its effect on plant water status. The availability of soil water is assessed through soil water content and soil water potential. The components of the soil water balance are illustrated in Figure 2.1.

$$\Delta (AWC * RZ) = \text{Balance of entering} + \text{Outgoing water fluxes} \quad (2.2)$$

(Itier et al., 1996)

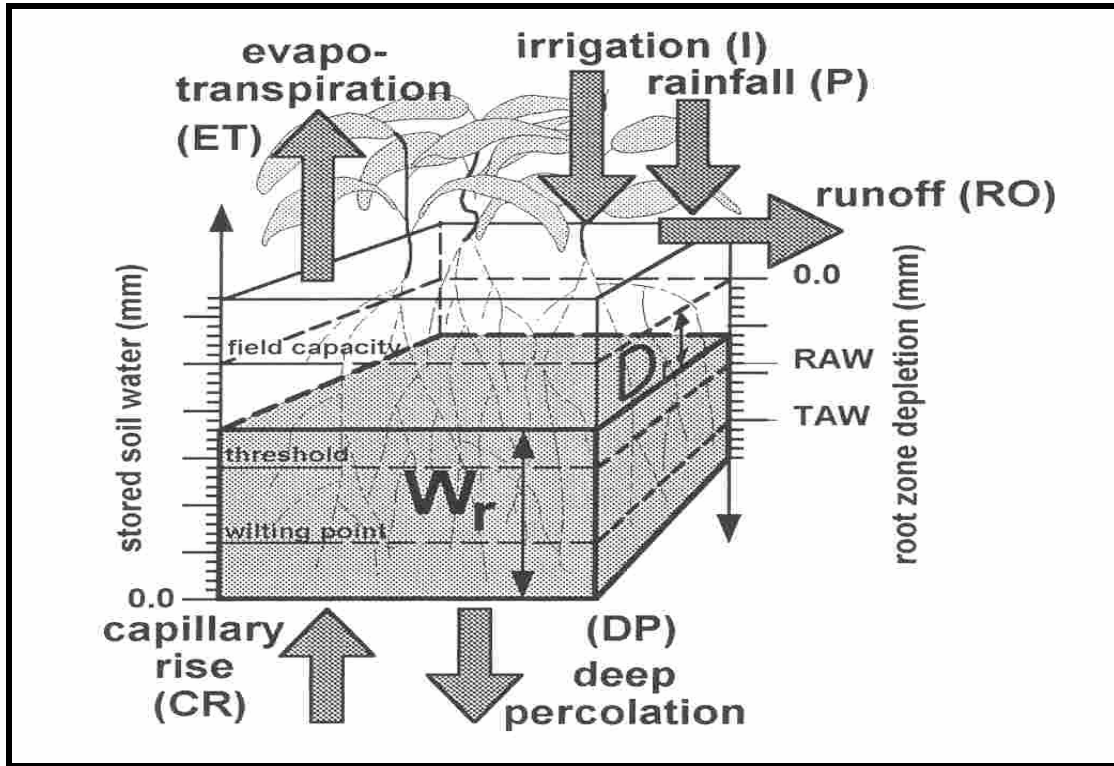


Figure 2.1: An illustration of the soil water balance showing the root zone as a reservoir (Adapted from Raes, 2001).

The soil water balance scheduling requires accurate measurement of the volume of water applied or the depth of application. It is the day to day accounting of the amounts of water coming into and going out of the effective root zone of the crop. The total water in the root zone can be represented using equation 2.3.

$$TW_T = TW_{T-1} + Irr_T + Rain_T - ET_{c_T} - DEEP_T - Runoff_T + FLUX_{netT} \quad (2.3)$$

(Harris, 2006)

Where TW_T is total water in the root zone on day T , TW_{T-1} is the total water in the root zone on previous day ($T-1$), Irr is the irrigation water applied, $Rain$ is the rainfall amount, ET_c is the evapotranspiration (soil evaporation and plant use), $DEEP$ is the drainage or percolation below the root zone and $FLUX_{net}$ is any change in total water in the root zone from underground water movement e.g. high water table or moving laterally into the ground on day T .

2.4.2.1 Basic procedure for water balance scheduling

The procedure for the basic water balance scheduling was outlined by Harris (2006) and its main objective is to illustrate how each of the water balance terms is established. The procedure consists of seven steps that are:

- a) Determination of the effective root zone depth
- b) Determination of the Total Available Moisture (TAM). This is the amount of soil water in the effective root zone that is available to plants and is soil specific.
- c) Determination of the Readily Available Moisture (RAM). This is the fraction of TAM that the crop can extract from the root zone without suffering water stress. It is found as the product of TAM and the depletion factor i.e. the fraction of plant available water that can be depleted from the effective root zone before irrigation is necessary.
- d) Determination of the refill point. This is the total soil water balance in the effective root zone at which irrigation is required. It is found by subtracting RAM from total soil moisture at field capacity.
- e) Determination of the starting point for total soil water in the effective root zone. This can be established from direct measurements e.g. gravimetric, neutron probes.

- f) Quantifying water movement into and from the effective root zone. This involves measurement of rainfall and irrigation depth. If rainfall / irrigation is greater than the depth of soil water depleted from the root zone, the difference is considered to be deep drainage and or runoff. $FLUX_{net}$ is usually considered to be negligible although it can be significant where a perched water table exists. ET_c is estimated from weather and crop information.
- g) Irrigation decision

2.4.2.2 Advantages and disadvantages of the soil water balance scheduling

The timing and depths of future irrigations can be planned through the calculation of the soil water balance of the RZ on a daily basis. Soil water measurements of the water balance method are necessary for feedback information on irrigation scheduling based on evapotranspiration. Since most models are unreliable in the prediction of the water balance terms, the soil water balance method is vital because periodical measurements of soil water may be used to ‘adjust’ model output for irrigation application. The soil water balance method is effective at assessing drainage losses and hence a good reference for estimation of optimum irrigation depths for a particular soil.

A lot of measurements are required in the field and the measurements are to be done over a long period. The method is not as accurate as direct measurement and needs local estimation of precipitation, runoff and evapotranspiration. The measurement of evapotranspiration offers the major problem for the water balance method since it requires good estimates of the crop coefficient and the associated climatic parameters for the computation of ET_o .

2.4.3 Estimates of water use from weather data

Irrigation scheduling is done more appropriately if meteorological data is used to estimate daily evapotranspiration, ET_c (Nakamura et al., 1996). The factors affecting daytime ET_c are radiation, air temperature, relative humidity, wind velocity, soil heat flux and vegetation coverage. Most of the automated irrigation control systems are based on the measurement of meteorological factors as inputs for feedback control (Ton and Kopyt, 2003).

Various methods have been developed for estimating ET_c , which is a basis for the development of irrigation calendars. Some of these methods are the FAO Penman Monteith, FAO radiation, FAO Blaney Criddle and the FAO pan evaporation.

2.4.3.1 The FAO Penman – Monteith method

A panel of experts and researchers organised by FAO in May 1990 in consultation with the World Meteorological Organisation (WMO) recommended the adoption of the Penman Monteith method as the standard for computing evapotranspiration (Allen et al., 1998). Penman and Monteith developed the method of estimating ET_o based on the correlation between energy conservation and the aerodynamics in the crop area (Aguila and Garcia, 1996; Allen et al., 1998). The energy component suggests the amount of water available for evaporation whilst the aerodynamic term relates the effect of advection on the crop surface in the removal of water vapour from the soil. Smith et al., (1996) rated the performance of the method as being superior. The expression of computing ET_o using the FAO Penman – Monteith method is shown in equation 2.4.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \quad (2.4)$$

(Smith et al., 1996)

Where:

ET_o is the reference crop evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$), G is the soil heat flux ($\text{MJ m}^{-2} \text{day}^{-1}$), T is the average air temperature ($^{\circ}\text{C}$), U_2 is wind speed measured at 2 m height (m s^{-1}), $(e_a - e_d)$ is the vapour pressure deficit (Kpa), Δ is the Slope of the vapour pressure curve ($\text{Kpa } ^{\circ}\text{C}^{-1}$), γ is the psychrometric constant ($\text{Kpa } ^{\circ}\text{C}^{-1}$) and 900 is a conversion factor.

The FAO Penman-Monteith equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. By using the FAO Penman Monteith definition for ET_o , one may calculate crop coefficients at research sites by relating the measured crop evapotranspiration (ET_c) with the calculated ET_o , i.e., $K_c = ET_c/ET_o$ (Allen et al., 1998). For computing ET_o , site data is required for the adjustment of some weather parameters. This data include the altitude above sea level and latitude (degrees North or South). Site elevation above the mean sea level is used for the adjustment of the local average value of atmospheric pressure and to compute extraterrestrial radiation, R_a and daylight hours, N (Allen et al., 1998). In situations where some weather variables are missing, it is not advisable to use other methods of estimating ET_o requiring few data. It is recommended that the missing weather data should be resolved first and then the FAO Penman Monteith equation used (Allen et al., 1998).

Irrigation control systems use environmental factors as inputs (Ton and Kopyt, 2003). Weather variables required for the computation of the FAO Penman Monteith equation are recorded using agrometeorological Automatic Weather Stations (AWS). The stations are supposed to be sited in the cropped area to expose instruments to conditions similar to that of the cropped area.

2.4.3.2 Class A evaporation pan

The evaporation pan is an instrument used to measure evaporation. This method is extensively used in agrometeorological stations. The measured evaporation of water has been used as an ET_o parameter applied in many irrigation studies. Evaporation is determined from the variations in water level from day to day. The evaporation pan (Figure 2.2) is made up of glass reinforced plastic, black on the inside and white on the outside. The inside diameter is 120.7 cm and the depth is 25.4 cm. Water level measurements are taken from a stilling well where a segment of the pan is protected by a barrier. The evaporation pan is to be installed where there is free air circulation around the pan. The pan should be level and the pan rim must be 36 cm above the ground. The instrument is read daily and readings entered in a daily register.

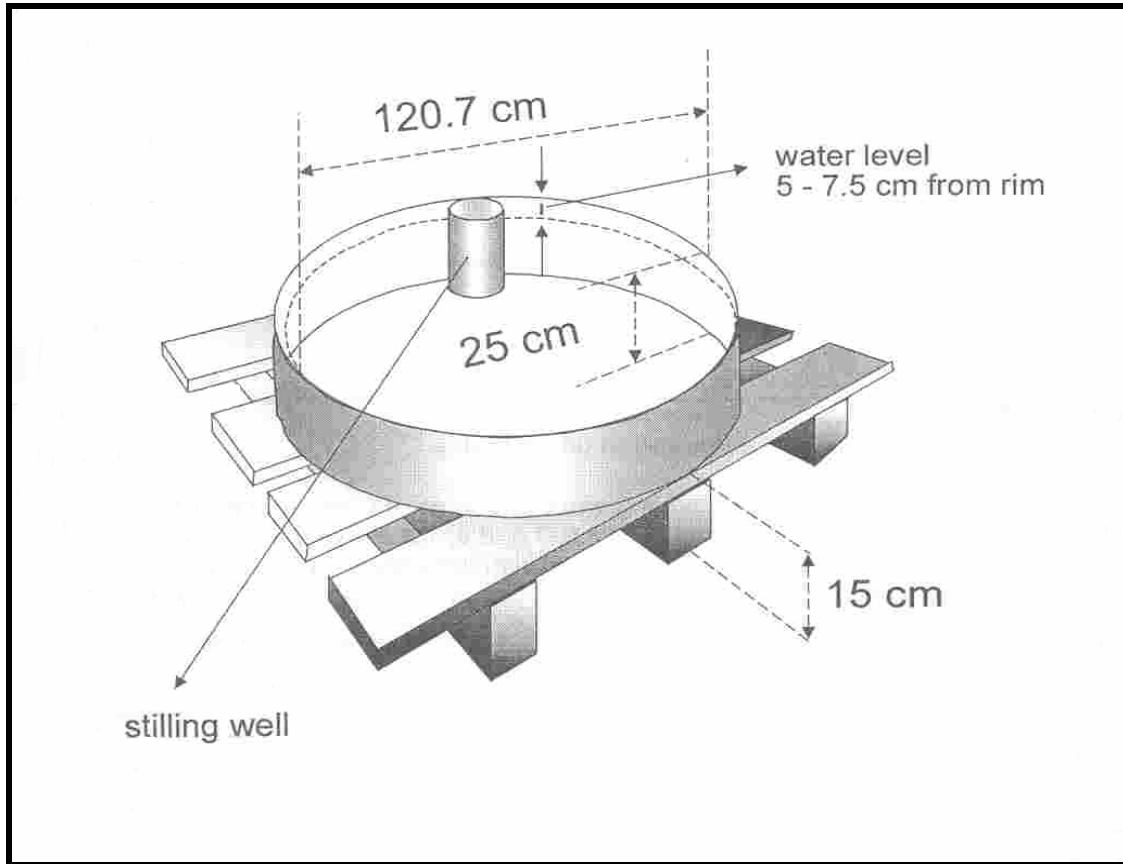


Figure 2.2: Features of the class A evaporation pan (Adapted from Allen *et al.*, 1998)

The measurement from evaporation pans is the integrated effect of radiation, wind, temperature and relative humidity on the evaporation from an open water surface. Pan readings do not give ET_o directly but have to be multiplied by a 'pan coefficient', K_{pan} (equation 2.5).

$$ET_o = E_{pan} \times K_{pan} \quad (2.5)$$

K_{pan} varies between 0.35 and 0.85 with an average of 0.7 (Natural resource and environment department, undated). The average value can be used for approximation if the exact value is not known. Table 2.3 outlines the estimated K_{pan} values for class A evaporation pan.

The K_{pan} value is empirically driven and is pan specific. K_{pan} is a function of pan type, ground cover in the station and its surroundings, wind, relative humidity and the upwind buffer zone i.e. fetch (Allen et al., 1998). Regression equations 2.6 and 2.7 (from Allen et al., 1998) are used to compute class A K_{pan} values for a site with a green fetch and a dry fetch respectively.

$$K_{pan} = 0.108 - 0.0286U_2 + 0.0422 \ln(FET) + 0.1434 \ln(RH_{mean}) - 0.000631[\ln(FET)]^2 \ln(RH_{mean}) \quad (2.6)$$

$$K_{pan} = 0.61 + 0.00341 RH_{mean} - 0.000162U_2 RH_{mean} - 0.00000959U_2 FET + 0.00327U_2 \ln(FET) - 0.00289U_2 \ln(86.4U_2) - 0.0106 \ln(86.4U_2) \ln(FET) + 0.00063 [\ln(FET)]^2 \ln(86.4U_2) \quad (2.7)$$

Where U_2 is the mean daily wind speed at 2 m height ($m s^{-1}$), RH_{mean} is the average daily relative humidity (%) = $(RH_{max} + RH_{min})/2$, FET is the fetch, or distance of the identified surface type (grass or short green agricultural crop for equation 2.6, dry crop or bare soil upwind of the evaporation pan for equation 2.7).

Table 2.3: K_{pan} values for class A pan for different pan siting and environment and different levels of mean relative humidity and wind speed (Allen et al., 1998).

Class A pan	Case A: Pan placed in a short green cropped area			Case B: Pan placed in a dry fallow area				
RH mean (%) →		Low <40	Medium 40-70	High >70		Low <40	Medium 40-70	High >70
Wind speed (m s^{-1})	Windward side distance of green crop (m)				Windward side distance of dry fallow (m)			
Light <2	1	0.55	0.65	0.75	1	0.7	0.8	0.85
	10	0.65	0.75	0.85	10	0.6	0.7	0.8
	100	0.7	0.8	0.85	100	0.55	0.65	0.75
	1000	0.75	0.85	0.85	1000	0.5	0.6	0.7
Moderate 2-5	1	0.5	0.6	0.65	1	0.65	0.75	0.8
	10	0.6	0.7	0.75	10	0.55	0.65	0.7
	100	0.65	0.75	0.8	100	0.5	0.6	0.65
	1000	0.7	0.8	0.8	1000	0.45	0.55	0.6
Strong 5-8	1	0.45	0.5	0.6	1	0.6	0.65	0.7
	10	0.55	0.6	0.65	10	0.5	0.55	0.65
	100	0.6	0.65	0.7	100	0.45	0.5	0.6
	1000	0.65	0.7	0.75	1000	0.4	0.45	0.55
Very strong >8	1	0.4	0.45	0.5	1	0.5	0.6	0.65
	10	0.45	0.55	0.6	10	0.45	0.5	0.55
	100	0.5	0.6	0.65	100	0.4	0.45	0.5
	1000	0.55	0.6	0.65	1000	0.35	0.4	0.45

2.4.3.2.1 Merits and demerits of the evaporation pan

The evaporation pan method is an easy, successful estimate when applying empirical coefficients. Although the evaporation pan is an archaic tool, it is a very practical device which most growers have confidence in only that they need appropriate pan coefficients and crop factors.

There are significant differences between water loss from an open water surface and the crop surface resulting in some errors in the estimation of ET_o . The method doesn't account for the adhesive and cohesive properties of water. Heat storage within the pan can be appreciable

and may induce significant evaporation during the night which is not the case with transpiring crops (Allen et al., 1998). Errors may arise due to differences in turbulence, temperature and relative humidity of the air immediately above a pan and that of a crop surface. The energy balance of the pan is affected by heat transfers through the sides.

2.4.4 Tracking crop condition

Under this method, irrigation is scheduled by assessing the crop condition i.e. ‘the speaking plant concept’ where messages are derived from the plant itself indicating that the time has come to irrigate. The idea employs plants themselves to schedule irrigation depending on the water levels in plant leaves or stems (Ton and Kopyt, 2003). Plant variables e.g. leaf – air temperature difference, sap flow rate (Sakuratani, 1981; Steinberg et al., 1989), and stem diameter micro variation (Huguët, 1985; Li et al., 1989; Itier et al., 1996; Garcia – Orellana et al., 2007) have been used for irrigation scheduling.

Measures of the plant water status provide a promising technique for irrigation management because of its dynamic nature that is linked with climatic and soil conditions (Garcia – Orellana et al., 2007). The strength of direct plant monitoring is in its ability to detect sub optimal growth conditions at an early stage. Growers can intervene when symptoms of physiological disorder e.g. wilting (Nortes et al., 2005), fruit cracking and blossom – end – rot are not visible (Vermeulen et al., 2007).

2.4.4.1 Stem diameter micro variation

One of the irrigation schedules is based on the maximum daily trunk shrinkage (MDS) measurements. This involves the measurements of stem water potentials and the micrometric trunk diameter fluctuations. MDS is calculated as the difference between maximum and

minimum daily trunk diameter (Garcia – Orellana et al., 2007). MDS values depend not only on the plant water status but also on the evaporative demand of the atmosphere. MDS has been found to be a very reliable tool for precise irrigation (Goldhamer and Fereres, 2001).

MDS signal intensity threshold values of 1.25 and 1.35 were adopted for irrigation scheduling of lemon trees (Garcia – Orellana et al., 2007). Stem diameter micro variation is however, not suitable for irrigation scheduling during periods of low evaporative demand. Trunk diameter fluctuations derived indices can be applied for automatic irrigation scheduling (Nortes et al., 2005).

2.4.4.2 Sap flow measurements

Sap flow is measured to determine transpiration rate of plants using a continuous supply of heat as a tracer (Sakuratani, 1981; Baker and Van Bavel, 1987; Steinberg et al., 1989). The flow of sap in the xylem vessel is equated to transpiration losses. Sap flow gauges fall into three categories i.e. heat balance method, heat probe (thermal dissipation probe) and heat pulse timing. In this section, the heat balance method and the heat probe methods are described.

2.4.4.2.1 Stem Heat Balance (SHB) method

A constant and known amount of heat is applied to a small segment of the stem from a thin flexible heater that encircles the stem. The heat input must be balanced by heat fluxes out of the segment (Figure 2.3) i.e. conduction up the stem, conduction down the stem, conduction outward through the foam sheath and convection in the moving transpiration stream (Baker and Nieber, 1989). The conductive fluxes are estimated using Fourier's law and the

temperature gradients are estimated from the output of strategically placed thermocouples. The energy balance equations (2.8 – 2.14) used to determine sap flow were outlined by van Bavel (1999).

$$P_{in} = Q_r + Q_v + Q_f \quad (2.8)$$

Where P_{in} is the power input to the stem from the heater, Q_r is the radial heat conducted through the gauge to the ambient, Q_v is the vertical or axial heat conduction through the stem and Q_f is the heat convection carried by the sap.

$$P_{in} = V^2 / R \quad \text{From Ohms law} \quad (2.9)$$

P_{in} is computed using Ohms law (equation 2.9), where V is the input voltage and R is the impedance of the gauge.

The vertical conduction through the stem is computed using equation 2.10.

$$Q_v = K_{st} A (BH - AH) / dX \times 0.040 \quad (2.10)$$

K_{st} is the thermal conductivity of the stem (W/m*K), A is the stem cross sectional area (m²), the temperature gradients are dT_u/dX (K/m) and dT_d/dX , is the spacing between thermocouple junctions (m).

After solving equation 2.8 for Q_f , the flow rate per unit time is calculated from the equation for sap flow that takes the residual of the energy balance in Watts and converts it to a flow

rate by dividing by the temperature increase of the sap and the heat capacity of water (equation 2.11).

$$F = \frac{(P_{in} - Q_v - Q_r)}{C_p \times dT} \quad (2.11)$$

The radial heat loss is computed by equation 2.12:

$$Q_r = K_{sh} \times CH \quad (2.12)$$

K_{sh} is the thermal conductance constant for a particular gauge installation and is computed using equation 2.14, C_p is the specific heat capacity of water (4.186 J/g*°C) and dT is the temperature increase of the sap.

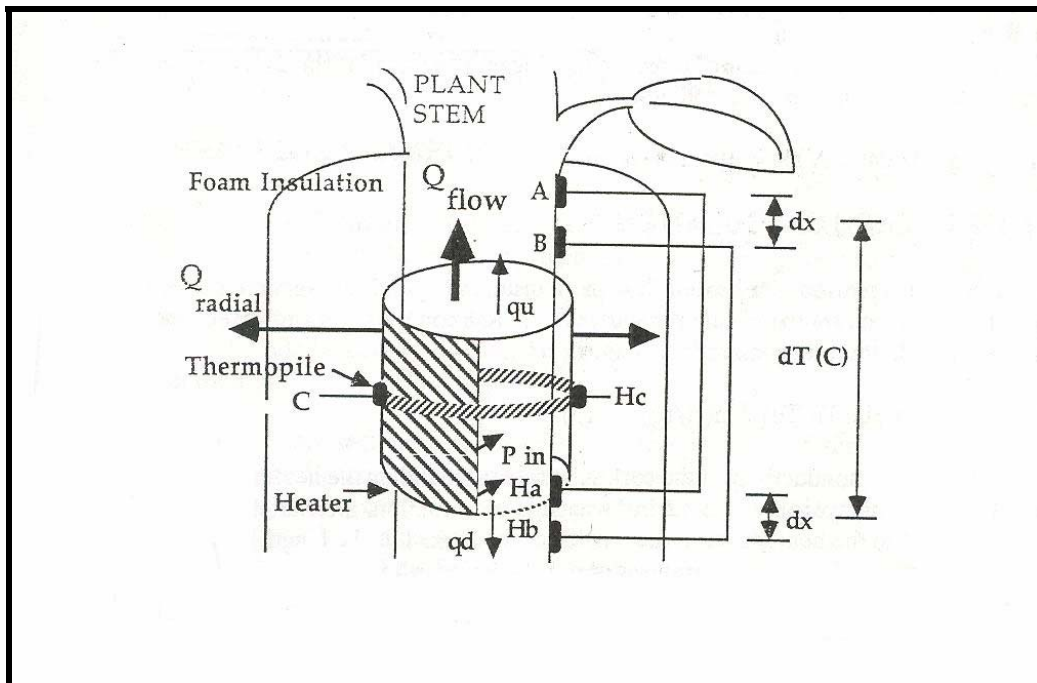


Figure 2.3: Outline of the Stem Heat Balance method for sap flow measurement

dT is measured in mV by averaging the AH and BH signals, and then converted to °C by dividing by the thermocouple temperature conversion constant (equation 2.13).

$$dT = \frac{(AH + BH)/2}{0.040} \quad (2.13)$$

$$K_{sh} = \frac{(P_{in} - Q_v)}{CH} \quad (2.14)$$

This method of sap flow measurement was reported to have an accuracy of $\pm 10\%$ (Baker and Van Bavel, 1987) and supported by Steinberg et al., (1989) who used young peach trees in a field and green house study. The use of the sap flow gauges does not alter any of the environmental and physiological factors affecting the transpiration process (Baker and Nieber, 1989). The SHB method is direct, requires no calibration and does not need the knowledge of the cross sectional area of the xylem vessel.

2.4.4.2.2 Thermal Dissipation Probe (TDP) method

The transpiration rate of a plant is approximated by sap flow rate in the main stem (Dynamax, 1997). The TDP heated needle is an improved heat dissipation sensor which measures the temperature of a line heat source implanted in the sapwood of a tree, referenced to a sapwood temperature at a location well below the heated needle (Dynamax, 1997). The probe measures sapwood heat dissipation, which increases with sap flow and the resultant cooling of the heat source. The temperature difference, dT is maximal when sap velocity is zero or minimal.

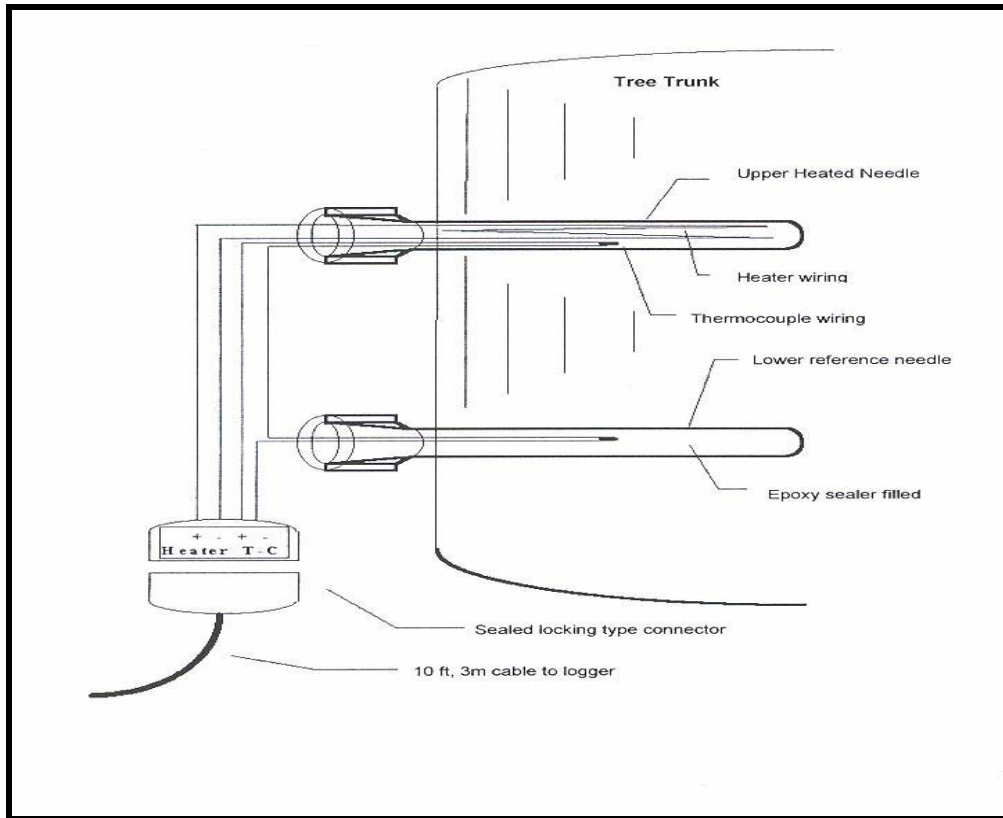


Figure 2.4: Thermal Dissipation Probe (TDP) sap velocity probe (Dynamax, 1997)

The mass flow rate of water through the stem xylem is estimated from steady state energy balances of undisturbed sapwood. The TDP consists of two cylindrical probes that are inserted into the sapwood area of a tree, one above the other (Figure 2.4). Each probe contains a copper – constantan thermocouple and the difference in temperature between the two probes is influenced by sap velocity close to the heated probe (upper probe). The upper probe contains a heating element that is heated with a constant power source and the lower probe serves as a reference. Whole tree sap flow for the TDP is calculated as the product of the measured sap velocity and the sapwood area and this is achieved by using equations 2.15, 2.16 and 2.17.

$$K = (dT_M - dT) / dT \quad (2.15)$$

Where: K is a dimensionless parameter, dT is the measured difference in temperature between that of the heated needle, referenced to the lower non-heated needle, placed at a fixed distance below the heated one and dT_M is the value of dT when there is no sap flow (zero set value).

