UNIVERSITY OF ZIMBABWE

Department of Physics
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PROJECT TITLE:

DETERMINATION OF WATER PRODUCTIVITY OF MAIZE VARIETIES GROWN IN ZIMBABWE

BY

LILIAN MAGODO

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Supervisors

Mr T Mhizha

Mr P Nyamugafata

Professor D. Raes

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ABSTRACT

The quantification of water use in plants is necessary to maximize water use efficiency in semi -arid areas where water is often limiting. The main objective of the study was to quantify maize water productivity and apply the determined water productivity and harvest index to predict yields for different seasons. A field trial was carried out at the University of Zimbabwe farm located in Harare. Three varieties of maize (SC719, SC635 and SC 403) were grown. Reference evapotranspiration was computed from daily weather data using the FAO Penman Monteith equation. The BUDGET model was validated by comparing simulated and measured root zone water content and used to simulate maize transpiration. Water productivity was then determined by plotting aboveground biomass against the cumulative transpiration. Normalized Water productivity (WP*) was determined by plotting above ground biomass against the sum of the ratio of transpiration to reference evapotranspiration. The normalized water productivity and harvest index were then applied to predict yield for 3 varieties at ART farm for 3 seasons (2000/01; 2002/03 and 2004/05).The BUDGET model was validated satisfactorily with the trend of simulated water content closely following the observed water content Aboveground biomass increased linearly with cumulative transpiration with R^2 value ranging between 0.95 and 0.96 for the three varieties. There were no significant differences in water productivity ($p>0.05$) due to variety. The maize water productivity obtained ranged between 7.7 and 9.5 g m^{-2} mm^{-1}. With the lowest mean water productivity value in SC 403 (7.7 g m^{-2} m^{-1}) There were no significant variety differences even after normalization ($p> 0.05$) and normalized water productivity showed a strong linear relationship with the values ranging between 30.4 to 39.0 g m^{-2}. Application of the normalized water productivity and harvest index to maize yields for 3 seasons at ART farm showed a strong agreement between observed and simulated yields (R^2 value of 0.98). The normalized water productivity for maize can be used to predict yield performance with aid of a validated BUDGET model.

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LIST OF SYMBOLS AND ABBREVIATIONS

λET	Latent heat of flux *(MJ m⁻² day⁻¹)*
γ	Psychrometric constant ($kPa\ °C^{-1}$)
Δ	Slope of vapour pressure curve ($kPa\ °C^{-1}$)
ρ_a	Mean air density ($kg\ m^{-3}$)
c_p	Specific heat capacity ($J\ kg^{-1}\ K,$)
r_s	Bulk resistance ($s\ m^{-1}$)
r_a	Aerodynamic resistance ($s\ m^{-1}$)
θ_m	Water content on mass basis ($cm^3\ cm^{-3}$)
m_w	Mass of water *(g)*
m_s	Mass of dry soil *(g)*
θ_v	Volumetric water content ($cm^3\ cm^{-3}$)
θ_m	Water content on mass basis *(g)*
ρ_b	Bulk density of soil
ρ_w	Bulk density of water.
θ	Volumetric water content of soil
§	Section
R_w	Count rate in water standard
R	Count rate in the soil
AB	Aboveground biomass (*g or Kg*)
AREX	Agricultural Research and Extension Department
AWC	Available water capacity (*mm per unit soil depth*)
B_m	Total biomass (*g or Kg*)
C	Intercept of the line
CN	Curve number
CRM	coefficient of residual mass
CWP	Crop water productivity ($g\ m^{-2}\ mm^{-1}$)
CWR	Crop water requirement *(mm)*
DOY	Day of year
E.yield	Economic yield ($t\ ha^{-1}$)
e_a	Actual vapour pressure *(kPa)*
e_s	Saturation vapour pressure (*kPa*)

E_0	Evaporation from a free water surface (mm day^{-1})
ETa	actual crop evapotranspiration *(mm/ day)*
ET_c	crop evapotranspiration under standard conditions *(mm/ day)*
ET_o	reference grass evapotranspiration *(mm/ day)*
FAO	Food and Agriculture organisation of the United Nations
FC	field capacity *(mm per unit soil depth*)
G	Soil heat flux density ($MJ\ m^{-2}\ day^{-1}$),)
Ha	Hectares
HI	Harvest index
K_c	Crop coefficient
K_{cb}	basal crop coefficient ratio
K_e	soil evaporation coefficient
K_s	stress reduction factor
K_y	Yield response factor
LAI	leaf area index
m	Constant governed by crop species and independent of soil nutrients and water availability.
m_f	mass of grain at harvest *(g or kg)*
m_{std}	grain mass at 12.5% moisture content *(g or kg)*
p	depletion factor
RAW	Readily available water (*mm)*
RCBD	Randomized complete block design
R_n	Net radiation at the crop surface ($MJ\ m^{-2}\ day^{-1}$),
s	Gradient of the line
T_p	Total transpiration per area from emergence to harvest *(mm)*
T	Mean daily air temperature (^0C)
Ta	Actual transpiration (*mm)*
TAW	total available water *(mm)*
u_2	wind speed ($m\ s^{-1}$)
VPD	Vapour pressure deficit
PWP	wilting point *(mm per unit soil depth*)
WP	Water productivity ($g\ m^{-2}\ mm^{-1}$)
WP*	Normalized water productivity ($g\ m^{-2}$)
y	Total dry matter mass per area (g *or* kg / m^2)
Y_a	Actual crop yield
Y_m	Maximum expected or potential yield
Zr	depth of root zone (*m*)