Granier (1987) found empirically that the average sap flow velocity; V (cm/s) could be related to K by an exponential expression:

$$V = 0.0119 \times K^{1.231} \quad (2.16)$$

To convert the velocity to sap flow rate, one uses:

$$F_s = A_s \times V \times 3600 (\text{s h}^{-1}) \quad (2.17)$$

Where: F_s ($\text{cm}^3 \text{ h}^{-1}$) is the sap flow and A_s is the cross sectional area of the sap conducting wood (cm^2).

2.4.4.2.3 Determination of the cross sectional area of the sap conducting wood

The conducting sapwood area is used for relating sap velocity to sap flux density as well as for scaling up transpiration from a single tree to plantation level. The conducting sapwood area of the trees could have been quantified using the coloured dye approach. This approach is limited when applied to trees of commercial value e.g. citrus because of high risk of contamination of the fruit by the dye (Dzikiti, 2007). Given the practical difficulties in the quantification of the sapwood area, allometric relationships between different plant organs

e.g. stem diameter can be developed (Medhurst and Beadle, 2002 in Dzikiti, 2007). The sapwood area can be estimated based on detailed knowledge of the statistical distribution of stem diameters at certain reference locations on the trees.

The conducting sapwood area of navel orange trees was estimated by Dzikiti (2007) by injecting a dye (methyl blue) in the stem just above the bud union and on the rootstock. The stem was cut under the methyl blue dye using a sharp chisel. Fresh stem discs, collected at 8 cm below the first branch point were cut after a day and estimates of the proportion of the conducting sapwood area were made using a travelling microscope. A typical relationship between the stem cross sectional area and the conducting sapwood area is shown in Figure 2.5. It was deduced that the sapwood area is approximately 83 % of the stem diameter in navel orange trees.

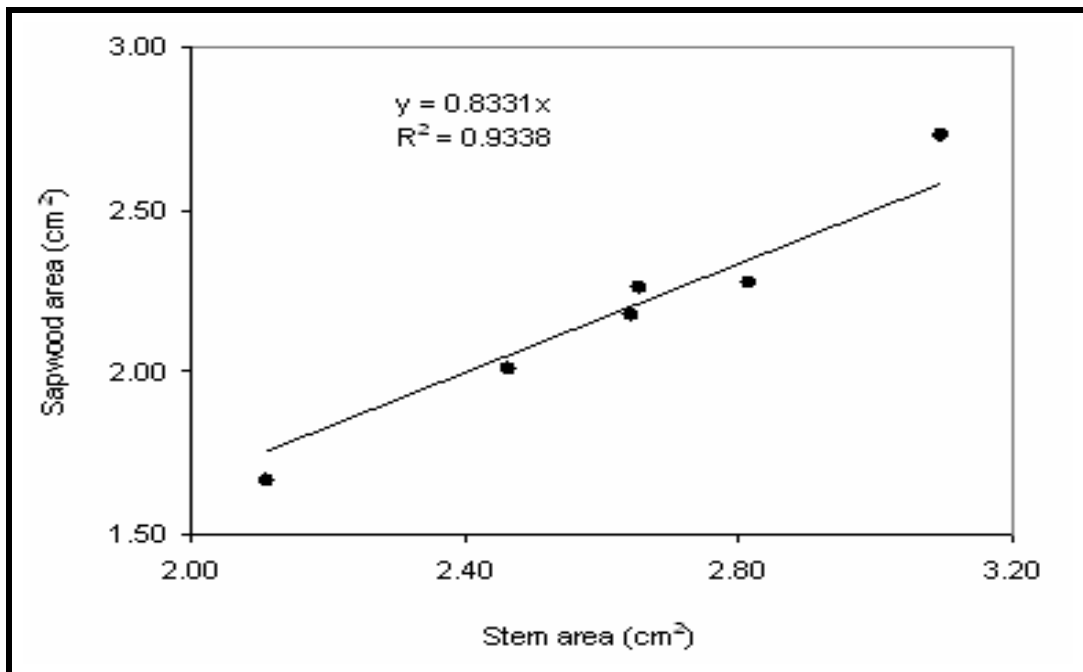


Figure 2.5: The linear relationship between the conducting sapwood area and the stem cross sectional area in young potted navel orange trees showing that approximately 83 % of the stem area comprised the conducting sapwood (Dzikiti, 2007).

2.4.5 Merits and demerits of tracking the crop condition

The method measures the plant stress response directly and it integrates environmental effects as well. Plant based methods are potentially very sensitive and stress can be detected early before there are any visible symptoms. This is essential since mitigation measures can be taken avoiding the resultant loss in yield or quality of the crop.

In general, the plant based methods do not indicate ‘how much’ water to apply, calibration is required to determine control thresholds. Most of these methods are still largely at the research stage and little used yet for routine scheduling. The major set back of the method that restricts its wider application is linked to the complex instrumentation and technical expertise. A major challenge is also associated with the scaling up of water use from one tree or plant organ to the whole tree or orchard.

2.5 The crop coefficient, K_c

ET_c is calculated from reference evapotranspiration, ET_0 that is derived from climatic data. K_c is a multiplicative crop coefficient introduced in the computation of ET_c to include the effect of different crops and their changing morphology (size and shape) through the season. ET_0 is calculated from a reference crop. The reference crop is a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} , an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered (Smith et al., 1996). K_c values range from 0.3 to 1.5 (Allen et al., 1998). Equation 2.18 gives the expression for the computation of ET_c from ET_0 and K_c .

$$ET_c = K_c * ET_o \quad (2.18)$$

K_c integrates the effect of characteristics that distinguishes a typical field crop from the grass reference, which has a constant appearance and a complete ground cover. The K_c takes into account crop growth stages and plant physiology. Several K_c can be used for the same crop throughout an irrigation season depending on the stage of development. K_c values are a function of crop type, climate, soil evaporation and crop growth stages.

Crop type: Crop characteristics that determine K_c are height, albedo, aerodynamic properties, leaf and stomata properties. K_c increases as plants are closely spaced, have taller canopy heights and roughness. The K_c values are smaller for species with stomata on only the lower side of the leaf and or large leaf resistances e.g. citrus and most deciduous fruit trees (Allen et al., 1998).

Climate: Variations in wind speed that ultimately determine the aerodynamic resistances of crops affect K_c . The ratio, ET_c / ET_o increases as wind speed increases and as relative humidity decreases. More arid climates and conditions of greater wind speed will have higher K_c values than the more humid climates and conditions of lower wind speed.

Soil evaporation: K_c integrates the difference in soil evaporation and crop transpiration. The contribution of soil evaporation is high when canopy is small or scarcely shades the ground and is reduced as canopy cover increases.

Crop growth stages: The growing period of crops is divided into four distinct growth stages as outlined in Table 2.4. The growth stages are the initial stage, crop development stage, mid season stage and the late season stage.

Table 2.4: Crop growth stages and their influences on the crop coefficient, K_c (Adapted from Allen et al., 1998)

Growth stage	Description	Influence on K_c
Initial	From planting date to approximately 10 % ground surface covered by green vegetation. For perennial crops e.g. citrus, planting date is replaced by the 'green up' date i.e. the time when the initiation of new leaves occurs.	Leaf area is small and evapotranspiration is mostly due to soil evaporation.
Crop development	From 10 % ground cover to effective full cover (occurs at the initiation of flowering for many crops). For crops above 0.5 m in height, full cover is achieved when the average fraction of the ground surface covered by vegetation is about 0.7 – 0.8.	Soil evaporation is reduced and crop transpiration is increased.
Mid season	From effective full cover to start of maturity – indicated by beginning of ageing, yellowing or senescence of leaves, leaf drop or the browning of fruit. For perennials, this is the longest stage.	Crop evapotranspiration is reduced relative to ET_o . K_c reaches its maximum value.
Late season	From start of maturity to harvest or full senescence.	Senescence is linked to reduced stomatal conductance due to ageing effects hence causing a reduction in K_c .

2.5.1 K_c for citrus

Citrus trees are evergreens (transpire throughout the year). The water requirement for citrus, which govern the K_c value, is a function of climate, ground cover, weed control, species and rootstock. Tables 2.5 and 2.6 present K_c values for the subtropics for large, mature trees providing approximately 70 % tree ground cover and K_c values for citrus under different canopy and ground cover conditions respectively.

Table 2.5: K_c values for the sub tropics for large, mature trees providing approximately 70 % tree ground cover (FAO, 2002).

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Clean, cultivated	0.75	0.75	0.70	0.70	0.70	0.65	0.65	0.65	0.65	0.70	0.70	0.70
No weed control	0.90	0.90	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85

Table 2.6: K_c for citrus under different canopy and ground cover conditions (Allen et al., 1998).

Ground cover	Canopy (%)	$K_{c\text{ ini}}$	$K_{c\text{ mid}}$	$K_{c\text{ end}}$
No ground cover	70	0.70	0.65	0.70
	50	0.65	0.60	0.65
	20	0.50	0.45	0.55
Active ground cover or weeds	70	0.75	0.7	0.75
	50	0.80	0.80	0.80
	20	0.85	0.85	0.85

CHAPTER 3

MATERIALS AND METHODS

3.0 Introduction

The objectives outlined in chapter 1 were achieved through a number of experiments carried out in the field at Mazowe citrus estate and the use of historical data.

3.1 Study site

The study was carried out at Mazowe Citrus Estate (MCE), a commercial citrus producing estate in Zimbabwe (17.46 °S, 31.00 °E, 1189 m above sea level). Trees used for the study belong to the Palmer navel variety budded to a Troyer rootstock. The 5239 trees were planted in 2001 at an area of 8.6 hectares in Urrys section. The study site was situated on a gentle sloping terrain with dark red clayey loam soils in excess of 1 m depth (Hussein, 1982).

3.2 Treatments and experimental design

To achieve the objectives of this study, the following treatments were established:

- 1) Control – One drip line, one side of the tree irrigated according to ET_o data from the Automatic Weather Station (AWS).
- 2) Well watered – Both sides of the tree irrigated, each line delivering half the quantity of water as the control;
- 3) Current grower's practice – Single drip line, scheduled according to the grower and
- 4) Partial Root zone Drying (PRD 50) – Two drip lines applying half of the control. Switching under PRD was done at 10 day intervals.

Each treatment (replicated twice) comprised of ten single trees in a row. The experimental design (Table 3.1) was established using computer generated random numbers (Genstat). The experimental design was generated from 8 treatments (4 of which were outside the scope of this study. Historical ET_o data for the corresponding periods was used to determine the irrigation depth for the control treatment. The procedure used for the determination of irrigation duration is outlined in Appendix 3.

Table 3.1: Experimental design using computer generated random numbers (Genstat)

Tree row	Replicate	Treatment
3	1	8*
4	1	6*
5	1	1
6	1	7*
7	1	3
8	1	2
9	1	5*
10	1	4
11	2	6*
12	2	1
13	2	7*
14	2	4
15	2	5*
16	2	2
17	2	8*
18	2	3

*Treatments falling outside the scope of this study

The orchard tree spacing was approximately 2.75 m in each row with an inter row spacing of approximately 6 m (Figure 3.1).

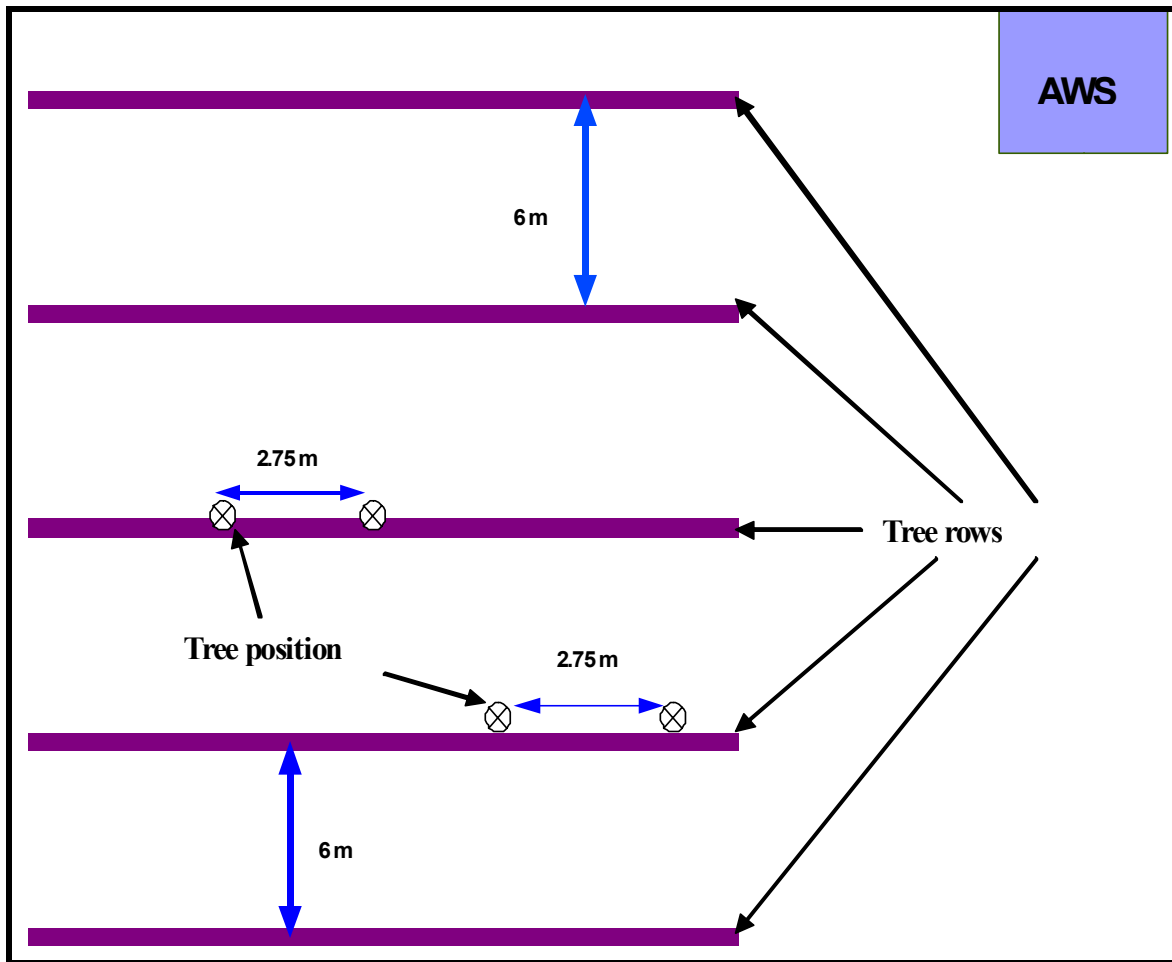


Figure 3.1: Schematic layout of the study site showing the row and inter row spacing as well as the position of the Automatic Weather Station (AWS).

The drip line positions for the control treatment and the grower's practice i.e. a single line and the well watered and PRD 50 treatments i.e. double lines is shown in Figure 3.2.



Figure 3.2: Drip irrigation of citrus trees showing a) a single line for the control and grower's practice and b) double drip lines for the PRD 50 and well watered treatments.

3.3 Microclimatic data collection

An automatic weather station was used to monitor the microclimate of the orchard. The Automatic Weather Station and the orchard background are displayed in Figure 3.3. The climatic parameters that were observed include wind speed and direction, incoming solar radiation, Photosynthetically Active Radiation (PAR), net radiation, ground heat flux, air temperature and relative humidity and precipitation. A NR light net radiometer (Kipp and Zonen, Delft, The Netherlands) was used to measure net radiation and this was positioned horizontal to the ground at about 1.5 m. Wind speed and direction were determined using a wind monitor consisting of a wind vane and a propeller (RM Young and Co., Traverse city, USA) fixed at 2 m height above the ground level. Air temperature and humidity were obtained using a temperature and relative humidity probe equipped with a capacitive relative humidity chip and a platinum resistance thermometer (model HMP 45 C, Campbell Scientific Limited, UK) inserted in a 12-plate Gill radiation shield at screen height of approximately 1.5 m above the surface.

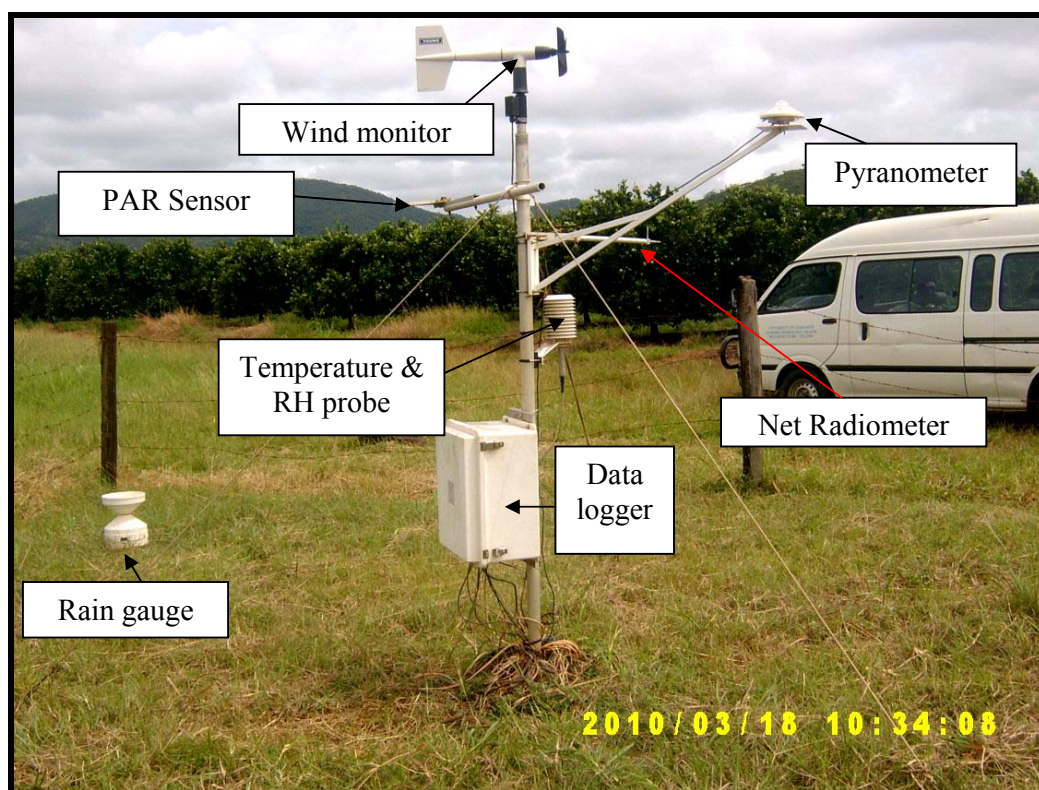


Figure 3.3: Automatic weather station to monitor orchard microclimate at the trial site at Mazowe Citrus Estate, Zimbabwe. The orchard can be seen in the background.

The ground heat flux was measured using the ground heat flux plates inserted 10 cm and 25 cm below the surface. Precipitation was evaluated using an RG1 tipping bucket rain gauge (Delta-T Devices, Cambridge, UK). All sensors were connected to a CR23X data logger (Campbell Scientific Limited, UK) programmed with a scan interval of 5 seconds and all signals averaged every 15 minutes.

3.4 Measurement of ET_0 using the class A evaporation pan

A class A evaporation pan (Fig 2.2) was used to determine the reference evapotranspiration of the orchard. The pan was made up of glass – reinforced plastic, black on the inside and white on the outside. The inside diameter and depth of the pan were 120.7 cm and 25.4 cm

respectively. The instrument was installed on a stand at a weather station adjacent to the orchard in a position that allowed free air circulation. The pan was level and its rim was 36 cm above the surrounding ground. Pan readings were taken daily (at 0800 hours) and entered in the daily register. E_{pan} was determined from day to day from the variations in water level taking into account precipitation recorded on that day (if any).

3.5 Determination of the pan coefficient, K_{pan}

Two methods (empirical and a plot of Penman Monteith ET_o against E_{pan}) were used to determine K_{pan} . The K_{pan} value, which is pan specific, was empirically determined from the pan type, ground cover in the station and its surroundings, wind speed, relative humidity and the upwind buffer zone i.e. fetch (Allen et al., 1998). Equation 2.6 was used to compute the average monthly pan coefficients. Since the buffer zone was constant, K_{pan} varied with wind speed and relative humidity.

The second method was used after the measurement of E_{pan} and the corresponding Penman Monteith ET_o from October 2009 to March 2010. K_{pan} was given by the slope of the graph of ET_o against E_{pan} .

3.6 Establishment of the crop coefficient, K_c curve for citrus

The following procedure was used for the determination of the K_c curve:

- a) Selection of crop growth stage lengths (stage lengths outlined in section 2.2.1 were adopted);
- b) Selection of values for $K_{c \text{ ini}}$, $K_{c \text{ mid}}$ and $K_{c \text{ end}}$ from typical values (Table 3.2) (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; Wright, 1981; Pruitt, 1986; Snyder et al., 1989);

- c) Adjustment of $K_{c \text{ ini}}$ to reflect the wetting frequency of soil surface;
- d) Adjustment of $K_{c \text{ mid}}$ and $K_{c \text{ end}}$ to local climatic conditions
- e) Construction of the K_c curve

Table 3.2: Single (time-averaged) crop coefficients, K_c , and mean maximum plant heights for non-stressed, well-managed crops in sub humid climates ($RH_{\text{min}} \approx 45\%$, $U_2 \approx 2 \text{ m s}^{-1}$) for use with the FAO Penman-Monteith ETo (Allen et al., 1998).

Crop	$K_{c \text{ ini}}$	$K_{c \text{ mid}}$	$K_{c \text{ end}}$	Maximum crop height, h (m)
Citrus, no ground cover				
- 70 % canopy	0.70	0.65	0.70	4
- 50 % canopy	0.65	0.60	0.65	3
- 20 % canopy	0.50	0.45	0.55	2
Citrus, with active ground cover or weeds				
- 70 % canopy	0.75	0.70	0.75	4
- 50 % canopy	0.80	0.80	0.80	3
- 20 % canopy	0.85	0.85	0.85	2

3.6.1 $K_{c \text{ ini}}$ for trees

The K_c value should reflect the ground condition during the low active period for evergreen trees i.e. just before spring and bud break. K_c depends upon the amount of grass or weeds cover, frequency of soil wetting, tree density and mulch density. $K_{c \text{ ini}}$ for an evergreen orchard (having no concerted leaf drop) with a dormant period has less variation from $K_{c \text{ mid}}$ as exemplified for citrus.

3.6.1.1 Time interval between wetting events

The mean time interval between wetting events was estimated by counting all rainfall and irrigation events that occurred during the initial period that are greater than $0.2ET_0$. The wetting events that occurred on adjacent days were computed as one event. The mean wetting interval was estimated by dividing the length of the initial period by the number of events.

The number of events within the month was also estimated by dividing the monthly rainfall depth by the depth of a typical rain event defined in Table 3.3. A typical rainfall depth was estimated for the region and time of the year.

Table 3.3: Characteristics of rainfall depths (Allen et al., 1998)

Rain event	Depth (mm)
Very light (drizzle)	≤ 3
Light (light showers)	5
Medium (showers)	≥ 10
Heavy (rainstorms)	≥ 40

$K_{c \text{ ini}}$ was derived from Figures 3.4 and 3.5, which provided estimates for $K_{c \text{ ini}}$ as a function of the average interval between wetting events, the evaporation power, ET_o and the importance of the wetting event. For average infiltration depths between 10 and 40 mm, the $K_{c \text{ ini}}$ value was estimated using both Figure 3.4 and 3.5 and using equation 3.1.

$$K_{cini} = K_{cini(\text{Fig. 3.4})} + \frac{(I - 10)}{(40 - 10)} [K_{cini(\text{Fig. 3.5})} - K_{cini(\text{Fig. 3.4})}] \quad (3.1)$$

Where:

$K_{c \text{ ini}}$ (Fig. 3.4) is the value for $K_{c \text{ ini}}$ from Figure 3.4; $K_{c \text{ ini}}$ (Fig. 3.5) is the value for $K_{c \text{ ini}}$ from Figure 3.5 and I is the average infiltration depth (mm).

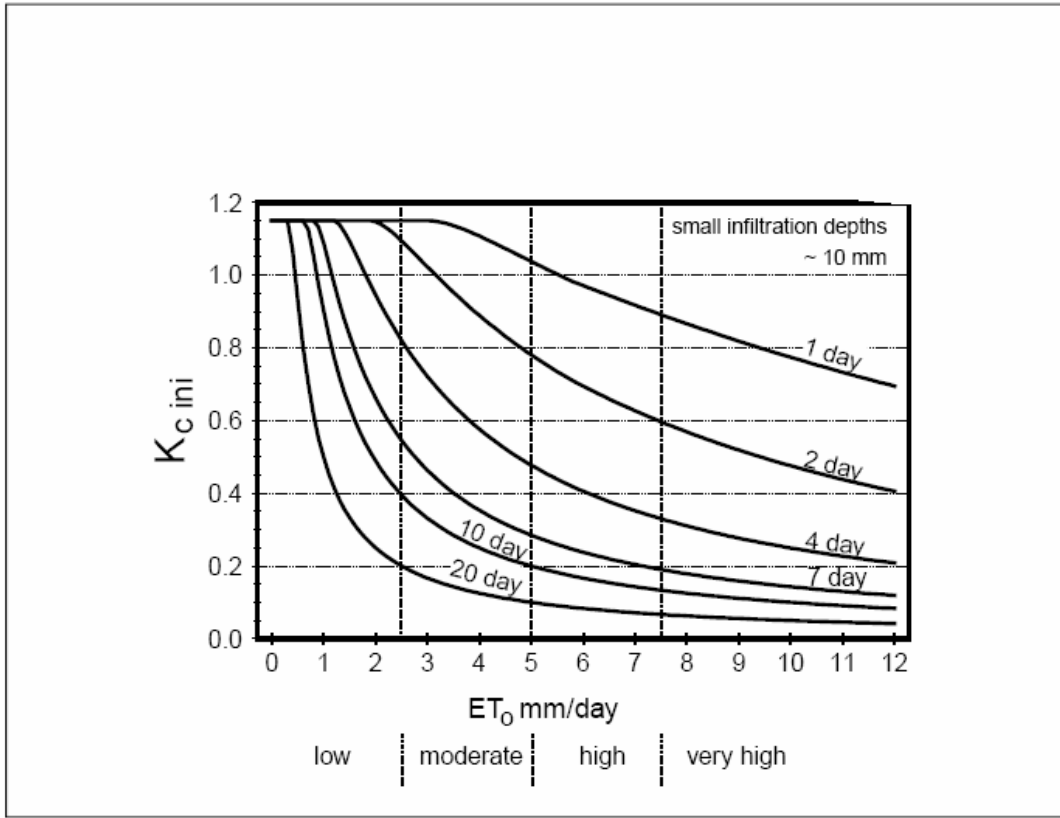


Figure 3.4: Average $K_{c \text{ ini}}$ as related to the level of ET_0 and the interval between irrigations and or significant rain during the initial growth stage for all soil types when wetting events are light to medium (3 – 10 mm per event). Adapted from Allen et al., 1998).

$$K_{c \text{ ini}} = f_w * K_{c \text{ ini(Fig)}} \quad (3.2)$$

Where;

f_w is the fraction of the surface wetted by irrigation or rain and $K_{c \text{ ini(Fig)}}$ is the value of $K_{c \text{ ini}}$ from Figure 3.4 or 3.5.

The average infiltrated depth (mm) over the entire field surface was divided by f_w to represent the true infiltrated depth of water for the part of the surface that was wetted. Since irrigation of part of the soil surface and precipitation over the entire soil surface both occurred during the initial period, f_w represented the average of f_w for each type of wetting, weighted according to the total infiltration depth received by each type.

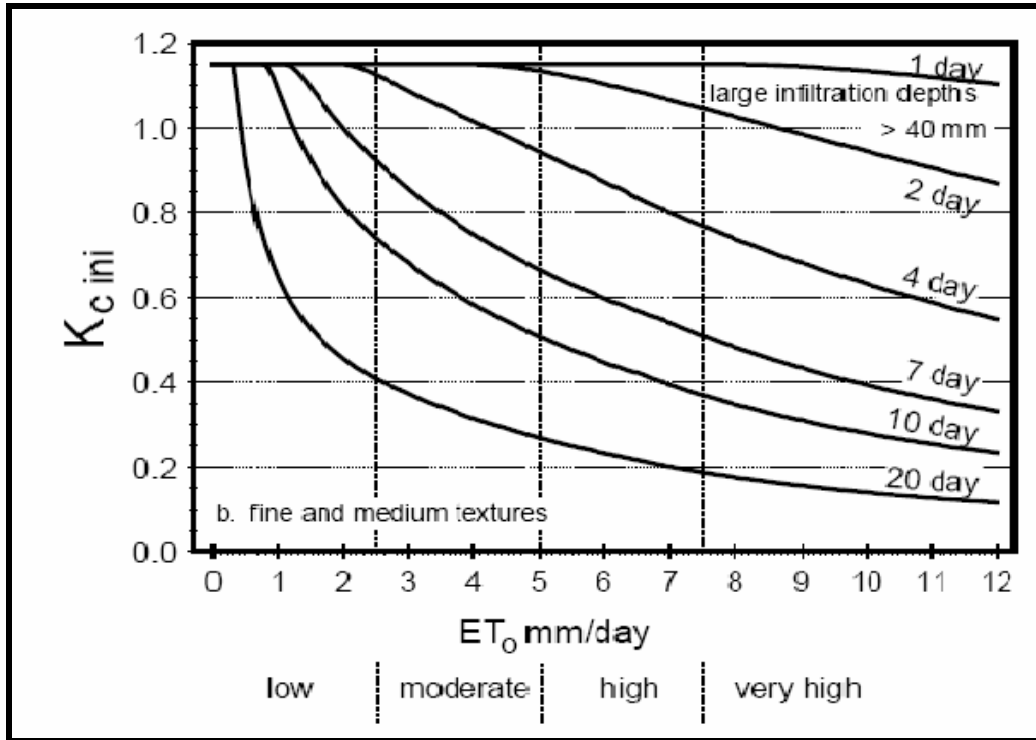


Figure 3.5: Average $K_{c\ ini}$ as related to the level of ET_0 and the interval between irrigations greater than or equal to 40 mm per wetting event, during the initial growth stage for medium and fine textured soils (Allen et al., 1998).

3.6.1.2 Adjustment for partial wetting by irrigation

Only a fraction of the soil was wetted and hence $K_{c\ ini}$ obtained from Figures 3.4 and 3.5 was multiplied by the fraction of the surface wetted to adjust for the partial wetting using equation 3.2.

3.6.2 $K_{c\ mid}$

The relative impact of climate on K_c is apparent at this stage. The K_c values were adjusted taking into account the differences in climate, mean daily wind speeds and crop heights between the study site and the non stressed, well managed citrus in sub humid climates. Equation 3.3 is used for the adjustment of the $K_{c\ mid}$ values.

$$K_{c mid} = K_{c mid (Tab)} + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)](h/3)^{0.3} \quad (3.3)$$

Where:

$K_{c mid (Tab)}$ is the value for $K_{c mid}$ taken from Table 3.2, U_2 is the mean value for daily wind speed at 2 m height over grass during the mid season growth stage ($m s^{-1}$) for $1 ms^{-1} \leq U_2 \leq 6 ms^{-1}$, RH_{min} is the mean value for daily minimum RH during the mid season growth stage (%), for $20 \% \leq RH_{min} \leq 80 \%$ and h is the mean plant height during the mid season stage (m) for $0.1 m < h < 10 m$.

3.6.3 $K_{c end}$ – end of the late season stage

The values given for $K_{c end}$ reflect crop and water management practices particular to the crop. Since citrus is irrigated frequently until harvested fresh, the topsoil remains wet and the $K_{c end}$ value will be relatively high. Adjustment to values given in Table 3.2 was done using equation 3.3.

The adjustment equation is only used when the tabulated values for $K_{c end}$ exceed 0.45. The equation reduces the $K_{c end}$ with increasing RH_{min} . This reduction in $K_{c end}$ is characteristic of crops that are harvested ‘green’ or before becoming completely dead and dry (i.e. $K_{c end} > 0.45$). No adjustment is made when $K_{c end} (Table) < 0.45$.

K_c values for any period of the growing period were derived by considering that during the initial and mid season stages K_c is constant and equal to K_c value of the growth stage under consideration. During the crop development and the late season stages, K_c varies linearly between the K_c at the end of the previous stage, $K_{c prev}$ and K_c at the beginning of the next stage, $K_{c next}$, which is $K_{c end}$ in the case of the late season stage.

K_c during the crop development and late season stages was estimated using equation 3.4. The curve was constructed by connecting straight-line segments through each of the 4 growth stages. Horizontal lines were drawn through $K_{c\text{ ini}}$ in the initial stage and through $K_{c\text{ mid}}$ in the mid season stage. Diagonal lines were drawn from $K_{c\text{ ini}}$ to $K_{c\text{ mid}}$ within the course of the crop development stage and from $K_{c\text{ mid}}$ to $K_{c\text{ end}}$ within the course of the late season stage (Allen *et al.*, 1998)

$$K_{ci} = K_{cprev} + \left[\frac{i - \sum(L_{prev})}{L_{stage}} \right] (K_{cnext} - K_{cprev}) \quad (3.4)$$

Where i is the day number within the growing season, K_{ci} is the crop coefficient on day i , L_{stage} is the length of the stage under consideration (days) and $\sum(L_{prev})$ is the sum of lengths of all previous stages (days).

3.7 Sap flow measurements

3.7.1 Measurement of branch sap flow by the SHB method

Branch sap flow was measured on one model tree using an SGB 35-ws trunk gauge. A branch free of petioles, leaves and scars was selected for the measurement of sap flow. To ensure that the branch diameter was within the range of the gauge, branch diameter was measured at four sections using a vernier calliper. The girth at the mid point for the gauge position was measured and recorded in order to figure out the cross sectional area for entering into the set up constant settings. A medium sand paper was used to remove roughness caused by the accumulation of naturally occurring dead bark. The sanding was done 10 cm above and below the gauge position to smoothen the stem around the gauge thereby enabling better measurement of heat flow in the xylem (Van Bavel, 1999).



Figure 3.6: An illustration of the installation of the SGB 35-ws gauge on the branch of a tree a) before and b) after wrapping with an aluminised shield.

3.7.2 Installation of the SGB 35-ws gauge

The selected branch was cleaned with a rag soaked in plenty of water to remove dust and grit. The top O – ring was placed in position above where the sensor was to be applied. Teflon liquid was sprayed in two coats around the circumference of the branch where the sensors went, avoiding the top O – ring area. The Teflon wax release compound prevents the sensor from sticking to the tree and aids insulation as well. The Teflon liquid was allowed to dry between coats.

Before the installation of the gauge on the plant, G4 Silicone insulating compound was applied onto the sensor heater and inner insulation. Approximately 2 g of the compound was used i.e. about 2 cm long from the tube. The compound was thoroughly rubbed on until it had a very thin layer on the inside of the sensor. This was done to seal out moisture from penetrating inside of the sensor, to prevent sensor thermocouples corrosion and aid the

expansion and contraction of the branch. During installation, it was made sure that the correct end of the gauge was up i.e. towards the plant apex.

The gauge was opened widely enough to slip the jacket around the branch. This was done carefully to prevent damage to the gauge components. The heater strip was tucked inside the gauge adjacent to the stem and the Velcro straps in the middle of the gauge were closed tightly. The remaining straps were tightened very snugly so that the thermocouple junctions A, B, H_a and H_b were in direct contact with the stem. The gauge was firmly in place and could not slide or twist with application of gentle force. The upper O – ring and shield mating surfaces were sealed with a film of G 4 compound. An aluminised shield was wrapped around the upper and the lower O – rings securely forming a cylindrical form. The shield keeps water out and prevents radiation from affecting readings. The installed branch gauge is outlined in Figure 3.6.

3.7.3 Determination of SHB sap flow

Equations 2.8 to 2.14 were used for the computation of sap flow rates. A voltage regulator was used to set the input voltage at 6 V and the heater impedance was noted from the gauge. This enabled the computation of input power. The thermocouple gap, dX for the SGB35-ws gauge was 10 mm and a K_{st} value of 0.42 was used. The branch cross sectional area (where the gauge was installed) was determined from the average diameter measured from four points along the branch. The K_{sh} value was determined using equation 2.14 from measurements taken predawn (0300 – 0600 hrs), when Q_f is zero.

3.7.4 Up scaling of sap flow measurements

Up scaling of branch sap flow was done after assuming that transpiration rate by a unit area of the leaf surface was the same for all the trees. The measured branch sap flow was scaled up to the whole tree and eventually to the whole orchard using the leaf area. The branch leaf area was used to determine the sap flux density ($\text{m}^3 \text{m}^{-2} \text{day}^{-1}$). Equation 3.5 was used to relate the branch diameter to the total leaf area (Dzikiti, 2007) for navel orange trees.

$$A_l = 13420 \times d^{2.3988} \quad (3.5)$$

A_l is the total leaf area (m^2) and d is the stem / branch diameter (m).

The sap flux density was obtained by dividing the sap flow with the total branch leaf area. The whole orchard transpiration rate (mm day^{-1}) was determined using the sap flux density and the total mean leaf area per hectare. The total leaf area per tree was determined using equation 3.5 considering the stem diameters. Stem diameters were measured on three trees per row (for sixteen rows) and three measurements were taken per tree. Tree stem diameters were measured using hand held callipers and were taken 8 cm below the first branch point. The average total leaf area for a single tree per row was obtained (Appendix 5) and subsequently the representative total leaf area of a single tree for the whole orchard was determined.

Considering an orchard tree spacing of 2.75 m and 6 m, 1 hectare of the orchard was assumed to have 606 trees. The average total leaf area per hectare was determined by multiplying the average total leaf area of a single tree by the number of trees per hectare. The total leaf area per hectare was used to calculate transpiration ($\text{m}^3 \text{Ha}^{-1} \text{day}^{-1}$) and this was converted to mm day^{-1} using the following conversion:

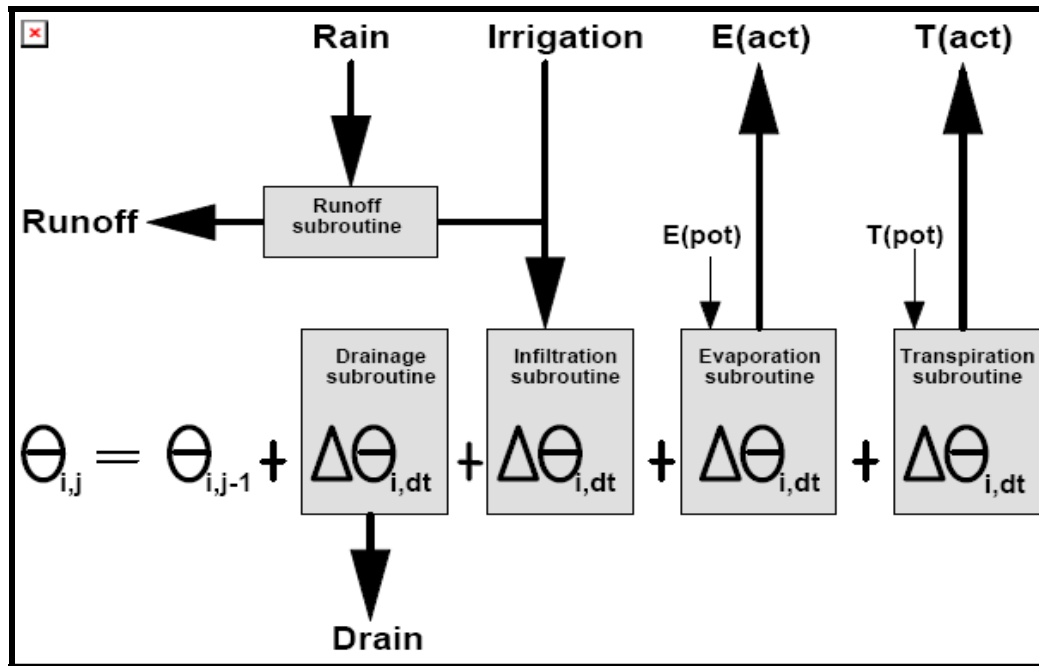
$$1 \text{ m}^3 \text{ Ha}^{-1} \text{ day}^{-1} = 0.1 \text{ mm day}^{-1} \text{ (Allen et al., 1998)}$$

3.8 The development of irrigation calendars

The irrigation scheduling guidelines were generated using BUDGET, (Version 6.2), a model developed by Raes (2005). BUDGET is comprised of a set of validated sub routines (Figure 3.7) describing the various processes involved in water extraction by plant roots and soil – water movement in the absence of a water table. Infiltration and internal drainage are described by an exponential drainage function (Raes et al., 1988 in Raes, 2005) that takes into account the initial wetness and the drainage characteristics of the various soil layers. Irrigation schedules were generated by time and depth criteria as described by Smith (1985) in Raes (2005) and used in the irrigation scheduling software packages Irrigation Scheduling Information Systems, IRSIS (Raes et al., 1988) and CROPWAT (Smith, 1990 in Raes, 2005). With the help of the dual crop coefficient procedure (Allen et al., 1998) the soil evaporation rate and crop transpiration rate of a well-watered soil were calculated.

3.8.1 Model description

Budget is composed of a set of validated subroutines describing the various processes involved in water extraction by plant roots and water movement in the soil profile. By calculating the water content in the soil profile as affected by input and withdrawal of water during the simulation period, the program can design irrigation schedules and evaluate irrigation strategies.



4. Irrigation data i.e. irrigation intervals and water application depths or criteria to generate the irrigation schedules.
5. Initial soil water conditions in the soil profile.

An illustration of the BUDGET main menu showing all the input requirements of the model is shown on Figure 3.8.

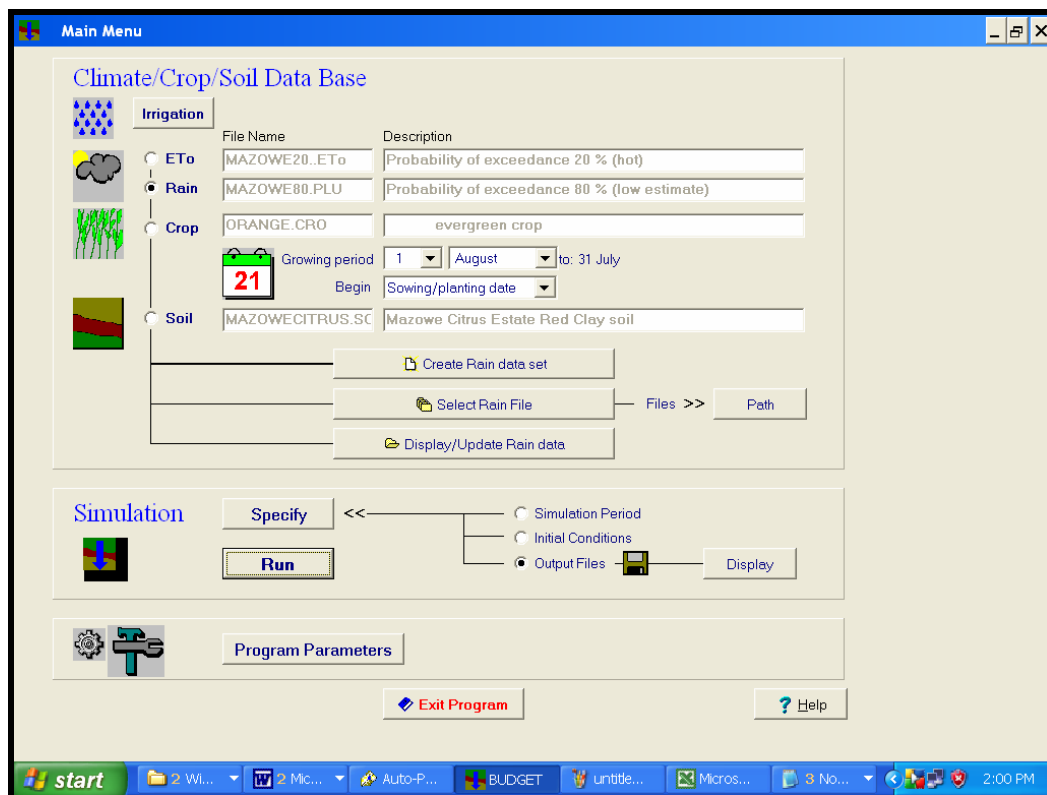


Figure 3.8: An illustration of the BUDGET main menu showing the model input requirements needed to run the model.

3.8.1.2 Output

With the described input and for given initial conditions, BUDGET simulates the water uptake in the specified climate / crop / soil environment and for the specified irrigation

option. During the simulation process, the variation of the soil – water content is visualised by displaying at the end of each day of the simulation period:

- The soil water content at different depths in the soil profile
- The water level in the soil – water reservoir
- The root zone depletion

At the end of the simulation process, BUDGET displays:

- The final soil moisture profile
- The total value for each of the parameters of the soil water balance
- The expected relative crop yield
- And the irrigation water requirement.

3.8.2 ET_o generation for the trial site

Average values for ET_o were obtained using historical and observed climatic data (2004 – 2009) of the trial site. An AWS was used for the collection of climatic data as described in 3.3. The FAO Penman Monteith equation (equation 2.3) was used for the computation of ET_o . The average ET_o values obtained using historical data were regarded as the representative (normal) values for the study site. Increasing the normal ET_o values by 30 % generated the hot environment for input into the model and the subsequent lowering of the normal ET_o values by 30 % generated the cool environment.

3.8.3 Rainfall data

The mean monthly rainfall data for the study site was generated using the FAO LocClim model. The generated mean monthly rainfall totals were assumed to be the normal values for

the study site. Raising the normal mean monthly rainfall totals by 30 % generated the humid condition and a dry condition was established by lowering the normal values by 30 %.

3.8.4 Crop parameters

The citrus crop type is a perennial evergreen, which completely covers the ground at maximum crop canopy. After studying the growth cycle and water requirements of citrus, the following parameters (Table 3.4) were specified. The file used for the creation of a crop file in BUDGET is outlined in Figure 3.9.

Table 3.4: Citrus crop parameters that were used to run the model

Parameter	Description
Water stress	Sensitive to water stress with a soil water depletion fraction, p for non stress of 0.3
Growth stages and K_c coefficients	Four growth stages were specified i.e. initial, crop development, mid season and late season. The stage lengths are 70 days, 81 days, 120 days and 94 days respectively
Aeration stress	Crop stress as a result of deficient aeration conditions i.e. when soil water is greater than saturation (50 %).
Mulch	No mulching was considered.
Water extraction pattern	Throughout the root zone of 40 % in the first quarter, 30 % in the second quarter, 20 % in the third quarter and 10 % in the last quarter.
Partitioning of ET_{crop}	Potential soil evaporation was considered to be 10 % and potential crop transpiration 90 % of the total evapotranspiration.
Yield response	A yield response factor of 1.2 was used for all the growth stages.
Rooting depth	Rooting depth was considered to be up to 1 m for all the growth stages.

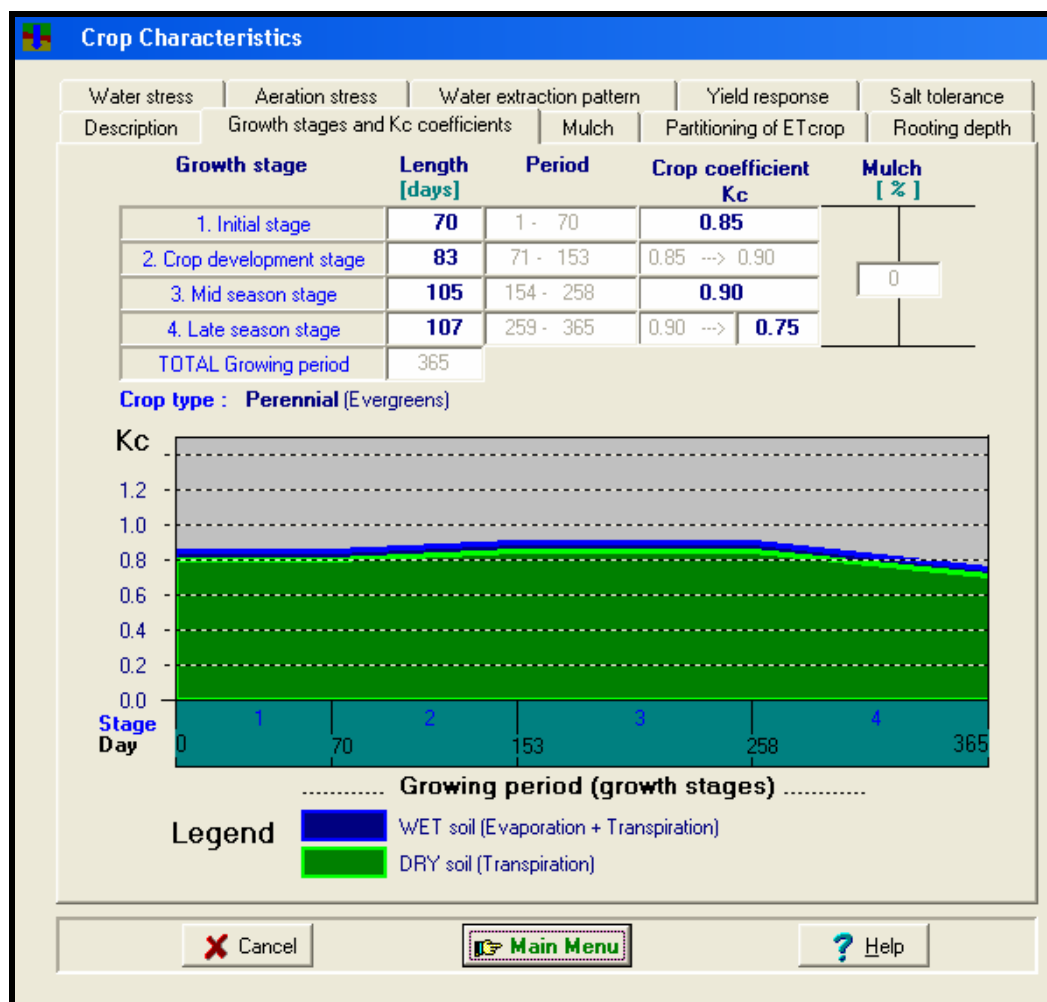


Figure 3.9: Creation of a crop file in BUDGET (Raes, 2005)

3.8.5 Soil parameters

Table 3.5 describes the soil properties at MCE that formed the basis for the creation of a soil file (Figure 3.10) in BUDGET

Table 3.5: Characteristics of the soil at Mazowe Citrus Estate (after Hussein, 1982)

Soil Property	Top soil	Sub soil
Sample depth (mm)	0 - 150	600 - 750
% Clay	63	81
pH (CaCl ₂)	6.6	5.7
Bases exchangeable (me %)	27.5	15.9
Cation exchange (me %)	33.2	18.1
E / C value (%)	53	22
S / C value	44	20
Bulk density (Kg.m ⁻³)	1330	1350
Available Water Capacity (mm / 100 mm)	14.9	14.3

The topsoil layer i.e. a clay loam was considered to have a saturated hydraulic conductivity of 70 mm day⁻¹, a field capacity of 39.0 %, a wilting point of 23.0 % and a saturation point of 50 %. The bottom layer, a sandy clay was considered to have a saturated hydraulic conductivity of 75 mm day⁻¹, a field capacity of 39 %, a wilting point of 27 % and a saturation point of 50 %. No soil bunds were considered for the soils.

Create SOIL file

File Name: - ← 1

Description: ← 2

Soil surface:

- ☒ NO bunds around field (surface runoff) ← 3
- ☐ BUNDS around field (water storage between bunds)

Number of Soil Layers: ← 4

Soil type: ← 5

Thickness: meter ← 6

Figure 3.10: Creation of a soil file in BUDGET (Raes, 2005)

3.8.6 Irrigation data

Irrigation events were generated by specifying the two key irrigation parameters required for the generation of irrigation schedules i.e. time and depth criteria. A fixed irrigation interval of 1 day and irrigation amounts of back to field capacity were used for the generation of the irrigation schedules. An illustration of the BUDGET file used to specify irrigation parameters is displayed in Figure 3.11. The fraction of soil wetted using drip irrigation was assumed to be between 30 % and 40 %.

Irrigation Options

Rainfed (no irrigation)
☐ No irrigation required (rainfed agriculture)

Irrigation water requirement
☐ Determination of Irrigation water requirement

Irrigation scheduling

Info ? Fraction of soil surface wetted..... 30 %
Water Quality...(Excellent) ECw : 0.00 dS/m

in crop season

☐ Manual Irrigation Schedules Events

☒ **Generation of Schedules** Parameters

Time Criteria

☐ Fixed interval
☐ Allowable depletion amount
☒ Allowable fraction of Readily Available soil Water (RAW)

Depth Criteria

☒ Back to Field Capacity
☐ Fixed application depth

out of crop season Events

Cancel Main Menu Help

Figure 3.11: A BUDGET file outlining the irrigation options used for the generation of irrigation schedules.

3.9 Fruit growth measurements

3.9.1 Fruit diameter

Four trees per treatment i.e. two trees per row were selected for the evaluation of fruit growth. Ten fruit were selected from each tree during the first decade of December. Fruit were tagged following a procedure outlined by Sithole (2005). Four fruit were tagged on the eastern side (exposed to sunlight in the morning); the other four on the western side (exposed to sunlight in the afternoon) and the remaining two fruit were tagged deep inside the canopy (shaded all day). For each fruit, a number was assigned, from 1 to 10 and a tag with the fruit number was tied to the last twig leading to the fruit for easy identification (Figure 3.12). Fruit numbering was made systematically for easy fruit location during the measuring process.



Figure 3.12: A tag with the fruit number tied to the last twig leading to the fruit for easy identification.

Fruit diameter was measured at 10 day intervals using a 0.05 mm accurate pair of vernier callipers. Two measurements were taken on each fruit and averaged to reduce errors. Figure 3.13 Illustrates how fruit diameters were measured. The first measurement was taken along the equator of the fruit and the second measurement was taken perpendicular to the first one. Fruit that dropped were quickly replaced by the nearest one whose diameter represented the one for the fruit that dropped.