CHAPTER 1

INTRODUCTION

1.1 Background

Agricultural production in Sub- Saharan Africa is limited largely by water availability. Most of the countries in Sub –Saharan Africa, which include Zimbabwe, have a semi-arid climate. The rainy season is often characterized by erratic and poorly distributed rains while drought is common. Thus there is a high risk of crop failure especially under rainfed conditions.

Supplementary irrigation can help maximize and stabilize yields by ensuring that fluctuations in the rainfall amounts do not result in water stress in the crop. Developing new water supplies for irrigation is not an option due to increasing water scarcity; rather existing water has to be reallocated. Available water in Zimbabwe has become scarce over the last two decades and this has been attributed to urbanization, declining rainfall and frequent droughts (Manzungu *et al.,* 1999). Water scarcity compromises underground water recharge and viability of irrigation. There is a consensus that conservation and efficient usage of water is necessary (Lal, 1991). The agriculture sector has to utilize water resources more productively.

Knowledge on the quantitative response of crop to water under specific environmental conditions is important as this helps in the understanding of the productive use of water and hence suitable interventions which can be made to save water. Such knowledge is important especially for maize, an important crop in the Southern Africa region including Zimbabwe. Maize is an integral component of the staple diet and an input into a range of animal feed and food products. National maize yields are on the decline and one of the major causes cited is the decline and changes in water availability (Gadzirayi *et al.,* 2006).

Researchers have addressed the challenges of water management in semi-arid areas for many years providing valuable insights, technologies and good practices (Gichuki and Merry, 2002).There are however many questions arising from changing water availability patterns. The efficient use of water requires a good understanding of the relationship between transpiration, evapotranspiration and dry matter accumulation and grain yield. Although transpiration is directly involved, in biomass production most studies use evapotranspiration which is the sum of transpiration and evaporation as the two are difficult to separate and transpiration is difficult to measure in the field (Steduto *et al.,* 2007).

The slogan of more ‘crop per drop’ or Crop Water Productivity (CWP) has been advocated for in the search for measures to improve water use efficiency in an environment of increasing water scarcity. In a broad sense, water productivity is related to the value or benefit derived from the use of water. Crop water productivity has been studied and documented for different crops however; the definitions of water productivity are not uniform and change with the background of the researcher or stakeholder involved (van Dam and Malik, 2003). The numerator ranges from the economic value or amount of grain yield, to aboveground or total biomass yield while the denominator ranges from value or amount of water input/applied to water consumed. Often it is not expressed explicitly whether dry or fresh weight of yield was used as numerator, which makes comparisons difficult (Toung, 1999, Droogers *et al.,* 2000, Bessimbinder *et al.,* 2004).

Research has indicated a simple linear relationship between biomass production and cumulative actual crop transpiration (deWit, 1958; Tanner and Sinclair, 1983). The range of water productivity that is reported in literature is very variable (Bastiananssen *et al.,* 2003, Zwart and Bastiansen, 2004). The high variability highlights the effect of environment, agronomic, social and economic conditions in influencing CWP. Normalized water productivity (WP*) is the ratio of aboveground biomass to sum (transpiration /reference evapotransipiration). The normalization allows water productivity to account adequately for climatic differences that govern crop growth.

To fully understand the magnitude and dynamics of components of crop water balance, modelling is often necessary because field measurements alone can only be used with careful and good instrumentation to reconstruct the water consumption throughout the season for any crop. Simulation models are excellent tools to explore limitations and opportunities for increasing crop water productivity as they use mathematical equations and assumptions to simplify complex soil physical processes, water relations and crop growth interactions (van Dam and Malik 2003).

Water scarcity is now a reality and there is a need to explore the limitations and opportunities for saving water, in different parts of the water scarce environments. Quantifying water productivity through simple water balance at field scale helps in the understanding of the productive use of water.

1.2 Problem statement

The major challenge to maize production is that of increasing production with limited water availability. The water scarcity has led to escalation in water prices. These challenges make proper water management and efficient use a necessity and one option is to increase agriculture yield per unit water consumed.

Literature findings point to the variability of CWP for any particular crop confirming the suggestion that there is scope for increasing water productivity (Toung, 1999). The WP values tend to be site and scale specific and to explore opportunities and limitations for saving water using the concept of crop water productivity the following questions need to be answered;

- What is the range of values for the crop water productivity in a particular environment?
- How do different locally available varieties perform in terms of water productivity?
- Can these findings be applied to predict performance in different weather scenarios?