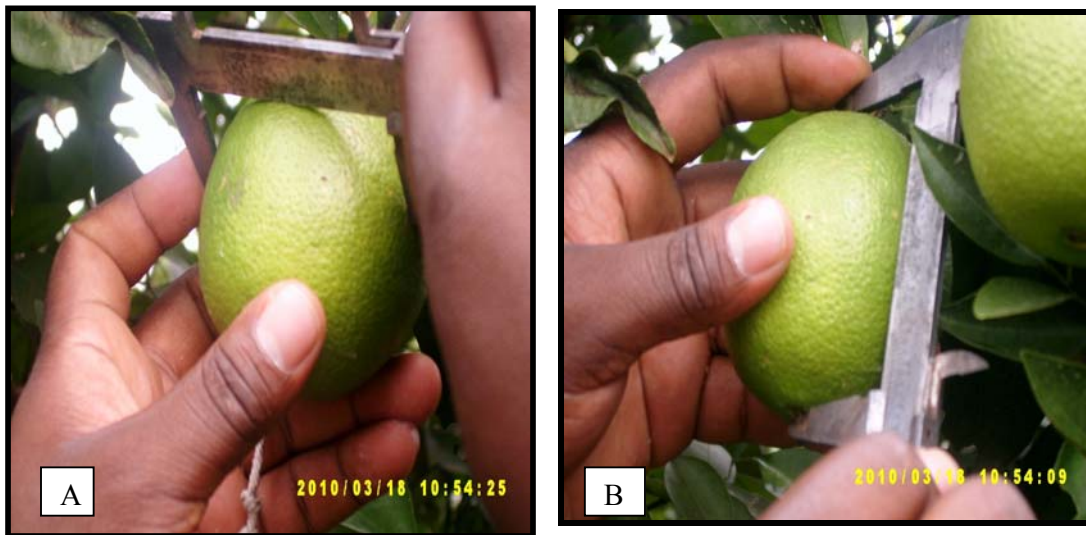


Figure 3.13: An illustration of the measurement of fruit diameter where a) the measurement was taken along the equator of the fruit and b) the measurement was taken perpendicular to the first one.

3.9.2 Fruit abscission

Fruit abscission monitoring was initiated during the same period as fruit growth measurement and was stopped during the first decade of January. The timing was chosen from the basis that fruit drop is prevalent after fruit set and usually decreases drastically at the end of December. The same tagged fruit used for measuring fruit growth rate were also used for the assessment of fruit abscission. The number of tagged fruit (per treatment) that dropped during the assessment period was noted.

4.0 Introduction

This chapter outlines the findings of the experiments outlined in Chapter 3. The study site climate is described first in terms of temperatures, relative humidity, solar radiation, wind speed and ultimately the monthly average ET_o values for the study site. Sap flow measurements are given for the estimation of transpiration rates. In this chapter, the whole season K_{pan} and K_c curve values are outlined. The chapter also presents the modelled soil moisture status under various actual weather conditions for the developed irrigation guidelines. The whole season irrigation calendars are displayed in terms of the irrigation depth taking into account the actual weather condition. The irrigation guidelines are compared to the grower's scheduling practices in terms of the total amount of water used, fruit growth rates and fruit abscission.

4.1 Study site climate

The irrigation guidelines were developed after evaluation of the crop water requirements of the citrus trees at the study site. This was done through the determination of the monthly average ET_o values from climatic parameters of the study site and the development of the crop coefficient curve. The climatic parameters under consideration were the wind speed, solar radiation, net radiation, relative humidity, air temperature, vapour pressure deficit and the soil heat flux.

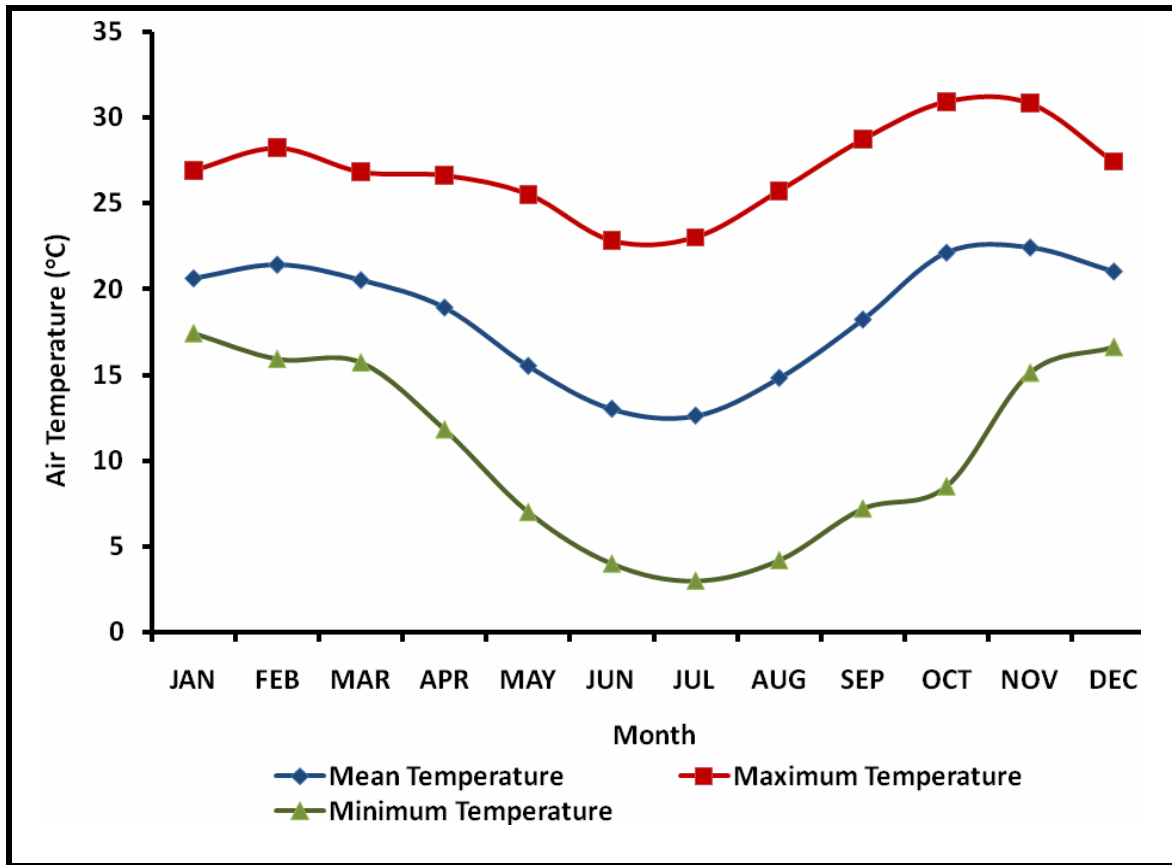


Figure 4.1: The average monthly mean temperature, maximum temperature and minimum temperature for MCE from 2006 to 2009.

Air temperatures are usually influenced by solar radiation and this is the reason why the mean air temperatures have the same trend (Figure 4.1) as solar radiation (Figure 4.3). Air temperatures were low in winter (April to early August) with values as low as 3 °C, 12 °C and 22 °C for the minimum temperature, mean temperature and maximum temperatures respectively. The maximum mean monthly air temperatures were experienced in summer with values of up to 17 °C, 22 °C and 31 °C for the minimum temperatures, mean temperatures and maximum temperatures respectively.

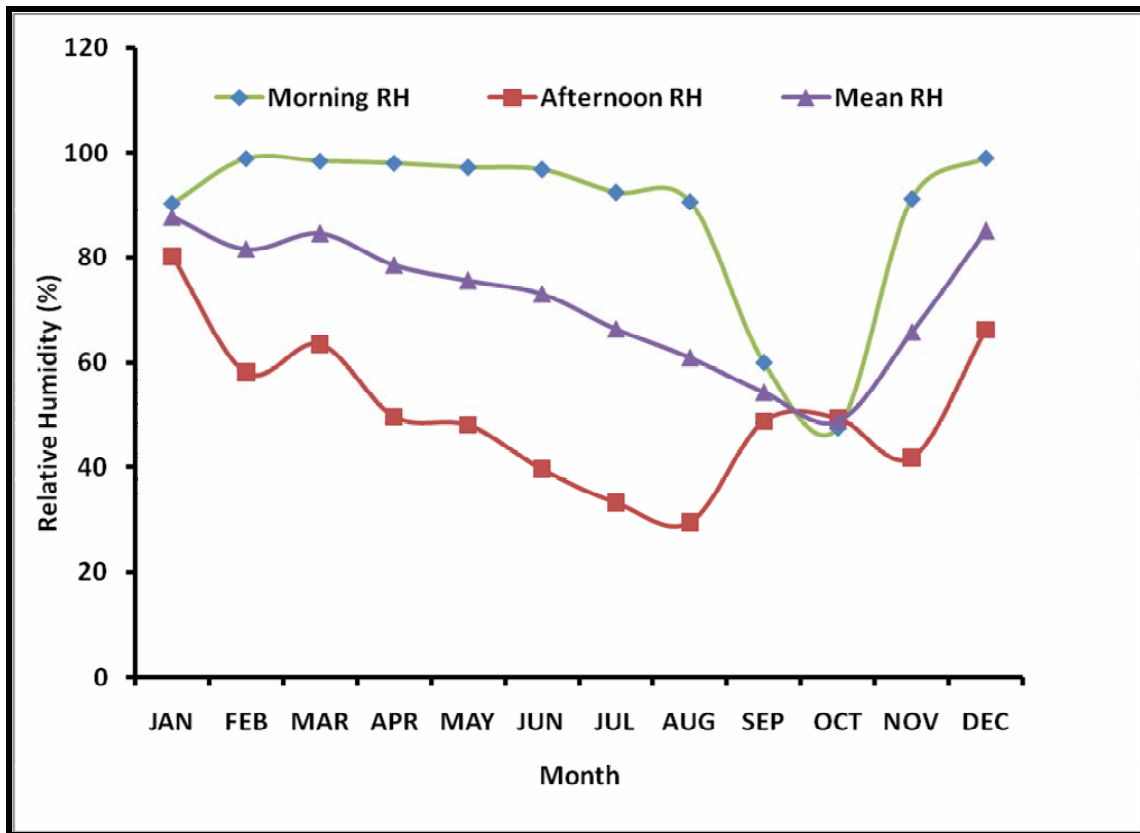


Figure 4.2: The mean monthly morning Relative Humidity (0200 hrs – 0600 hrs, local time: GMT + 2 hrs), afternoon Relative Humidity (1200 hrs – 1600 hrs) and the mean Relative Humidity for MCE from 2006 to 2009.

The Relative Humidity (RH) trends for the trial site are outlined in Figure 4.2. The mean RH decreased from January (approximately 90 %) to October (about 50 %). From October, RH increased to almost 85 % in December. Relative humidity was generally high during the rainfall season (November to March). Generally, the morning RH was greater than the afternoon RH. In October, there was a small variation in the morning and afternoon RH as well as being the period with the lowest mean RH. Plants transpired more during this period for cooling especially because of the high temperatures experienced during this period.

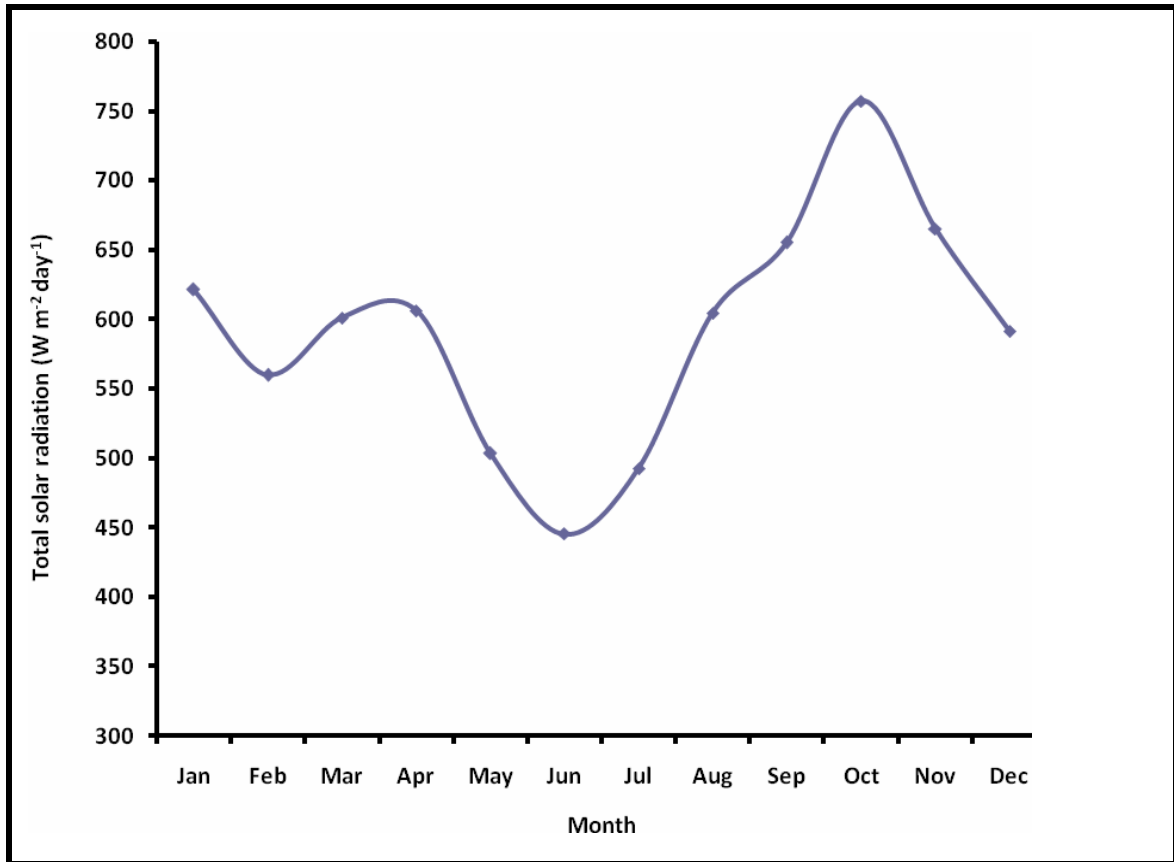


Figure 4.3: The average daily total solar radiation for MCE from 2006 to 2009.

The daily total solar radiation values decreased from January to June (Figure 4.3) as winter approached. This was caused by the increasing cloud cover conditions in winter. From August, solar radiation increased as summer was approaching. Peak solar radiation values were experienced during October and November.

The mean wind speed generally decreased (Figure 4.4) from January (1.1 m s^{-1}) to May ($< 0.9 \text{ m s}^{-1}$). The mean wind speed was observed to increase from June to October with a peak of 1.6 m s^{-1} in October. The peak mean wind speed corresponds to the peak ET_o value. The mean monthly rainfall totals for the study site are outlined in Figure 4.12. The rainfall season stretched from October to March with effective rains expected in November (about 100 mm for an average season). This amount approximately doubled in December with the highest

rainfall amount received in January. The dry season occurred from winter to spring (April to September).

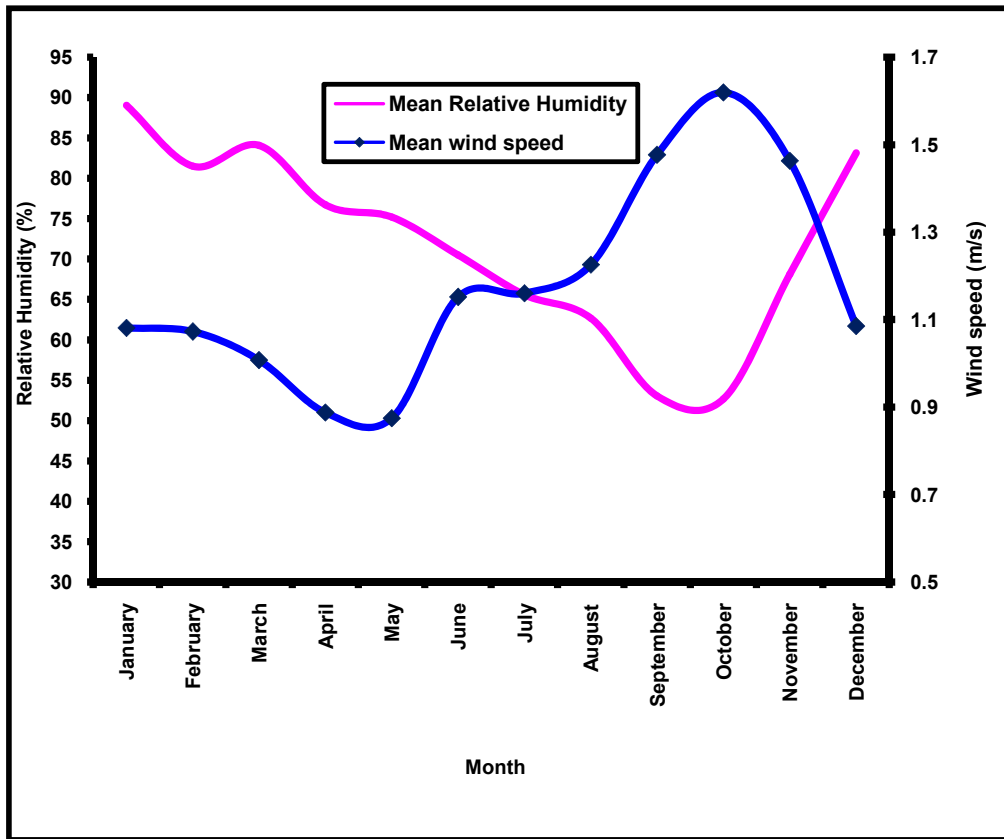


Figure 4.4: Average (2005 – 2009) Relative Humidity and Wind speed at 2 m height for Mazowe Citrus Estate.

ET_o values were slightly above 4 mm a day from January to April. During winter (May to early August), ET_o was low i.e. around 3 mm a day. Peak values were observed in summer especially in October with values greater than 5 mm a day. The trend shown in Figure 4.5 reflects that there was little variation (about 2 mm a day) in ET_o values throughout the year.

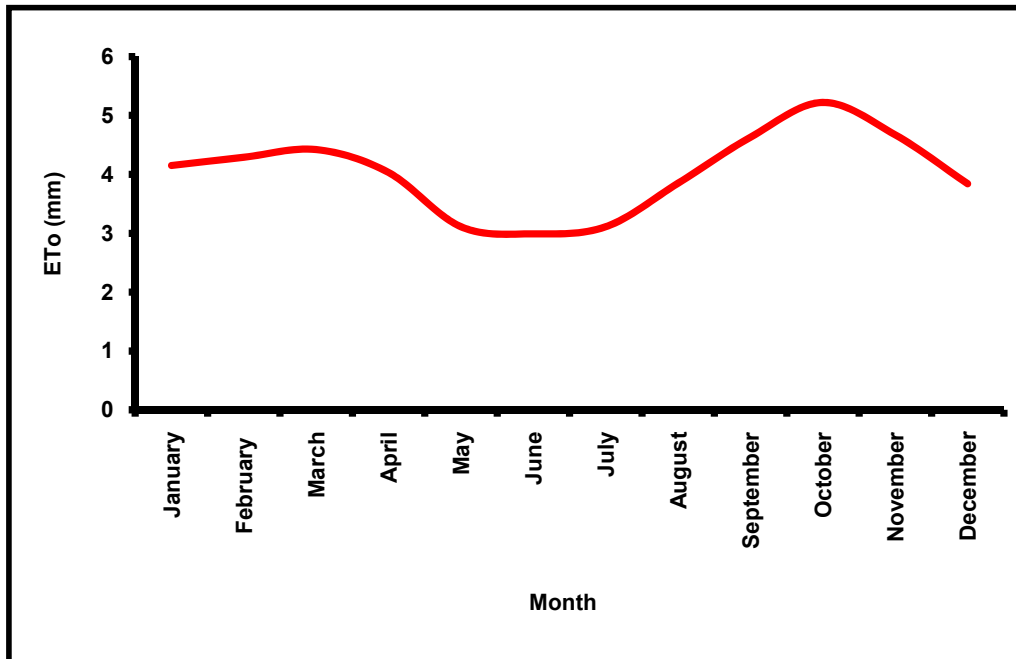


Figure 4.5: The average (2005 – 2009) annual variation of ET_0 calculated using the FAO Penman – Monteith equation

4.2 Sap flow

Sap flow was measured on 1 model tree using the SHB method. The sap flow sensor however, could not be aligned to any of the irrigation treatments because the period of installation coincided with rains where no irrigation was applied. Prolonged use of sap flow sensor was not feasible because of high frequency power failures which could last for more than a day in some cases. Sap flow sensors require more energy and could not be sustained by back up sources. It was hence not possible to get a continuous data set.

A 24 hour recording of sap flow measurements was achieved from DOY 82 – 83. A continuous record of sap flow would have been more favourable but Figure 4.6 serves as an example. The corresponding solar radiation trend during the same period is outlined in Figure 4.7.

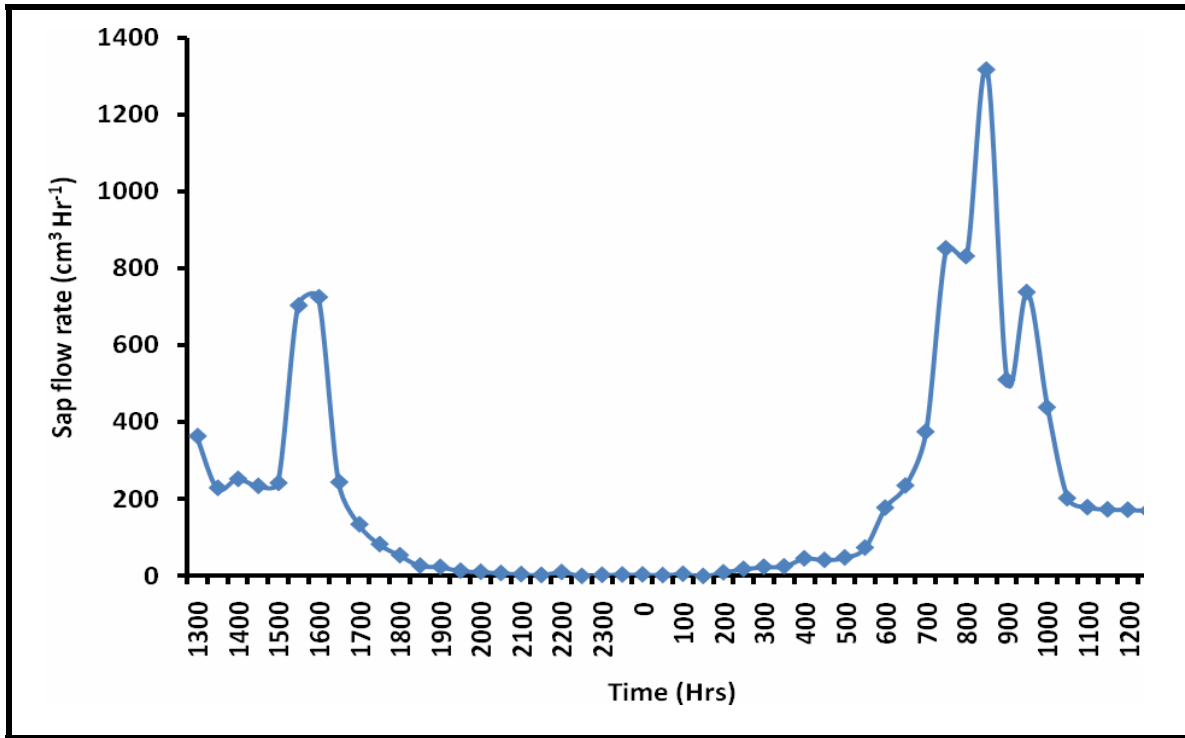


Figure 4.6: The typical course of sap flow measured on DOY 82 – 83.

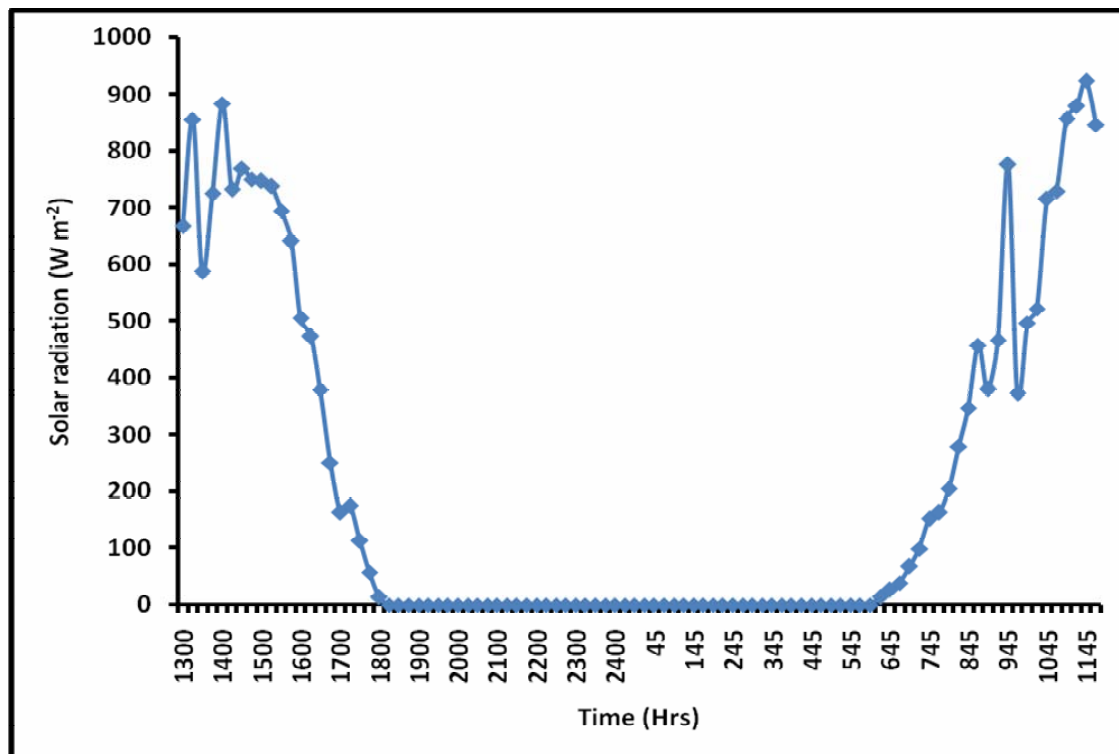


Figure 4.7: The typical course of solar radiation measured on DOY 82 - 83.

The sap flow rates for the SHB on DOY 82 – 83 (see Appendix 1 for the day of year calendar) are outlined in Figure 4.6. It was evident that solar radiation is the major drive for transpiration since there was no sap flow when solar radiation was zero.

4.2.1 Sap flux density

Up scaling of the sap flow measurements was done using the branch diameter. Table 4.1 outlines the parameters used for the determination of the sap flux density.

Table 4.1: Branch leaf area determination using the branch diameter.

DOY	Mean branch diameter (*10 ⁻² m)	Whole tree / branch leaf area (m ²)
82 – 83	4.2588	6.9

The leaf area was used to determine the sap flux density. Transpiration rate (mm / day) was determined from the product of sap flux density and the average leaf area per hectare (Table 4.2).

Table 4.2: Determination of the transpiration rate (mm/day) on DOY 82 – 83 using the sap flux density and leaf area per hectare.

DOY	Sap flux density (m ³ m ⁻² day ⁻¹)	Number of trees per hectare	Mean leaf area per tree (m ²)	Mean leaf area per hectare (m ²)	Sap flux density (m ³ Ha ⁻¹ day)	Transpiration (mm day ⁻¹)
82 – 83	7.28x10 ⁻⁴	606	47	28 482	20.74	2.1

The data for the determination of mean leaf area is outlined on Appendix 6.

DOY 82 and 83 fall into the third decade of March. The observed ET_o was 3.9 mm day^{-1} and 4.1 mm day^{-1} for DOY 82 and 83 respectively and these values fall into the normal ET_o range i.e. average values for the study site. The transpiration rates obtained using the sap flow are analogous to the prescribed 2 mm to be applied during the third decade of March (Irrigation calendar, Figure 4.14). The SHB method can hence be effectively used for irrigation scheduling but its application is however limited since the gauges can not be used for a long period.

4.3 The pan coefficient, K_{pan}

The pan coefficient was determined using two procedures:

- (i) Empirically determined (Fig. 4.8) from the pan type, ground cover in the station and its surroundings, wind speed, relative humidity and the upwind buffer zone i.e. fetch (Allen et al., 1998).
- (ii) A plot of the FAO Penman – Monteith ET_o against daily pan readings for the corresponding days (Fig. 4.9)

For the empirical determination of the pan coefficient, it was necessary to establish the mean monthly relative humidity and wind speed, as these are the main determinants of the pan coefficients. The mean relative humidity and wind speed seasonal distributions are expressed in Fig. 4.4. Generally, the pan coefficient was directly proportional and inversely proportional to relative humidity and wind speed respectively. The second method of pan coefficient determination resulted in a single representative coefficient from October 2009 to March 2010 but the first method took into account the variation of pan coefficients throughout the season.

Depending on the condition of the windward side prior to the weather station (dry fetch or green fetch), the pan coefficients for the study site followed a trend shown in Figure 4.8. K_{pan} values for a green fetch are higher than those for a dry fetch. Generally, K_{pan} was highest in January and decreases up to October and the values rise again in November and December. It implies then, that K_{pan} is high during the rain season and low during the dry season.

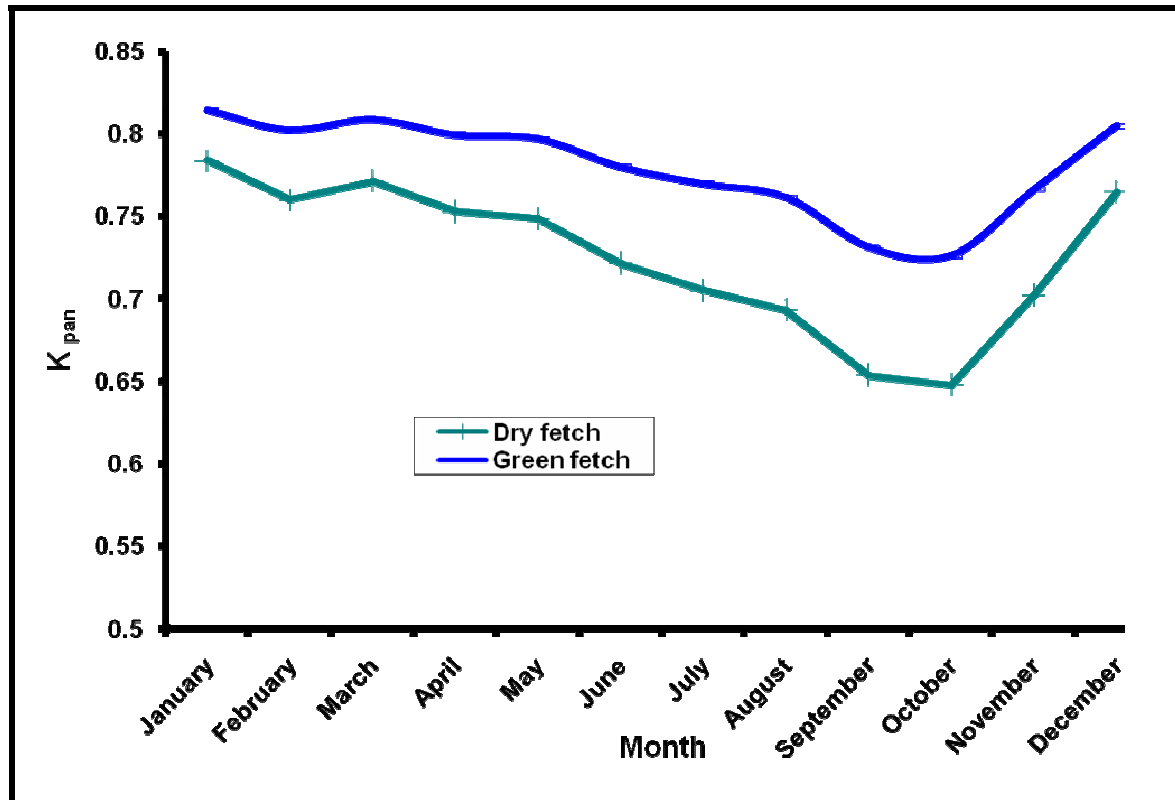


Figure 4.8: Whole year K_{pan} values for a class A evaporation pan with a dry fetch and a green fetch at Mazowe Citrus Estate

For a green fetch (the study site's windward side condition), K_{pan} was approximately 0.8 from January to April (Figure 4.8). K_{pan} fell from May and the lowest value (0.72) was in October. Throughout the season, K_{pan} varied between 0.72 and 0.82. The green fetch K_{pan} values from May to November are in the 0.7 to 0.77 range (Doorenbos and Pruitt, 1977) for days of light to moderate wind ($< 425 \text{ Km day}^{-1}$) and median relative humidity (40-70 %). The K_{pan} values

for both green fetch and dry fetch conditions in summer is synonymous to the 0.8 value given by Penman (1948) for summer months.

The dry fetch K_{pan} was lower than the green fetch one but followed the same trend (Figure 4.8). The highest K_{pan} value of 0.78 was recorded in January and the lowest value (0.65) in October giving a range of 0.13. In situations where the windward side fetch condition is ill defined, an average value of 0.75 (dry and green fetch) can be assumed to be the representative K_{pan} throughout the year. This value is close to 0.7 which was recommended as the average K_{pan} value (Natural Resources and Environment, undated).

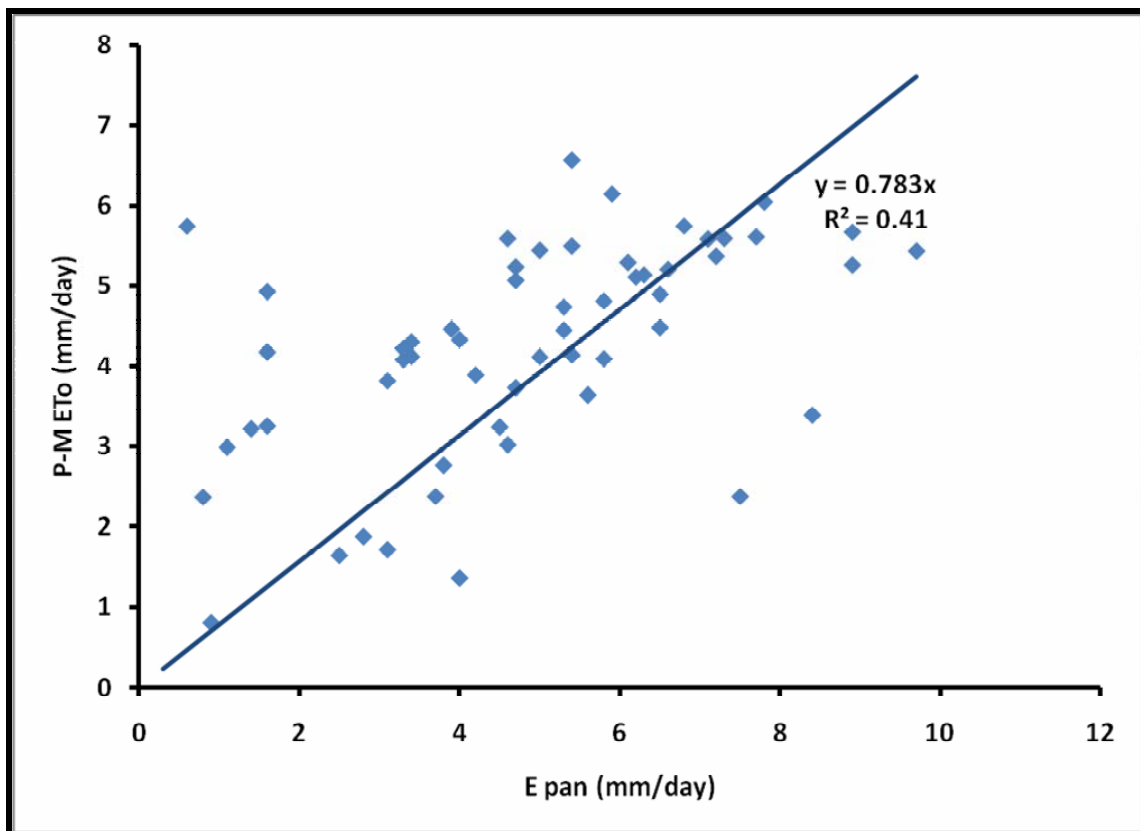


Figure 4.9: Estimation of the pan coefficient (K_{pan}) for the class –A evaporation pan measurements at Mazowe Citrus Estate. The data used was collected during the period October 2009 to March 2010, but spurious pan evaporation readings were filtered.

An average pan coefficient value of 0.78 was determined from October 2009 to March 2010 (Figure 4.9). This value was obtained from a plot of the FAO Penman Monteith ET_o against the corresponding daily pan readings. Considering the first method, the average K_{pan} from October to March is 0.79. There is a similarity in the K_{pan} value using both methods implying that they are both suitable for estimating K_{pan} . The choice however depends on the availability of data required to compute the estimations.

For the second method to be more effective there is need for the determination of K_{pan} at least on a monthly basis to cater for the variations throughout the season. Considering the study site's climate and fetch condition (light winds i.e. $< 2 \text{ m s}^{-1}$, a windward side distance of green fetch between 10 m and 100 m and medium to high relative humidity i.e. $> 40 \%$), K_{pan} must be between 0.8 and 0.85 (Allen *et al.*, 1998). The average K_{pan} (green fetch) of 0.78 that was estimated from this study is close to the values given in literature. It is suggested that the K_{pan} values from this study be adopted by the local farmers.

4.4 K_c curve for citrus

The determination of K_c values for the initial, mid season and late season stages is outlined in Appendix 4. The first step involved the selection of the growth stages and their corresponding durations.

4.4.1 The K_c curve

Figure 4.10 outlines the whole season K_c curve that was generated for Mazowe Citrus Estate. K_c was low during the initial stage probably because of the low wetted fraction when using drip irrigation. K_c rose sharply during the crop development stage, with the value changing remarkably every decade until the mid season stage (Table 4.3). The reason for this sharp rise

can be linked to the critical fruit development processes associated with this stage. The processes include flowering, fruit let drop (fruit set) and cell division.

Table 4.3: Whole season K_c values per decade for the study site derived from the daily values.

Month	August			September			October			November		
Decade	1	2	3	1	2	3	1	2	3	1	2	3
K_c	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.50	0.54	0.59	0.63	0.68

Month	December			January			February			March		
Decade	1	2	3	1	2	3	1	2	3	1	2	3
K_c	0.72	0.77	0.81	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84

Month	April			May			June			July		
Decade	1	2	3	1	2	3	1	2	3	1	2	3
K_c	0.84	0.84	0.84	0.84	0.83	0.82	0.81	0.80	0.79	0.78	0.77	0.76

K_c was highest (0.84) and constant during the mid season stage for almost 13 decades. The high value may be linked to the increased wetted fraction of the soil because of rainfall during this period. During the late season stage, K_c gradually fell ending the season (last decade) with an average value of 0.76. There is a small shift from the K_c values from mid season to late season because the fruit is harvested ‘green’ i.e. the fruit requires water until harvested. The flowering stage K_c and the maximum K_c values (September to October and January to April respectively) relationship shows a closer resemblance to that of Table grape cultivars i.e. K_c at flowering = $K_{c \text{ max}} * 0.5$ (Gurovich, 1996).

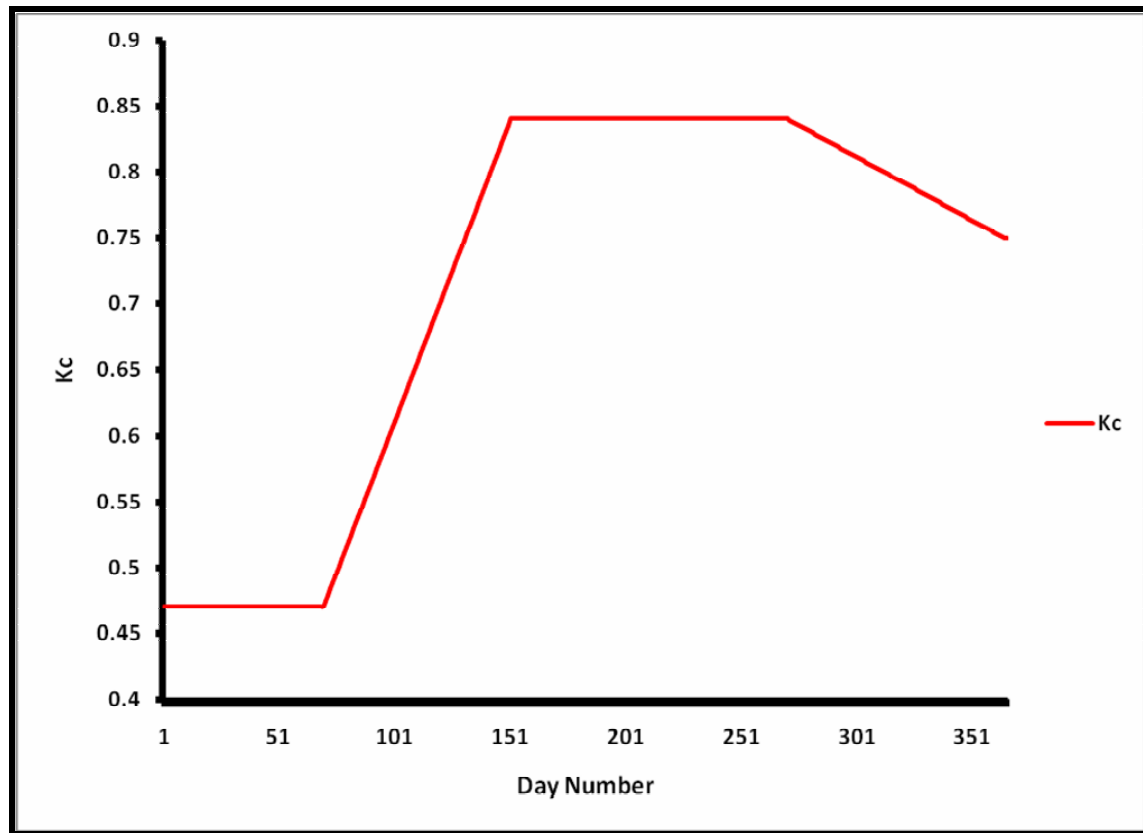


Figure 4.10: Whole season crop coefficient curve for citrus at MCE. Day 1 refers to the start of the initial phenological stage during the first decade of August.

4.5 Irrigation guidelines

Irrigation calendars were developed considering the probable climatic scenarios for the study site. The climatic parameters used are the ET_0 and rainfall. ET_0 integrates solar radiation, net radiation, relative humidity, wind speed, vapour pressure deficit and soil heat flux. The climatic scenarios are displayed in Figures 4.11 and 4.12. The normal condition was regarded as the mean monthly values for the study site and these are expected for ‘normal’ seasons.

A hot season (high estimate) was assumed to have ET_0 values that are 30 % higher than the average values where as a cool season (low estimate) was assumed to have ET_0 values that are 30 % lower than the average. A humid scenario (high estimate) was considered to have

rainfall values that are 30 % greater than the average rainfall and consequently a dry season (low estimate) was assumed to have rainfall values that are 30 % lower than the average rainfall values. There is however no difference in rainfall amount for the three rainfall scenarios from May to September because this is a dry period.

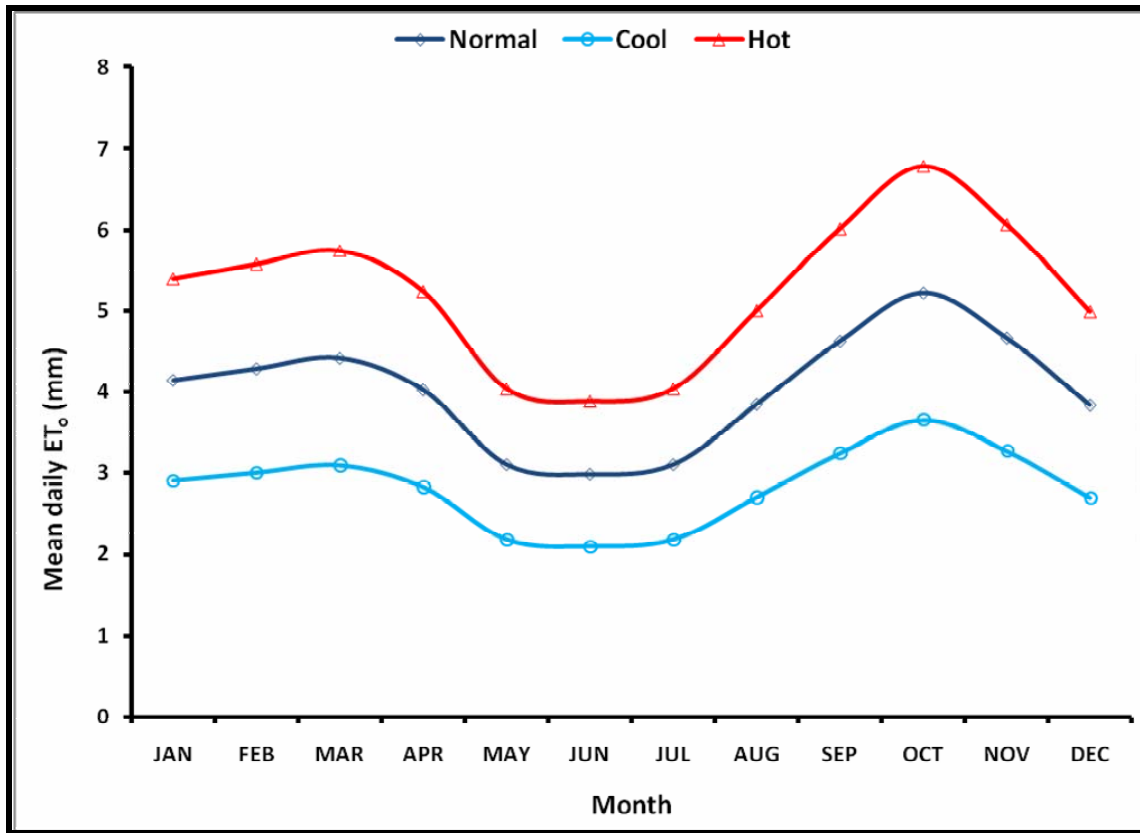


Figure 4.11: Mean daily ET_0 of MCE for the cool, normal and hot scenarios

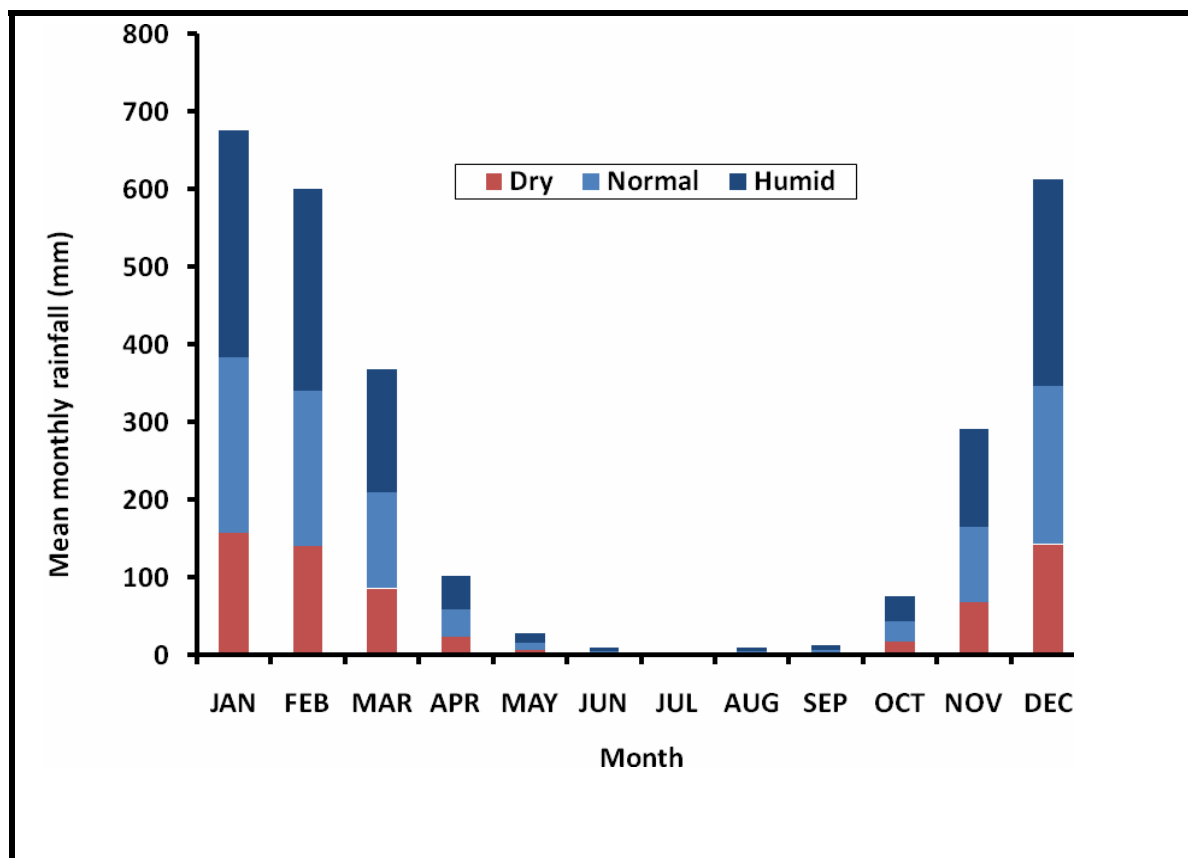


Figure 4.12: Mean monthly rainfall amounts of MCE for the dry, normal and humid scenarios.

4.5.1 Soil moisture status for the irrigation guidelines

A projection of the daily soil moisture status in the root zone and beyond for the irrigation scheduling guidelines under all climatic conditions was done. The projection was also done considering the grower's irrigation scheduling practices. There was an assessment of the soil moisture depletion, soil moisture content and the soil water balance. Soil moisture depletion is presented in terms of the daily initial and final depletion amounts.

The initial depletion amount is the amount of water to be applied to the soil to reach FC. The FC is represented by the 0 mm line. The final depletion amount refers to the soil moisture level after irrigation and or rainfall. The soil moisture content projection indicates the soil

moisture level after input through irrigation and rainfall (Input) and the amount of soil water leaving the root zone (Output). The soil water balance is outlined with the four main parameters i.e. irrigation, rainfall, infiltration and drainage. The water balance levels were obtained after taking into account the daily evapotranspiration losses i.e. the difference between infiltration and drainage. The infiltration amount is the sum of the irrigation and rainfall amounts.

4.5.2 Normal conditions

Under normal climatic conditions, the soil moisture depletion, soil water content and some terms of the soil water balance are displayed in figures 4.13, 4.14 and 4.15 respectively. The maximum final depletion amount is approximately 6 mm and the maximum initial depletion amount is about 14 mm. From day 1 to nearly day 120, the final depletion amount is zero indicating that the soil will be at field capacity.

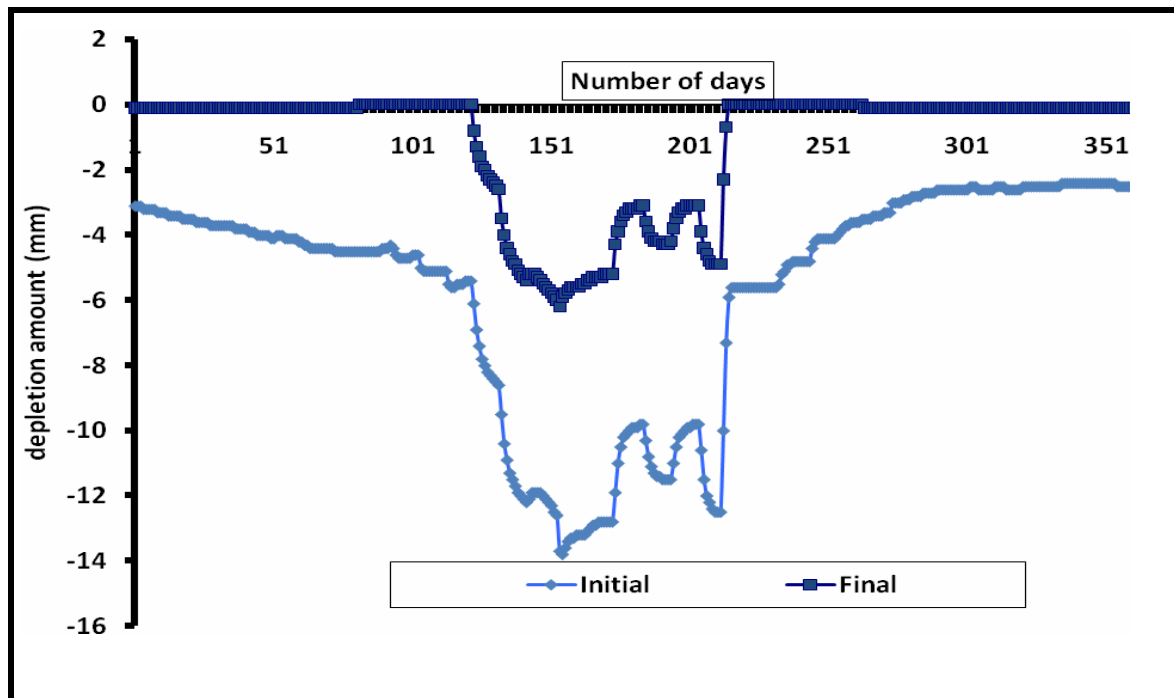


Figure 4.13: BUDGET simulated initial and final soil moisture depletion under normal conditions.

From day 120 (a period almost 90 days) the final moisture depletion is greater than zero hence the soil moisture will be above field capacity. This scenario is brought about by the effective rain season where there will be uncontrolled application of water into the soil. During the same period, the initial soil moisture depletion is also increased.

The movement of water out of the root zone is almost zero from day 1 to about day 90. For a period lasting approximately 140 days, water moved out of the root zone. The maximum rate of water movement out of the root zone is approximately 4 mm per day and the corresponding moisture input is about 7.5 mm per day. From day 250 to maturity, water flow out of the root system is zero. This period resembles the end of the rain season and the resumption of a proper irrigation schedule.

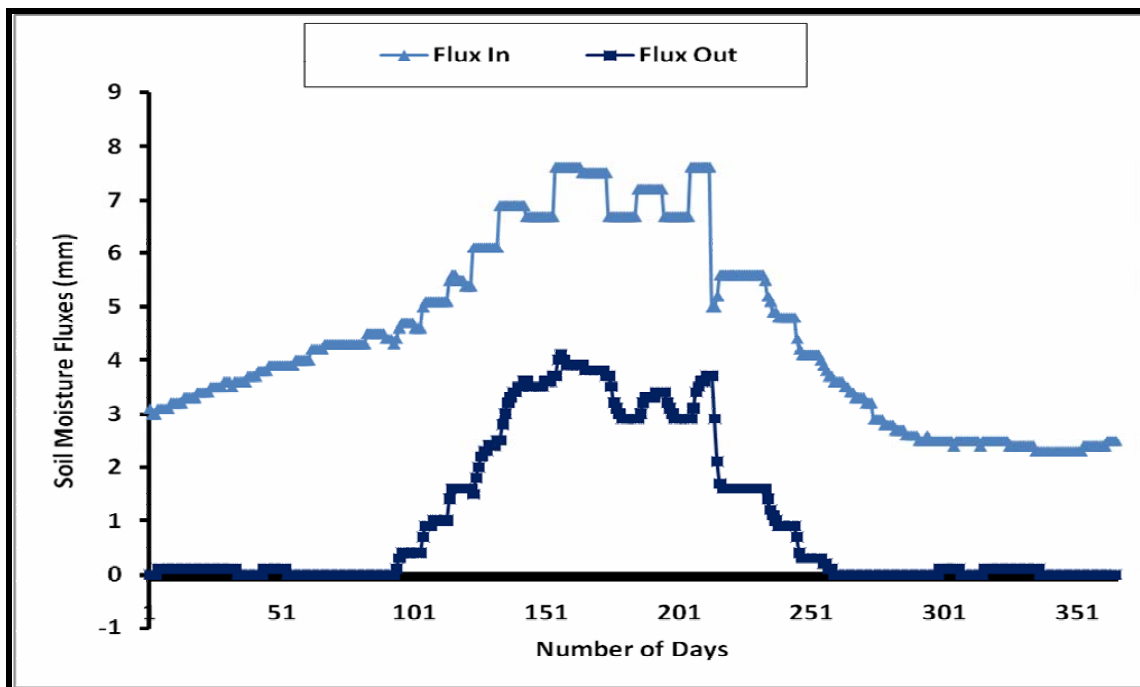


Figure 4.14: BUDGET simulated water movement in and out of the root zone under normal conditions.

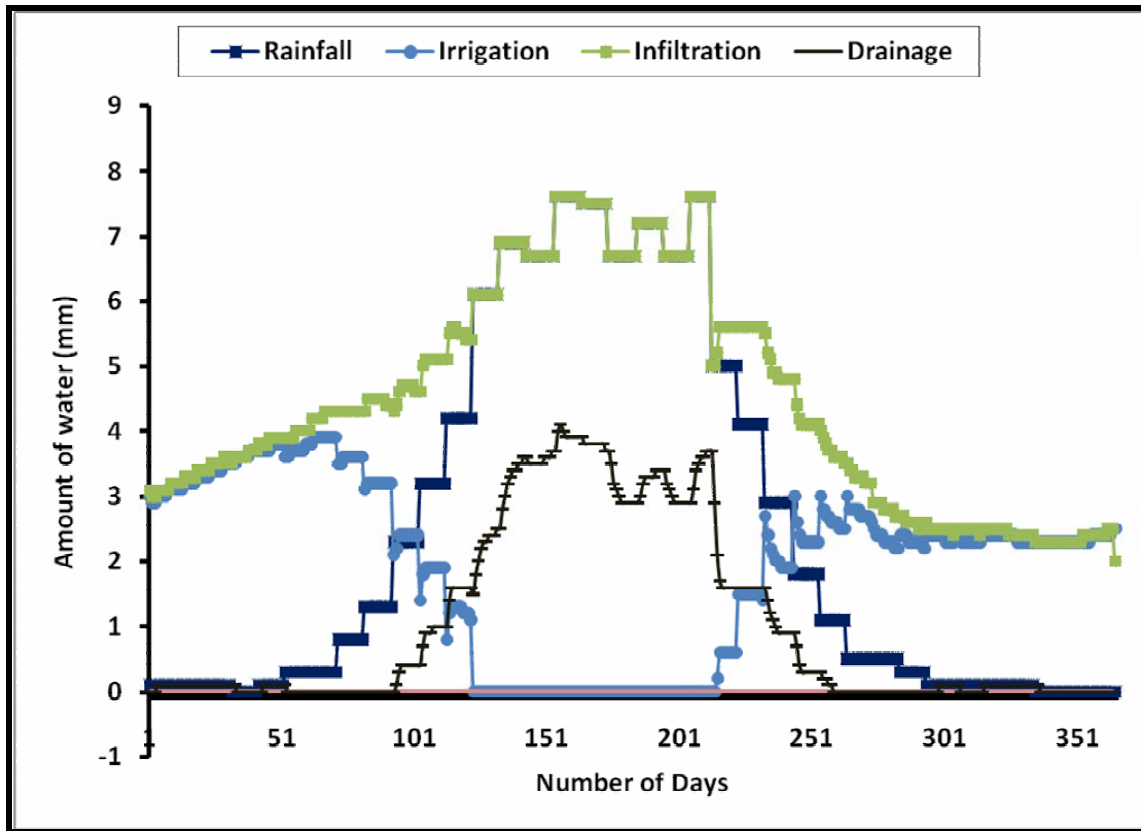


Figure 4.15: BUDGET simulated soil water balance terms under normal conditions

Rainfall input into the soil under normal conditions begins around day 50, reaching its peak of about 7.5 mm a day around day 150. Rainfall input end around day 300. The initial irrigation amount is 3 mm reaching a peak of 4 mm around day 75. Irrigation is terminated from day 120 to day 220 and after day 220, irrigation is resumed. Infiltration increases gradually from day 1 to reach a maximum of 7.5 mm around day 150 and then drops to 2.5 mm at the end of the season. Drainage losses are experienced from day 90 to day 250. The maximum drainage loss is 4 mm.

4.5.3 Hot and dry condition

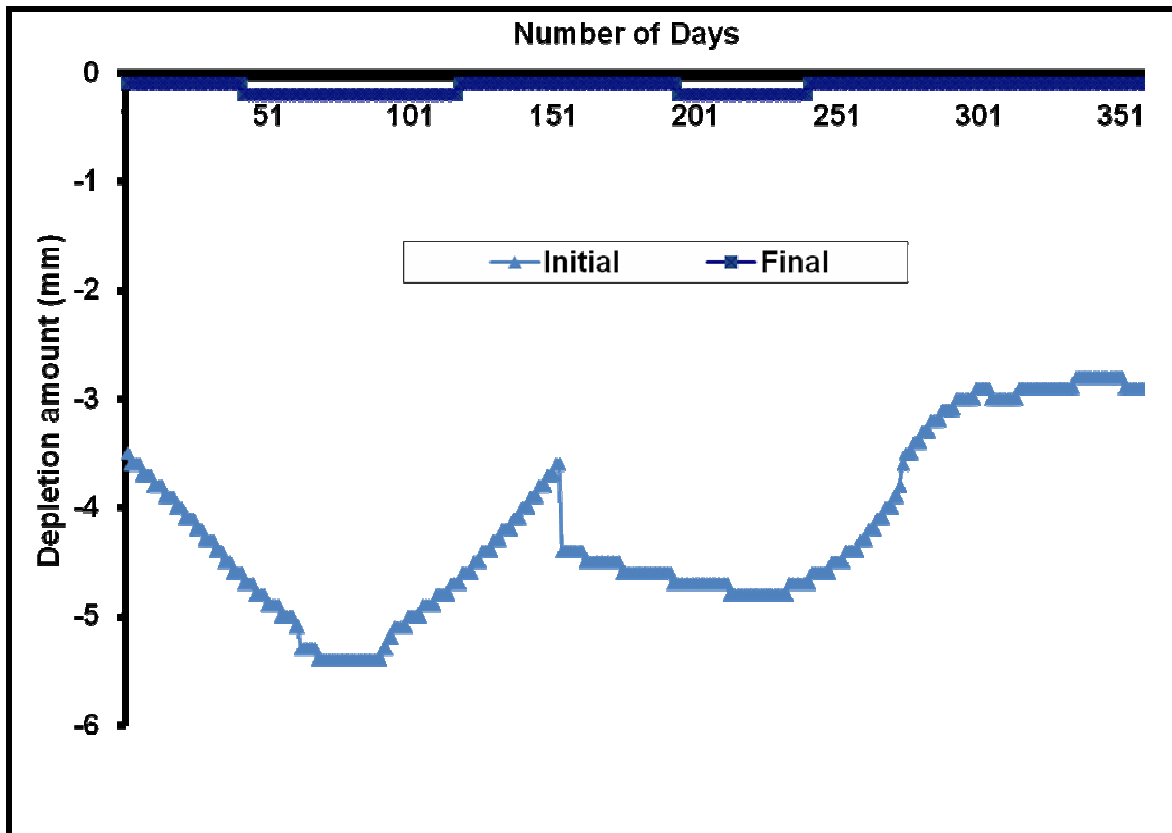


Figure 4.16: BUDGET simulated initial and final soil moisture depletion under hot and dry conditions

The final moisture depletion throughout the whole season is zero indicating a soil environment of almost field capacity. This condition is achievable because irrigation is the only input into the soil system. The initial depletion amount reaches a peak of approximately 5.5 mm (Figure 4.16) from day 60 to about day 90 and is reduced to 3.7 mm around day 150. The minimum initial depletion amount of 2.8 mm is experienced at the end of the season.

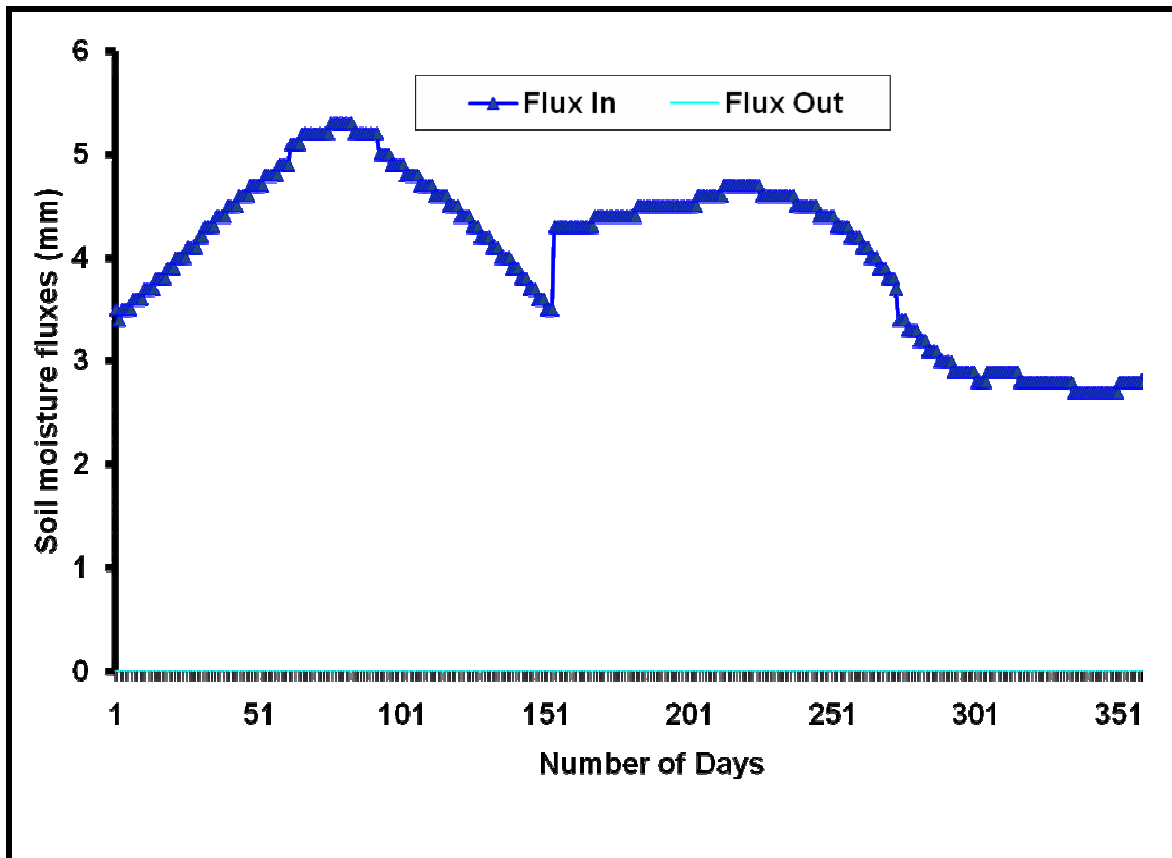


Figure 4.17: BUDGET simulated water movement in and out of the root zone under hot and dry conditions.

All the water applied (through irrigation) is held and used within the root system hence there is no water movement out of the root zone throughout the season (Figure 4.17). Water input follows the same pattern as the initial depletion for the reasons already given. Since irrigation is the only input into the root zone, the infiltrated water is the same as the irrigation amount (Figure 4.18). Drainage from the root zone is zero.

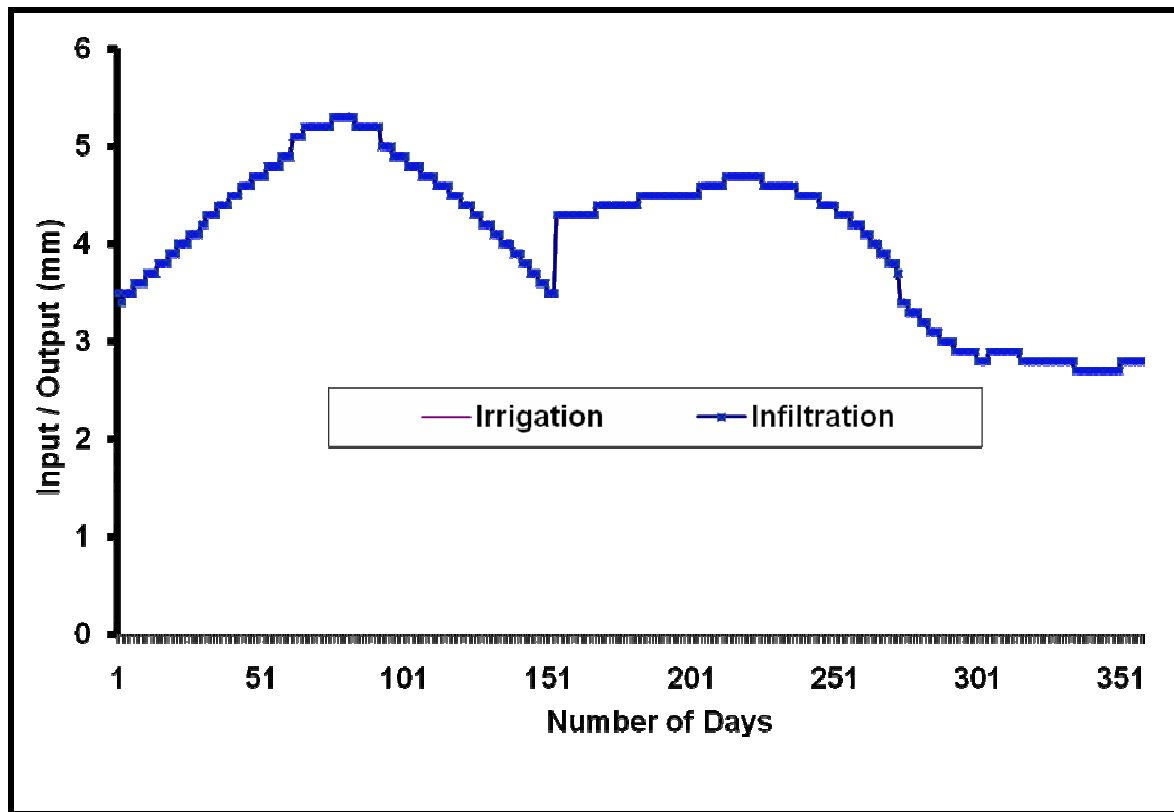


Figure 4.18: BUDGET simulated soil water balance terms under hot and dry conditions

4.5.4 Cool and humid condition

The soil moisture status in a cool and humid climate is outlined in Figures 4.19, 4.20 and 4.21 representing the soil moisture depletion, water movement in and out of the root zone and terms of the soil water balance respectively. There is a low initial depletion amount of 2 mm at day 1, increasing gradually to nearly 5 mm on day 100. From day 100, the initial depletion amount rises steeply to 25 mm day⁻¹ around day 150 for almost 60 days. This rise is associated with the large rainfall amounts experienced during this period. After day 250, the initial depletion amount falls back to about 2 mm a day indicating the end of the rain season. From day 1 to day 100, the final depletion amount is zero. From approximately day 100 to day 240, there is a peak final depletion of almost 15 mm. During this period, the soil water

content will be above the FC. The soil moisture level will return to FC from day 250 to maturity.

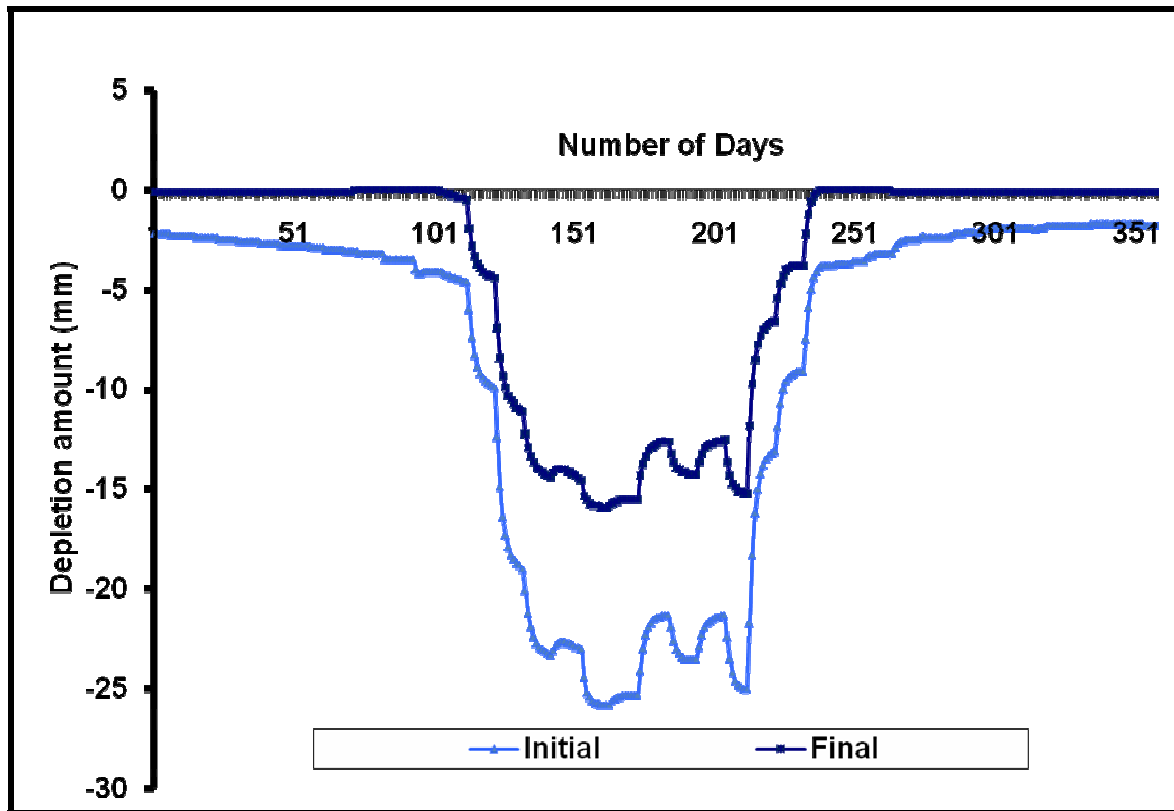


Figure 4.19: BUDGET simulated initial and final soil moisture depletion under cool and humid conditions

Water input reaches a peak of 10 mm per day from day 150 to 200. Before and after this period, the moisture input is nearly 2 mm reflecting that low irrigation levels are associated with the cool and humid condition. Water flow out of the root zone is maximum (almost 7 mm day⁻¹) for about 70 days from day 150. After day 250 and before day 80, there will be no water movement out of the root zone.

The rainfall input reaches a maximum of approximately 10 mm day⁻¹ for almost 5 decades. The rains start at around the 10th decade and ends around the 25th decade. Because of the high input and long duration of rainfall, irrigation levels are relatively low (a maximum of 2.5 mm

day⁻¹). For almost 15 decades from the 10th decade, there is no need for irrigation. Drainage losses are high (7 mm day⁻¹) during the same period as the peak of rainfall.

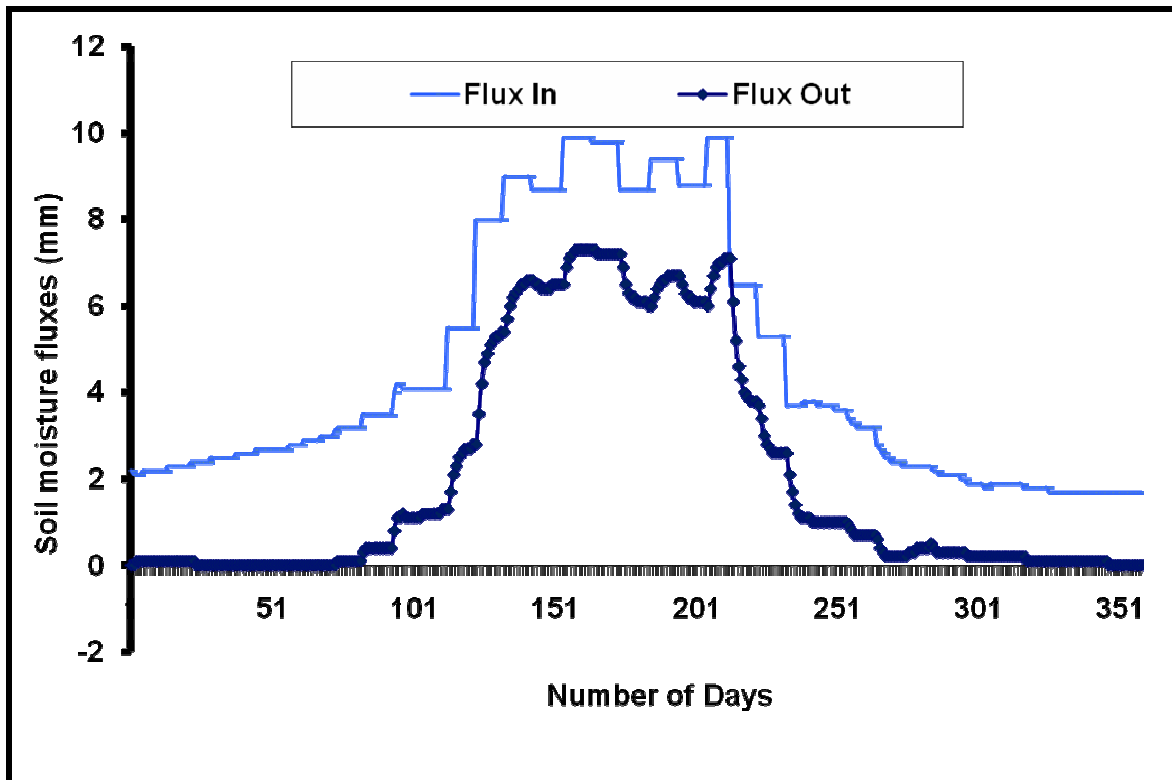


Figure 4.20: BUDGET simulated water movement in and out of the root zone under cool and humid conditions.

There are no drainage losses during the first 8 decades and the last 6 decades. For most of the growing season, water is being lost because the crop requirements will be relatively depressed by the low evaporative demand. Generally high infiltration amounts are expected since there will be high input of water (through rainfall) into the soil system.

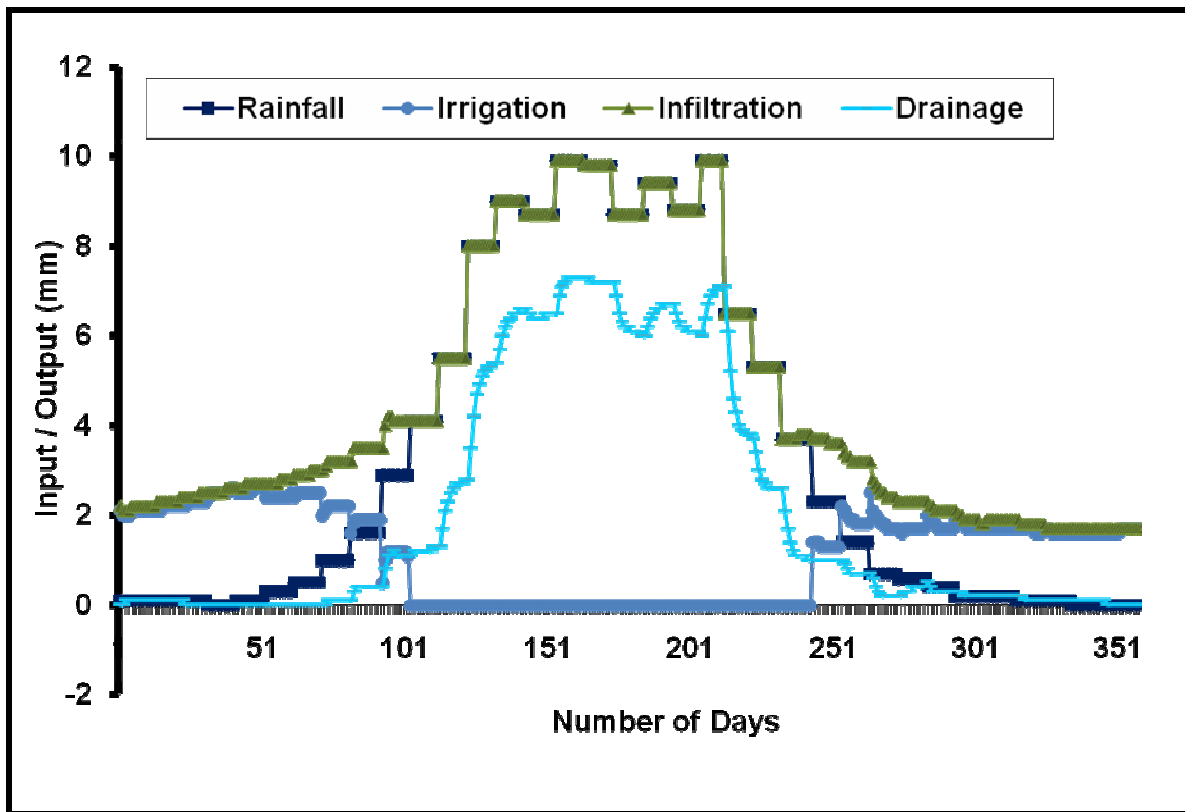


Figure 4.21: BUDGET simulated soil water balance terms under cool and humid conditions

4.5.5 Dry condition

Under dry conditions, the soil moisture level will relatively be at FC throughout the season (Figure 4.22). The initial soil moisture depletion (irrigation water requirements) is generally high with a starting value around 3.5 mm and a peak initial depletion amount of 6.8 mm a day. There is much dependence on irrigation in order to meet the crop water requirements.

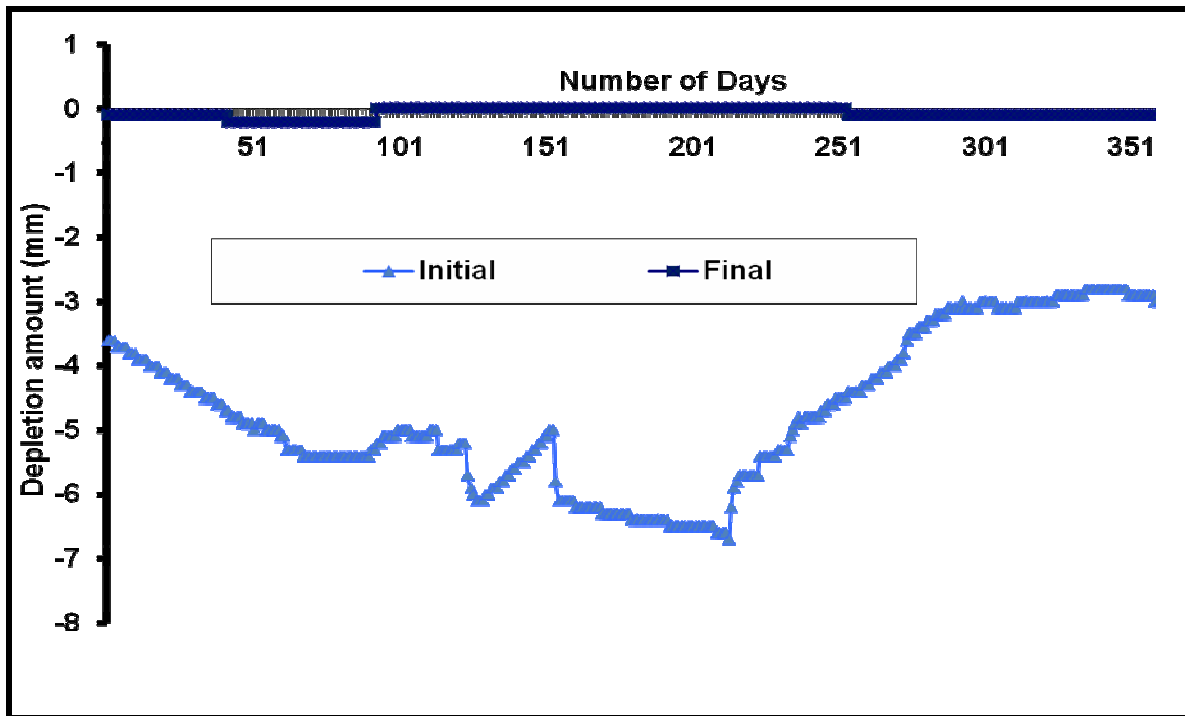


Figure 4.22: BUDGET simulated initial and final soil moisture depletion under dry conditions

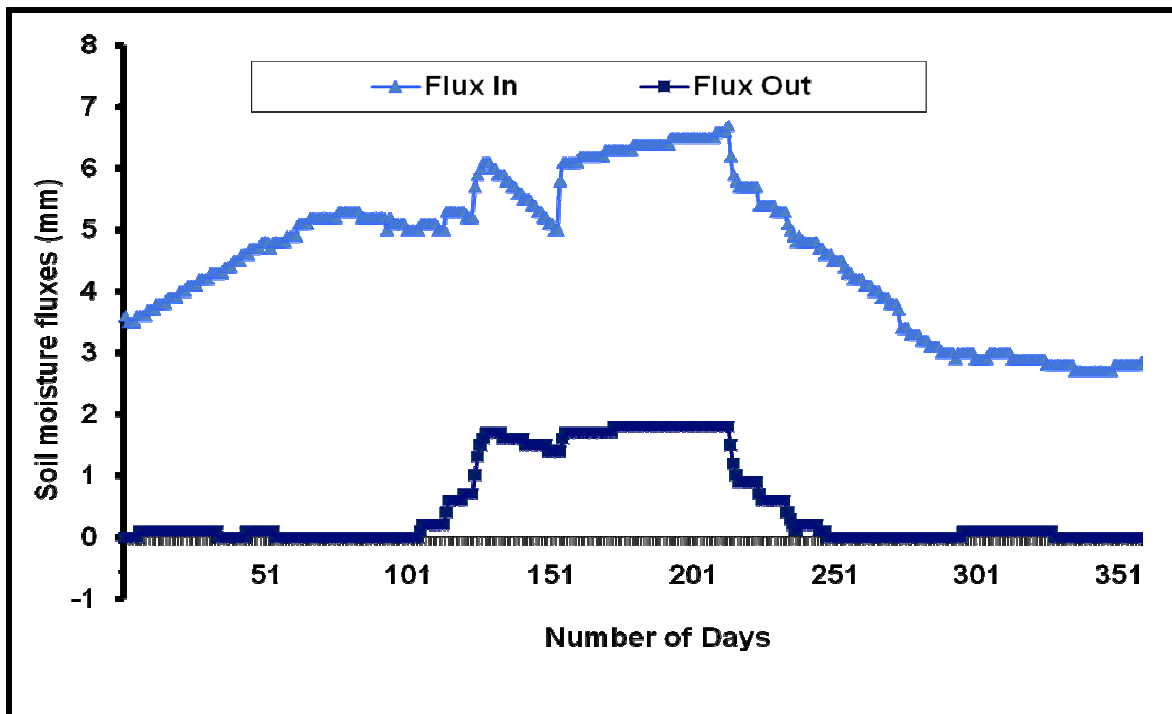


Figure 4.23: BUDGET simulated soil moisture movement into and out of the root zone under dry conditions.

There are generally very low values of water movement out of the root zone (< 2 mm) at peak and as a result, drainage losses are very low during dry conditions (Figure 4.23). For the major part of the season (the first 10 decades and the last 11 decades), there is no water flow out of the root zone. Soil moisture input to the root zone is relatively high with values above 5 mm a day for most of the season.

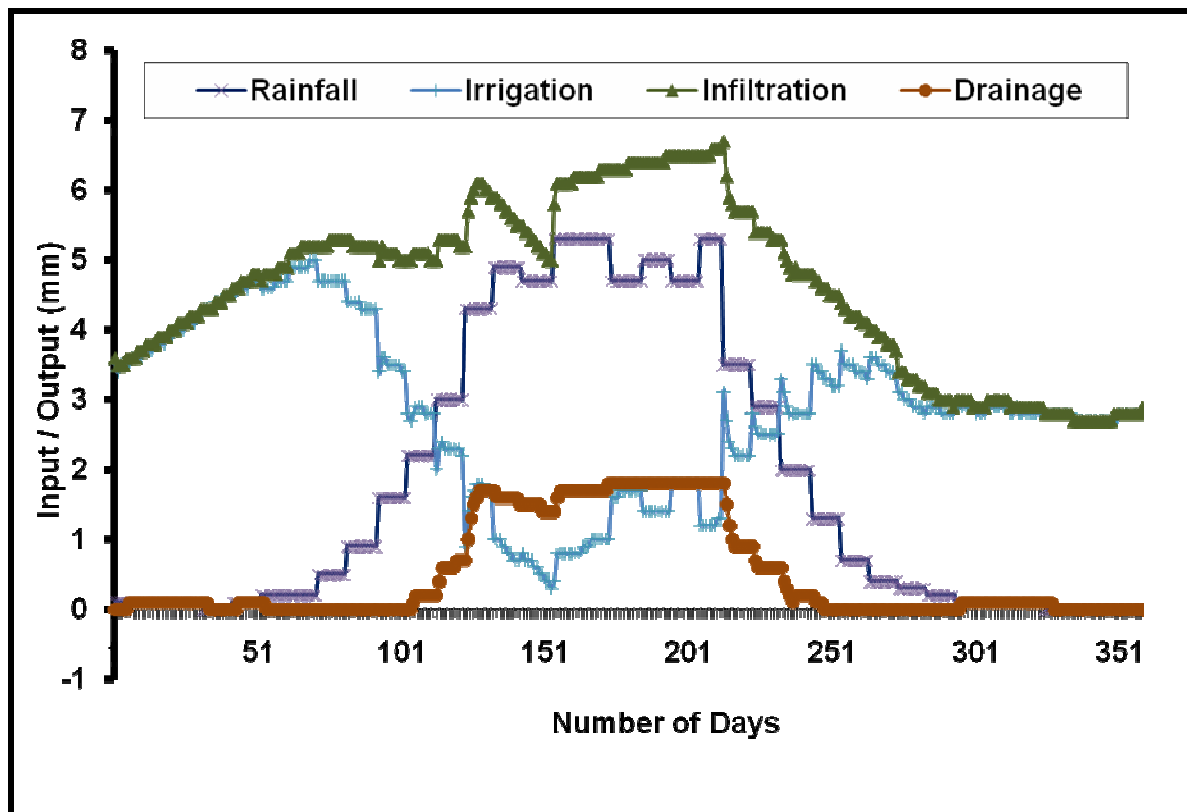


Figure 4.24: BUDGET simulated soil water balance terms under dry conditions

The soil water balance of the irrigation guidelines under dry conditions is outlined in Figure 4.24. The rainfall input into the water balance is low throughout the season with a maximum value of approximately 5 mm a day. Although the rainfall season seems to be long, the resultant rainfall amounts are low. High irrigation levels are anticipated throughout the season. Irrigation will still be required even during the rain season. Infiltration levels are

moderate and even close to that under normal conditions. Drainage losses are also very low (< 2 mm a day) during peak values.

4.5.6 Irrigation calendars

Irrigation calendars were produced for a citrus growing season beginning during the first decade of August. A fixed irrigation interval of one day was used. This was done for operational purposes. An irrigation interval of more than one day results in longer irrigation duration and this is usually not practical. Depending on the drip line specifications, the irrigation duration may be very long and usually disrupted by power cuts. With shorter irrigation duration, irrigation can be timed to periods where there will be uninterrupted power supplies.

Irrigation amounts shown in the calendars were based on a depth criterion of back to FC. The initial soil water content was assumed to be at FC. The irrigation calendar for the whole season was divided into three segments (Figures 4.25, 4.26 and 4.27) for the first trimester, second trimester and third trimester respectively. The calendars show irrigation depth instead of duration because of the differences in the design of drip lines. Irrigation duration is affected by the drip line emitter discharge and emitter spacing. The determination of irrigation duration for specific emitter discharge and spacing is shown in Appendix 3.

Month		August			September			October			November			
Decade (10 days)		1	2	3	1	2	3	1	2	3	1	2	3	
Actual weather condition	Hot and dry	3.8 mm		4.4 mm		4.9 mm		5.2 mm			4.6 mm			
	Dry	3.7 mm		4.2 mm	5.0 mm					4.4 mm	3.6 mm	3.0 mm	2.3 mm	
	Normal	3.0 mm	3.5 mm		3.8 mm					3.2 mm	2.4 mm	1.9 mm	1.2 mm	
	Humid	2.2 mm			2.6 mm				2.2 mm		1.2 mm			
Growing stage		1 Bud break, Shoot elongation, Flowering, Fruit set begins							2 Flowering, Fruit set, Fruit growth (cell division)					
Sensitivity to water stress		Very sensitive							Very sensitive					
Irrigation interval is 1 day														

Figure 4.25: Irrigation calendar for the first trimester of citrus production. 1 and 2 are the initial and crop development stages respectively

Month		December			January			February			March		
Decade (10 days)		1	2	3	1	2	3	1	2	3	1	2	3
Actual weather condition	Hot and dry	4.2 mm	3.6 mm		4.6 mm								
	Dry	1.8 mm	1.0 mm				1.8 mm		1.2 mm	3.0 mm			
	Normal										1.5 mm		2.0 mm
	Humid												
Growing stage		2 Fruit let drop (Fruit set), cell expansion			3 Cell expansion								
Sensitivity to water stress		Very sensitive			Moderate sensitivity								
Irrigation interval is 1 day													

Figure 4.26: Irrigation calendar for the second trimester of citrus production. 2 and 3 refers to the crop development and mid season stages respectively.

Month		April			May			June			July		
Decade (10 days)		1	2	3	1	2	3	1	2	3	1	2	3
Actual weather condition	Hot and dry	4.0 mm			3.5 mm	3.0 mm							
	Dry	3.5 mm			3.0 mm								
	Normal	3.0 mm			2.5 mm								
	Humid	1.4 mm	2.0 mm										
Growing stage		3 Maturation			4 Maturation								
Sensitivity to water stress		Moderate sensitivity			Moderate sensitivity								
Irrigation interval is 1 day													

Figure 4.27: Irrigation calendar for the last trimester of citrus production. 3 and 4 refers to the mid season and the late season stages respectively.

4.5.7 Grower's practice soil water status

The grower's irrigation depths throughout the season were input into the model (BUDGET) and the projected soil moisture status is given in Figures 4.28, 4.29 and 4.30

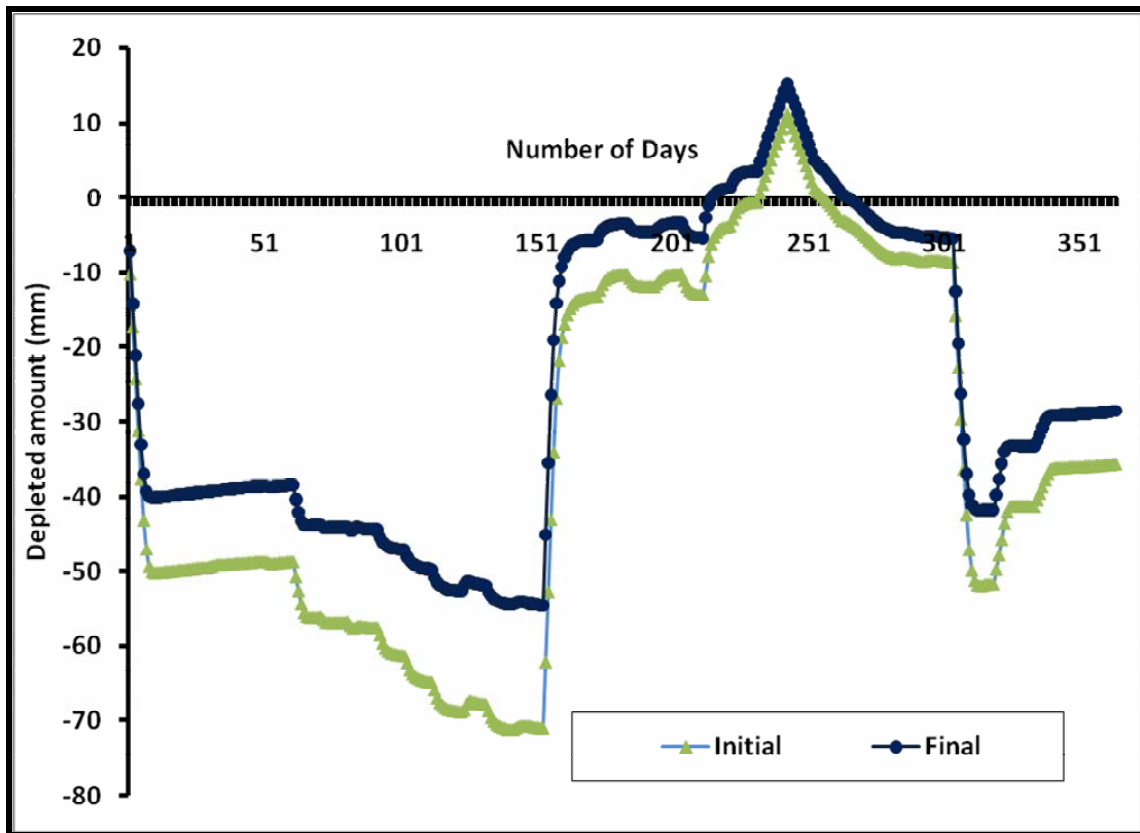


Figure 4.28: BUDGET simulated initial and final soil moisture depletion under normal conditions considering the grower's irrigation scheduling practices.

The grower's scheduling practices is a reflection of soil moisture conditions that are usually above the FC (Figure 4.28) since the final depletion is usually greater than zero. Final depletion amounts of high as 55 mm day^{-1} show that a lot of water is being added into the soil. The level of irrigation is high and is compatible with a 2 day or 3 day irrigation interval. The margin between the initial and the final depletion is very low indicating that more water is being applied than the water requirements of the trees. It is assumed that the grower's guidelines were developed under very extreme weather conditions and non limiting irrigation water conditions.

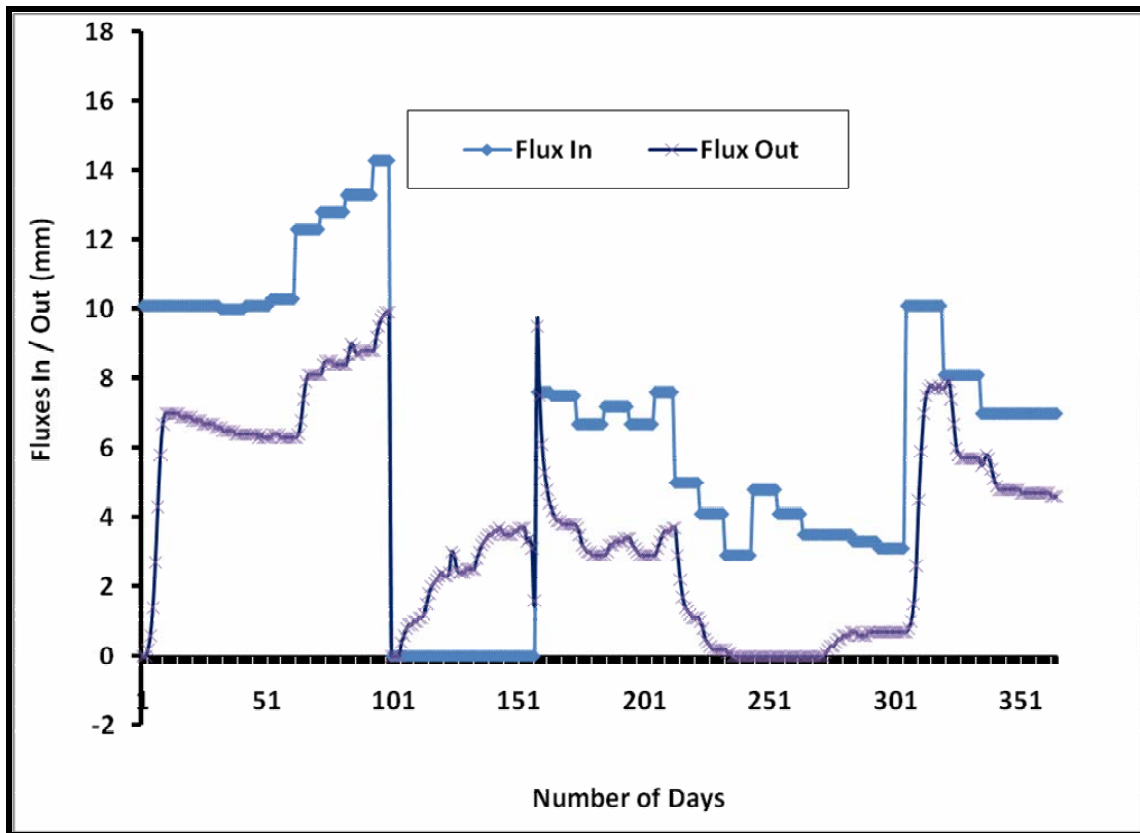


Figure 4.29: BUDGET simulated soil moisture movement in and out of the root zone under normal conditions considering the grower's irrigation scheduling practices.

This irrigation scheduling practice is not economic and adds no value in terms of fruit yield and quality. Excess application of water can have negative impacts on the quality and yield of the fruit. There are operational constraints mainly due to the need for high water use efficiency especially during these periods of increased pressure on water resources. Weather varies from season to season and even from day to day and hence there is need to have irrigation guidelines that take into account the water requirements under specific weather conditions. A water deficit condition is predicted for almost 3 decades from day 220 (Figure 4.28).

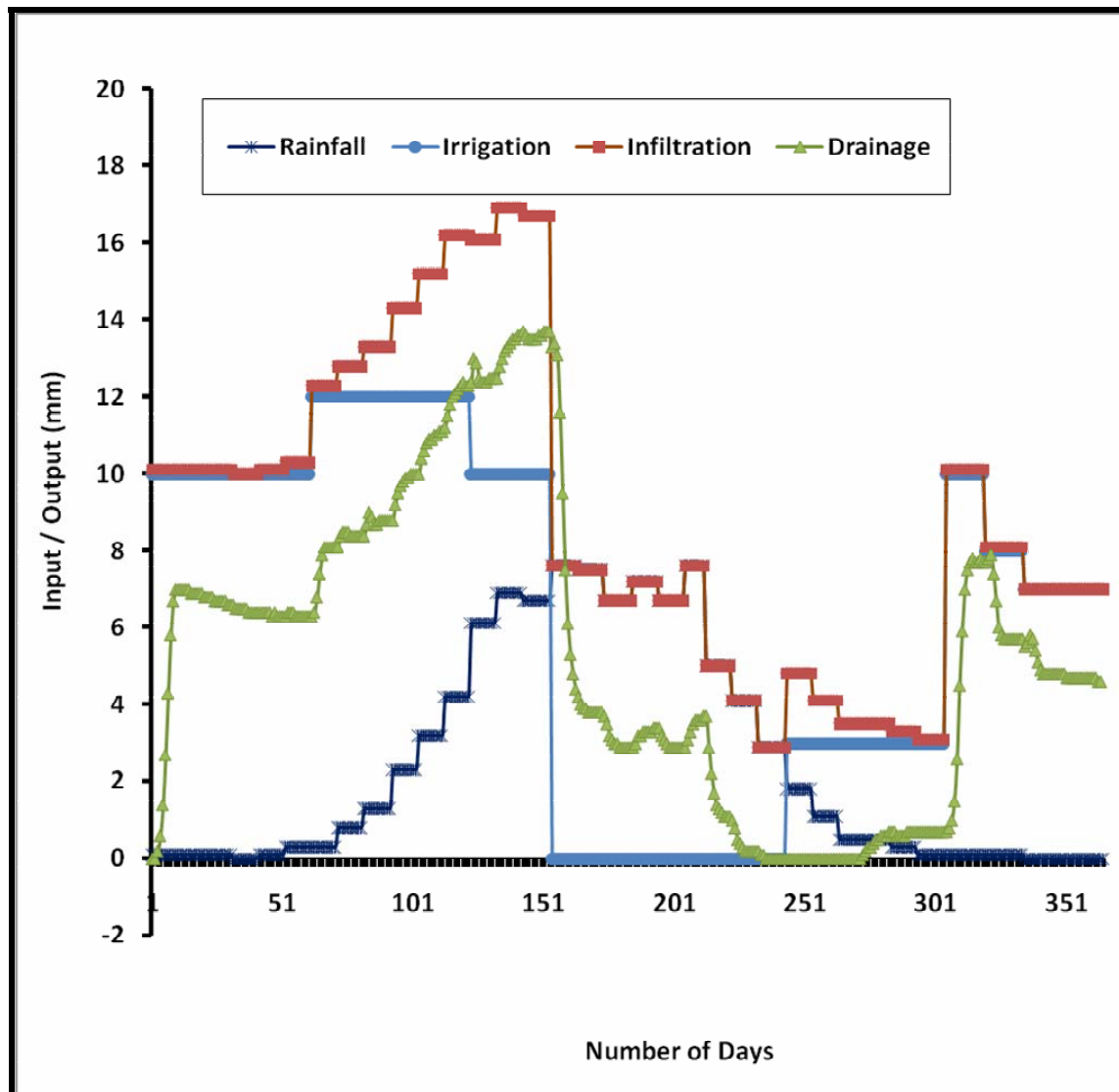


Figure 4.30: BUDGET simulated soil water balance terms under normal conditions considering the grower's irrigation scheduling practices.

There are generally very high soil water flows out of the root zone with a peak of about 10 mm a day (Figure 4.29). The high drainage losses of as high as 14 mm a day are as a result of the excessive application of irrigation water (Figure 4.30). These losses can be very high under cool and humid conditions. This type of scheduling is short coming because there are even drainage losses when it is not raining. From day 240 to day 270, the irrigation level is appropriate since there are no drainage losses.

4.6 Comparison of the irrigation guidelines with the grower's practice

The comparison of the soil water status was done under normal weather conditions only and this serves as a guideline for all weather conditions. After receiving the same total rainfall amount of 926.6 mm, the projected drainage losses, water deficiency and irrigation requirements are outlined in Table 4.4. The grower's practice total irrigation amount is too much and approximately only a third (of 2322 mm) is required for the whole season. The application of excess water is the major cause of the high drainage losses beyond the root zone under the grower's practice. The drainage losses could be reduced if the irrigation guidelines are implemented.

Table 4.4: Irrigation requirements, drainage losses and water deficiency under normal conditions for irrigation scheduling guidelines and grower's practice.

Scheduling Method	Total Rainfall	Total Irrigation	Total Drainage Losses	Drainage loss duration	Total water deficiency	Water Deficiency duration
	(mm)	(mm)	(mm)	(days)	(mm)	(days)
Guideline	926.6	709.5	381	150	-	-
Grower's practice	926.6	2322	1963.9	290	275.1	49*

* From first decade of March to second decade of April.

These high drainage losses cause the leaching of plant nutrients and consequently affect fruit yield and quality. There are however, drainage losses of 381 mm under the irrigation scheduling guidelines. These losses are experienced during the rain season where there is uncontrolled input of water into the soil system. With proper scheduling, about 1582.9 mm would have been saved. The drainage losses can be even higher under cool and humid conditions. For nearly 290 days, there will be drainage losses considering the grower's scheduling practices compared to almost 150 days considering the irrigation scheduling guidelines. Water deficiency of about 275 mm is experienced from the first decade of March

to the second decade of April. This deficiency coincides with the cell expansion to maturation stages that are moderately sensitive to water stress and hence does not affect yield and growth. It is actually a form of regulated deficit irrigation. Under hot and dry and dry conditions, this deficiency can lead to reduction in fruit quality and yield.

4.7 The effect of irrigation strategies

The irrigation strategies under consideration were the well watered, control, grower's practice and PRD 50 %. The assessment period was from October 2009 to December 2009. Irrigation strategies were compared in terms of fruit diameter growth rate and fruit abscission against the irrigation water used.

Table 4.5: Total irrigation water received per treatment per hectare from October 2009 to December 2009.

Treatment	Total water received (ML/Ha)
Control	2.6
Well – watered (Both sides of the tree irrigated, each line delivering half the quantity of water as the control).	2.6
Grower's practice	3.06
PRD: 2 drip lines applying half of control	1.3

4.7.1 Effects of irrigation treatments on yield variable

There were no significant differences ($p < 0.05$) between the fruit growth rates among all the treatments (Table 4.6). The control treatment however, exhibited the highest fruit diameter compared to other treatments (Figure 4.31). This may be linked to the fact that the trees required adequate water especially during the critical phases of flowering and fruit set. The trees were irrigated according to the evaporative demand of the atmosphere. The fruit diameter growth rates are shown in Fig. 4.31. The well watered treatment; the grower's practice and PRD 50 % do not show much difference in fruit diameters. The well-watered

treatment did not perform well may be because of restricted irrigation depth. Although both sides of the tree row were irrigated, the halved irrigation duration resulted in some water deficiency that restricted fruit growth. The PRD treatment supplying half the amount of water as the control also had reduced fruit growth rate. This may be due to water deficiency especially during the critical stages of fruit development.

The PRD method however, has potential in balancing fruit yield and water conservation if the PRD is correctly timed. An improved growth rate may have been realised if PRD was initiated after the flowering and the fruit set stages. At exactly half the amount of water applied as the control and well watered treatment and almost 42 % of the grower's practice (Table 4.5), the PRD performed even slightly better than the well watered and the grower's practice. Although the grower's practice used about 15 % more water (Table 4.5) as the control, this did not have any advantage towards fruit growth during this period. This may have been due to limited aeration (soil moisture condition usually above FC) thereby affecting root respiration and subsequent growth and development.

Table 4.6: The effect of irrigation treatments on fruit growth rate.

Treatment	Mean Fruit diameter (cm)
Control	5.571 ^a
Well watered	5.146 ^a
Grower's practice	5.140 ^a
PRD 50 %	5.228 ^a

The fruit growth rates were not significantly different from the control at $p (\leq 0.05)$

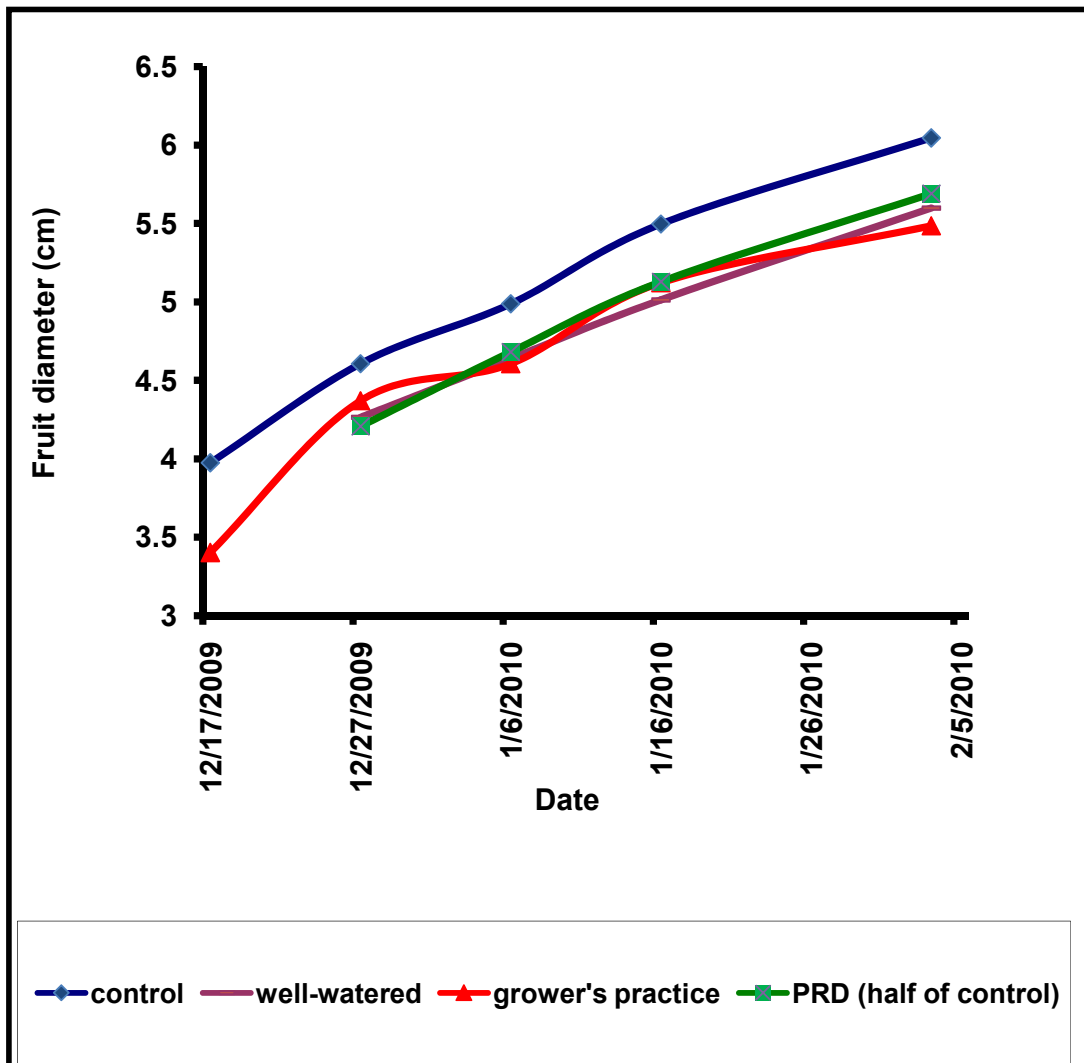


Figure 4.31: Fruit growth rates of the control, well – watered, grower’s practice and PRD applying half of the control from 16 December 2009 to 03 February 2010.

4.7.2 Fruit drop

The fruit drop was generally low for all the treatments with a highest value of 10 % (Figure 4.32) although the grower’s practice and well watered had higher fruit drops. The well watered treatment, with half the amount of water as the control applied on both sides of the tree (although the total amount was the same), might have induced a form of stress that resulted in the doubling of fruit drop. Despite the fact that the grower’s irrigation scheduling practise was over irrigating, the fruit drop is higher than the control. The PRD 50 treatment

had the same fruit drop as the control. It is assumed that the PRD 50 treatment had adjusted to the water deficit condition through the root to shoot chemical signals and has proved to be a better method of deficit irrigation than the application of reduced amount of water on both sides of the tree.

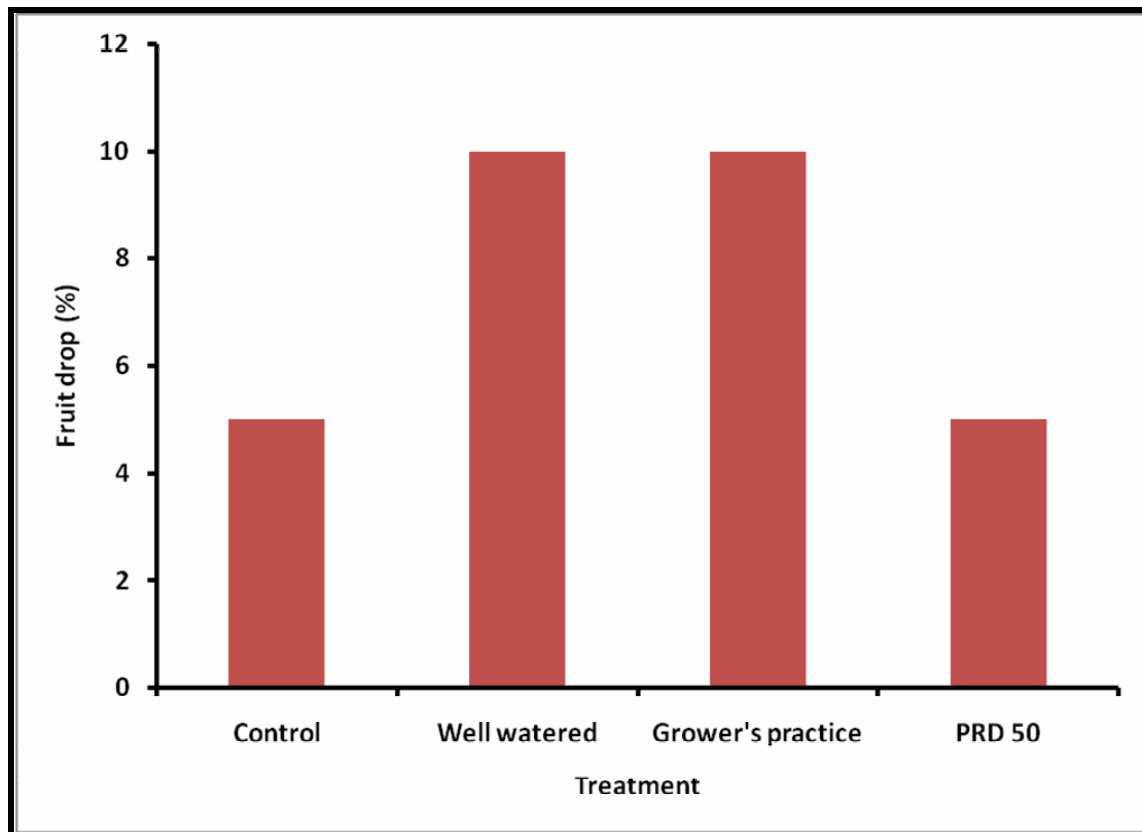


Figure 4.32: Treatment effects on fruit abscission monitored from the first decade of December to the first decade of January at MCE.

4.8 Summary

The outcomes of the experiments described in chapter 3 are presented in this chapter. The k_{pan} was found to range between 0.72 and 0.82 and that it changes throughout the season. The K_c curve for the entire season of citrus production was produced as well as the K_c values per decade. Whole day transpiration rates were given for two days and were found to match

to the irrigation depth recommended (irrigation calendar) for that period. The soil water status of the developed irrigation calendars was projected for the actual weather condition of the day. The soil water status was presented in terms of the soil moisture depletion, movement of water in and out of the root zone and the soil water balance. Irrigation calendars of the whole season for a fixed irrigation interval of 1 day were presented in terms of the actual irrigation depth the corresponding weather condition of the day. A comparison of the total irrigation water required under the grower's scheduling practice and that required using irrigation guidelines was done. The effect of the different irrigation strategies on fruit growth rate and abscission concludes the contents of chapter 4.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.0 CONCLUSIONS

The FAO Penman Monteith ET_o for the study site was between 4 and 4.5 mm day⁻¹ from January to April. From May to early August, ET_o was approximately 3 mm day⁻¹. Peak ET_o values (up to 5.5 mm day⁻¹) were experienced around October. ET_o for the study site ranged between 3 mm day⁻¹ and 5.5 mm day⁻¹.

Zimbabwean citrus farmers without sophisticated equipment and the required expertise are able to do daily ET_o estimations using the class A evaporation pan. More accurate estimations of ET_o using the evaporation pan are possible if site specific pan coefficients are used. It was observed that a single K_{pan} value cannot be used throughout the season since it changes throughout the season. The K_{pan} for the study site was found to be highest in January and lowest in October i.e. 0.82 and 0.72 respectively.

The main factors controlling the K_{pan} values are the fetch condition, the mean wind speed at 2 m height and the mean relative humidity. K_{pan} values follow almost the same trend as the mean RH. K_{pan} can also be successfully estimated from a plot of the FAO Penman Monteith ET_o against pan evaporation. This method can be applied for sites without or with unreliable RH and wind speed data.

The local $K_{c\ ini}$ for citrus is low (0.47) during the initial stage (spring) where there is shoot initiation. During the crop development stage, K_c rises rapidly and changes every decade because of the higher demand for water for flowering and fruit set. K_c changes during this stage should be noted to avoid inaccurate estimations of ET_c . Peak K_c values (0.84) occur during the mid season stage. K_c values after the mid season stage decrease gradually as reflected by a $K_{c\ end}$ value of 0.76.

The irrigation depth varies significantly during each day after considering the actual weather condition. It is essential to take into account the actual weather condition for a particular day for efficient irrigation scheduling. A variation in irrigation depth of up to 3 mm day⁻¹ is possible if the actual weather condition is not taken into consideration. This results in both unregulated water deficit and over irrigation. Both scenarios are not desirable for citrus production. The seasonal or monthly irrigation scheduling guidelines (blanket recommendations) should therefore be replaced by the developed irrigation calendars. During the rain season, irrigation can only be terminated under normal and humid conditions alone. During the dry condition, irrigation depth can only be reduced during the rain season. If the weather is hot and dry, irrigation is required throughout the season even during the rainfall season.

The grower's irrigation scheduling practices usually resulted in soil moisture conditions above the FC. The irrigation depths are not compatible with a 1 day irrigation interval. Almost a third of the current irrigation depth is required under normal weather conditions. The excessive application of water results in high drainage losses. Irrigation depth was reduced after considering the developed irrigation calendars.

There were no significant differences ($p < 0.05$) in the fruit growth rates of the well watered, control, PRD 50 and the grower's practice. The only difference was in the fruit sizes where the control produced the largest fruit diameters. The conventional irrigation scheduling was the better method compared to the other methods under consideration. The PRD 50 method showed great potential at balancing water use and fruit size. PRD was done during the flowering and fruit set stage and if it was well timed (linked to the less critical growth stages), it could have been better than the control. PRD could have done better may be at PRD 75 / 80. Applying water to both sides of the tree (well watered) was not beneficial especially when

the irrigation depths are low. Halving the irrigation duration resulted in low irrigation depths and the fact that both sides were irrigated did not offer any advantage at all. Increasing the irrigation duration on both sides may lead to the use of more irrigation water and this is not sustainable. The grower's irrigation scheduling practice of applying excess water was not beneficial to the fruit as the fruit diameters were even less than those of the control.

5.1 RECOMMENDATIONS FOR FURTHER STUDIES

Although the modelled soil moisture status using the developed irrigation calendars gave a forecast of the soil water movement and balance, future research may look into the soil water dynamics of the citrus trees using the irrigation calendars. Substantial amount of water was projected to be lost through drainage especially during the rain season and the loss is even more under humid conditions. Devising ways by which the excess water received through rainfall can be harvested in the orchards may be beneficial.

Future research may also be aimed at assessing the feasibility of the installation of sub surface drainage systems to enable the harnessing of the drained water for reuse during periods of need. More research should be linked to the use of PRD as a drip irrigation strategy. The research should look at the best timing of the PRD as well as the right deficit level for the growth stages of the citrus crop. Since the daily water requirements of citrus is linked to the actual weather condition of a particular day, future research can assess the possibility of automating irrigation of citrus using sap flow.

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APPENDICES

APPENDIX 1: Day of the year (Julian days) calendar

Month Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29		88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365

Add 1 to unshaded values during leap years

APPENDIX 2: Determination of K_{pan} using RH_{mean} , U_2 and FET

Month	RHmean (%)	U2 mean m/s	ln (RH mean)	FET m	ln (FET)	ln (86.4U2)	Kpan dry fetch	Kpan green fetch
January	89.02	1.0809	4.48882366	15	2.708	4.536782	0.7839	0.8142
February	81.5	1.07243	4.40056216	15	2.708	4.528918	0.7599	0.8022
March	84.07	1.0076	4.43164979	15	2.708	4.466559	0.7711	0.8084
April	76.7	0.8875	4.33990171	15	2.708	4.339641	0.7526	0.7991
May	75.2	0.8746	4.32008474	15	2.708	4.324999	0.7482	0.7967
June	70.5	1.15173	4.25565994	15	2.708	4.600255	0.7211	0.7799
July	65.56	1.1603	4.18296575	15	2.708	4.607666	0.7049	0.7695
August	62.66	1.22567	4.13767014	15	2.708	4.662473	0.6930	0.7614
September	53.05	1.47637	3.97129763	15	2.708	4.848572	0.6536	0.7311
October	52.67	1.61927	3.9640935	15	2.708	4.940961	0.6477	0.7260
November	68.11	1.4632	4.22112405	15	2.708	4.839613	0.7018	0.7662
December	83.12	1.0853	4.42028535	15	2.708	4.540844	0.7646	0.8046

RH_{mean} is the mean monthly relative humidity (%), FET is the fetch (m) and U_2 is the mean monthly wind speed at 2 m height.

APPENDIX 3: Determination of the irrigation duration from October to December 2009

The duration of irrigation events at the experimental site was calculated using orchard characteristics, drip line specifications and the evaporative demand of the atmosphere. Tree spacing in the orchard is approximately 2.75 m in each row, with an inter-row spacing of approximately 6 m. The trees were surface drip irrigated using standard 15 mm polypropylene dripper lines with pressure compensated button emitters delivering water at a rate of 1.7 L/h. The emitter spacing along the line is 0.3 m. The irrigation depth for October was calculated using potential evapotranspiration, ET_o data of the same site from past studies. A daily average ET_o value of 5.5 mm for October was used for the determination of irrigation duration. Since there is a smaller variation in the extend of vegetation cover throughout the year in citrus because its evergreen (Allen *et al.*, 2004), a constant value for the crop coefficient, K_c was used. For citrus, an assumed K_c value of 0.7 was used (Allen *et al.*, 2004; Dzikiti, 2007). The mean daily crop evapotranspiration, ET_c (irrigation depth), for the month of October was determined using equation 1.

$$\begin{aligned} ET_c &= ET_o \times K_c \\ &= 5.5 \text{ mm day}^{-1} * 0.7 \\ &= \mathbf{3.85} \text{ mm day}^{-1} \end{aligned} \tag{1}$$

The irrigation duration for the control was calculated by considering a hypothetical one-hectare area of the orchard with simplified dimensions of 100m * 100 m. given the fact that the rate of emission of water by the drippers is 1.7 L/h and if we consider an irrigation event lasting X hours, then the total volume of water, V_w applied per hectare in litres is

$$V_w = X \times 1.7 \times n \quad (2)$$

Where n is the total number of emitters per hectare and is given by:

$$n = \frac{100}{0.3} \times \frac{100}{6} \quad (3)$$

$$= 5\,555.55 \text{ emitters}$$

The fraction of the orchard that is irrigated can be estimated by considering the region between four emitters in neighbouring tree rows. The wetted region around each emitter is almost elliptical extending approximately 1.0 m along the major axis of the ellipse at right angles to the drip line and 0.375m along the minor axis parallel to the drip line (Dzikiti, 2007).

$$\text{The wetted fraction of the soil} = \frac{\pi \times 0.375 \times 1.0}{6 \times 0.3} \approx 0.65 \quad (4)$$

$$\text{Irrigation depth} = \frac{V_w}{10000 \times 0.65} \quad (5)$$

Since the irrigation depth is 3.85 mm day^{-1} , $V_w = 25\,025$ litres. From equation 2, the irrigation duration, X is

$$X = \frac{V_w}{1.7 \times n} \quad (6)$$

$$= \frac{25025}{1.7 \times 5555.55} \approx 3 \text{ Hours}$$

APPENDIX 4: The determination of the K_c curve

Determination of $K_{c\text{ ini}}$ for partial wetting of the soil surface			
During the initial stage, the trees are irrigated using drip system daily with 4.0 mm each application expressed as an equivalent depth over the field area. The average fraction of surface wet is 0.4 and little to no precipitation is expected during the initial period.			
The average depth of infiltration per event in the wetted fraction of the surface:			
$I_w = \frac{I}{f_w} = \frac{4\text{mm}}{0.4} =$	10	mm	
Therefore, the chart using light wetting events is used for the determination of $K_{c\text{ ini}}$			
For: and: $K_{c\text{ ini}}$ Fig for light events	$ET_o = 4\text{ mm/day}$ a 1 day wetting interval: $K_{c\text{ ini}} = 1.1$	4 - 1.1	mm/day - -
Contribution of rainfall during the initial period			
Mean monthly rainfall: $f_w\text{ rain}$	August September First decade of October Initial period	3 4 5 12	mm mm mm mm
$f_w\text{ rain} + f_w\text{ irrigation}$ Wetted fraction (irrigation) Wetted fraction (rainfall) Mean wetted fraction, f_w	Initial period $= \left(\frac{12 * 1}{292} \right) + \left(\frac{280 * 0.4}{292} \right) =$	292 0.4 1 0.42	mm - - -
Because the fraction of soil surface wetted by irrigation and rainfall is 0.42, the actual $K_{c\text{ ini}}$ for the initial period was calculated as:			
From equation 3.2:	$K_{c\text{ ini}} = f_w * K_{c\text{ ini fig}} = 0.42 * 1.1 =$ The value 0.47 represents the $K_{c\text{ ini}}$ as applied over the entire field area.	0.47	-

Determination of $K_{c\text{ mid}}$ under the local wind speed, relative humidity and crop height conditions			
During the mid season period, the mean wind speed is 1.06 m s^{-1} , the mean minimum relative humidity is 41.62 % and an average tree height of 3 m was observed.			
From equation 3.3:	$K_{c\text{ mid}} = 0.70 + [0.04(1.06 - 2) - 0.004(41.62 - 45)] \left(\frac{3}{3} \right)^{0.3} =$	0.84	-

$K_{c\text{ end}} = 0.75$ (The fruit is harvested as ‘green’) hence no adjustment was made to the table value. Equation 3.4 was used for the estimation of the daily K_c values during the crop development and the late season stages.

APPENDIX 5: Calculation of the amount of irrigation water used per treatment

The amount of irrigation water used per treatment was computed from October to December. During the last decade of December, irrigation was stopped because of considerable rainfall. The total amount of water used for each treatment was calculated using the emitter discharge rate of the drip lines, irrigation duration and the number of emitters per hectare. For all treatments, the emitter discharge rate was 1.7 l hr^{-1} and there were 5555.55 emitters per hectare. The only variation was on irrigation duration.

Control treatment and well watered treatment

$$\begin{aligned}\text{Emitter discharge per day} &= 1.7 \text{ l hr}^{-1} * 3 \text{ hr day}^{-1} \\ &= 5.1 \text{ l day}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Water received per hectare per day} &= \text{emitter discharge per day} * \text{number of} \\ &\quad \text{emitters per hectare} \\ &= 5.1 \text{ l day}^{-1} * 5555.55 \\ &= 28\,333.3 \text{ l}\end{aligned}$$

$$\begin{aligned}\text{Total irrigation water received (October to December)} &= 2\,606\,663.6 \text{ l} \\ &= 2.6 \text{ MI / Ha}\end{aligned}$$

For the PRD treatment applying half of the control, total water received per hectare is
 1.3 MI / Ha

Grower's practice

$$\text{Emitter discharge} = 2.3 \text{ l hr}^{-1}$$

$$\text{Emitter spacing} = 0.75 \text{ m}$$

$$\text{Number of emitters per hectare} = 2\,222.22$$

$$\text{Irrigation duration} = 6.5 \text{ hrs}$$

$$\text{Water received per hectare per day} = 2.3 \text{ l hr}^{-1} * 6.5 \text{ hrs} * 2\,222.22$$

$$= 33\,222.19 \text{ l / Ha}$$

$$\text{Total irrigation water received (October to December)} = 3.06 \text{ Ml / Ha}$$

APPENDIX 6: Determination of the average leaf area per tree

ROW	D1 cm	D2 cm	D3 cm	Mean cm	mean diameter (m)	leaf Area (m2)	row leaf area (m2)
3	11	11.4	8.4	10.26667	0.102666667	57.06496	58.61812946
	10.6	11	8.8	10.13333	0.101333333	55.30332	
	11.4	11.6	9.2	10.73333	0.107333333	63.48611	
4	11.2	10.4	10.2	10.6	0.106	61.61071	43.98249336
	6.5	6.7	6.4	6.53333	0.065333333	19.29736	
	9.6	9.8	10	9.8	0.098	51.03941	
5	11.7	7.9	8.3	9.3	0.093	45.01419	53.49550627
	10.8	10	10.3	10.36667	0.103666667	58.40737	
	10	11.3	9.5	10.26667	0.102666667	57.06496	
6	10.7	10.4	10.2	10.43333	0.104333333	59.31244	55.28531811
	9.3	9.6		9.45	0.0945	46.77549	
	10	10.1	11.3	10.46667	0.104666667	59.76802	
7	10	10.2	10	10.06667	0.100666667	54.43456	49.94515743
	9.1	8.9	9.4	9.13333	0.091333333	43.10326	
	10.4	9.5	9.8	9.9	0.099	52.29766	
8	10.3	10	10.5	10.26667	0.102666667	57.06496	49.05439566
	9.4	9	8.9	9.1	0.091	42.72686	
	10	9.6	8.9	9.5	0.095	47.37137	
9	10.9	10.7	10.9	10.83333	0.108333333	64.91422	56.78112014
	11.8	10.2	10.8	10.93333	0.109333333	66.36089	
	9	8.5	8.8	8.76667	0.087666667	39.06824	
10	8.4	8.6	9	8.66667	0.086666667	38.00775	46.80962537
	8.6	8.1	8.3	8.33333	0.083333333	34.59494	
	11	10.9	11.2	11.03333	0.110333333	67.82619	
11	10.1	9.3	8.9	9.43333	0.094333333	46.57784	50.67596747
	9.6	10	10	9.86667	0.098666667	51.87625	
	10.1	9.7	10.2	10	0.1	53.57381	
12	9	8.8	9.1	8.96667	0.089666667	41.24049	33.88140376
	8.5	8.1	7.9	8.16667	0.081666667	32.95836	
	7.4	7.7	7.6	7.56667	0.075666667	27.44536	
13	9.2	9.4	9.1	9.23333	0.092333333	44.24401	44.98776342
	8.5	8.7	9.5	8.9	0.089	40.50879	
	10	9.5	9.7	9.73333	0.097333333	50.21049	
14	7.3	7.9	7.2	7.46667	0.074666667	26.58331	31.89570686
	8.4	7.6	7.8	7.93333	0.079333333	30.74446	
	8.5	8.6	9	8.7	0.087	38.35936	
15	10.4	9.8	10.2	10.13333	0.101333333	55.30332	59.00617001
	10.9	11.3	10.7	10.96667	0.109666667	66.84725	
	10.4	10	9.9	10.1	0.101	54.86794	
16	9.4	9.8	10.1	9.76667	0.097666667	50.62396	43.30068833
	8.6	8.4	7.9	8.3	0.083	34.26392	
	9.4	9.6	8.9	9.3	0.093	45.01419	
17	9.62	8.91	9.35	9.29333	0.092933333	44.93682	43.01728596
	9.6	9.5	8.9	9.33333	0.093333333	45.40218	
	9.3	8.4	8.5	8.73333	0.087333333	38.71285	
18	10.03	9.91	9.82	9.92	0.0992	52.55145	34.91777173
	7.14	7.15	7.03	7.10667	0.071066667	23.61178	
	7.75	8.01	7.33	7.69667	0.076966667	28.59008	

Average Leaf Area/ tree = 47 m²

APPENDIX 7: Analysis of Variance for fruit growth rates

Treatments	Replications										Treatment Total, x_i	Mean $\bar{x}$
1	4.66	4.55	5.03	4.95	5.58	5.42	6.19	5.91	6.79	6.64	55.71	5.571
2	4.37	4.16	4.64	4.64	5.07	4.96	5.75	5.45	6.31	6.11	51.46	5.146
3	4.35	4.39	4.65	4.57	5.30	4.94	5.55	5.42	6.16	6.07	51.4	5.140
4	4.52	3.89	5.01	4.35	5.48	4.78	6.09	5.29	6.85	6.03	52.28	5.228
											$x_{..}$ =206.85	$\bar{x}_{..}$ =5.2713

Source of Variation	Degrees of Freedom	Sum of Squares (SS)	Mean Sum of Squares (MS)	Observed F	Required F	
					5 %	1%
Total	39	65.1681				
Treatments	3	43.02	14.34	23.309	2.87	4.38
Error	36	22.1481	0.6152			
LSD					0.712	

APPENDIX 8: Data logger program for the SHB sap flow gauge

```
;{ CR23X}  
;  
*Table 1 Program  
01: 10      Execution Interval (seconds)  
  
1: Panel Temperature (P17)  
1: 1      Loc [ IntTemp  ]  
  
2: Batt Voltage (P10)  
1: 2      Loc [ BattVot  ]  
  
3: Volt (SE) (P1)  
1: 1      Reps  
2: 35      5000 mV, 50 Hz Reject, Fast Range  
3: 1      SE Channel  
4: 3      Loc [ Vin      ]  
5: 0.004   Mult  
6: 0.0     Offset  
  
4: Volt (SE) (P1)  
1: 3      Reps  
2: 35      5000 mV, 50 Hz Reject, Fast Range  
3: 2      SE Channel  
4: 4      Loc [ AH      ]  
5: 1      Mult  
6: 0.0     Offset  
  
5: Volt (Diff) (P2)  
1: 2      Reps  
2: 21      10 mV, 60 Hz Reject, Slow Range  
3: 3      DIFF Channel  
4: 7      Loc [ dV_1     ]  
5: 1.0     Mult  
6: 0.0     Offset  
  
6: Beginning of Loop (P87)  
1: 0      Delay  
2: 2      Loop Count  
  
7: Step Loop Index (P90)  
1: 1      Step  
  
8: Z=X*F (P37)  
1: 7      X Loc [ dV_1    ]  
2: 25     F  
3: 9      Z Loc [ dT      ]  
  
9: End (P95)
```

10: Volt (Diff) (P2)

1: 1 Reps
2: 35 5000 mV, 50 Hz Reject, Fast Range
3: 4 DIFF Channel
4: 10 Loc [SWC_25]
5: 0.050 Mult
6: -5.0 Offset

11: Volt (Diff) (P2)

1: 1 Reps
2: 35 5000 mV, 50 Hz Reject, Fast Range
3: 5 DIFF Channel
4: 11 Loc [SWC_75]
5: 0.050 Mult
6: -5.0 Offset

12: If time is (P92)

1: 0 Minutes (Seconds --) into a
2: 30 Interval (same units as above)
3: 10 Set Output Flag High (Flag 0)

13: Real Time (P77)

1: 110 Day,Hour/Minute (midnight = 0000)

14: Average (P71)

1: 11 Reps
2: 1 Loc [IntTemp]

15: Sample (P70)

1: 11 Reps
2: 1 Loc [IntTemp]

16: Maximum (P73)

1: 3 Reps
2: 10 Value with Hr-Min
3: 7 Loc [dV_1]

*Table 2 Program

02: 0.0000 Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-

1 IntTemp 1 2 1
2 BattVot 1 2 1
3 Vin 1 2 1
4 AH 5 2 1

5 BH	9 2 1
6 CH	17 2 1
7 dV_1	5 4 1
8 dV_2	17 3 1
9 dT	1 3 1
10 SWC_25	1 2 1
11 SWC_75	1 2 1
12	0 0 0
13	0 0 0
14	0 0 0
15	0 0 0
16	0 0 0
17	0 0 0
18	0 0 0
19	0 0 0
20	0 0 0
21	0 0 0
22	0 0 0
23	0 0 0
24	0 0 0
25	0 0 0
26	0 0 0
27	0 0 0
28	0 0 0
-Program Security-	
0000	
0000	
0000	
-Mode 4-	
-Final Storage Area 2-	
0	
-CR10X ID-	
0	
-CR10X Power Up-	
3	
-CR10X Compile Setting-	
3	
-CR10X RS-232 Setting-	
-1	