1.3 Justification

Water is increasingly becoming scarce and it is imperative that water be used efficiently. The evaluation of biomass water productivity in maize at field scale allows the better understanding of the productive use of water. This is the first step towards identifying opportunities for improving water use efficiency. Normalized water productivity can be used in assessing the performance of maize under different seasonal conditions.

The quantification of crop water relations using field techniques alone is often complicated by dynamism of water and solutes movement in the soil and in the plant. To have realistic estimates of the crop transpiration all significant components of the water balnce have to be assessed, however as direct measurement is not possible estimates are often based on models of soil water. Models can help to integrate soil physical processes, water relations and crop growth interactions by using simple assumptions to replace the details of plant response to the environment (Castrignano, 1998).

Numerous models have been developed from simple functional models to complex process based models. The BUDGET model was chosen mainly because of availability and to reduce costs and time involved in sourcing alternative model. In addition the BUDGET model is a simple functional model requiring minimum input which can aid in quantifying water productivity through a simple water balance at field scale (Raes , 2002)

Maize being the staple crop for Zimbabwe was chosen for this study as it is widely grown and its production has to be maintained at adequate levels to feed the country. The three maize varieties used were selected on basis of

(i) length of the growing season so as to represent all classes from late maturing, medium, and early maturing varieties.
(ii) Availability.

The existing knowledge on water use and yield relationships and advances which have been made in crop modelling can be combined to define and evaluate crop water productivity. This study undertakes the quantification of maize water productivity under Zimbabwean conditions by relating above ground biomass production to cumulative transpiration which is estimated using the BUDGET model.

1.4 Objectives

Overall objective

To obtain water productivity values for selected maize varieties grown under irrigation in Zimbabwe.

Specific objectives

- To validate the BUDGET model by comparing measured and simulated root zone water content.
- To determine actual transpiration for maize using the validated BUDGET model.
- To determine water productivity of 3 maize varieties grown in Zimbabwe.
- To do a scenario analysis by applying the derived water productivity and harvest index to predict the performance of maize varieties under different seasons.

1.5 Hypothesis

H_0: There are no differences in water productivity among the 3 varieties.

The varieties are SC 719 (Late maturing), SC 635 (medium maturity) and SC 403 (early maturing)

1.6 Thesis structure

Chapter 1 provides the introduction, which encompass the background and significance of the problem being addressed, objectives of the study and justification for the study and the outline for the rest of the thesis. Chapter 2 is a review of the available literature on studies, which have been done on crop water productivity, with emphasis on maize. Chapter 3 gives information on the procedure and materials used and theory of these methods. The results and observations and interpretation and the analysis of these findings are presented in Chapter 4. Chapter 5 discuses the conclusions drawn from the results and the recommendations for further research in related work. References and appendices are provided at the end of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review provides an insight into research on crop water productivity with emphasis on maize together with approaches used to quantify the crop water productivity components. In the end the emerging issues which justify carrying out the research work are presented and summarized.

2.2 The concept of crop water productivity

The concept of crop water productivity (CWP) has evolved from what is traditionally referred in literature as water use efficiency (WUE) (Steduto and Albrizio, 2005). The term WUE covers a range of observations, it can refer to gas exchange by individual leaves for a few minutes to grain yield for the whole season. The agronomic view of water use efficiency which describes yield (biological, photosynthetic or economic) per unit of water differs from the engineering view where water use efficiency refers to the ratio of water stored in root zone to that delivered for irrigation (Kijne *et al.,* 2002). Because of the different connotations attached to the term efficiency the term WUE has outlived its usefulness. Furthermore with concerns over water scarcity the term has evolved towards the concept of CWP.

CWP has several definitions and expressions. In physical terms it is the ratio of the product, which is usually the weight of biomass or harvestable component (fresh or dry), to that amount of water depleted or applied to achieve this production (Kijne *et al.,* 2002). The economic CWP is concerned with the value of the product and the value of the water diverted or applied. The choice of denominator or numerator vary with objective and domain of interest. Crop production is governed by transpiration (beneficial depletion hence increasing product per unit transpiration is of interest, as agriculture production should rise without an increase in water depleted by agriculture.

It is logical to express agricultural performance in terms of crop production per m^3 of water used. At field scale assessing how the water is converted to beneficial output is of importance. At this scale the output can be quantified as total biomass or crop yield and the water depleted is usually expressed as evapotranspiration. This is the approach taken in this thesis with separation of transpiration and evaporation being achieved at the end using the BUDGET model.

2.3 Research on crop water productivity

The relationship between crop yield and water use has interested many, with research largely divided to cover two aspects; research aimed at investigating different water regimes which maximize yield per unit land and research focussing on maximizing the efficiency of water use (Zhang, *et al.,* 2003).

Water related research aimed at maximizing yield per unit land has focussed on water requirement of crops and climatic factors influencing water use for maximum production (Doorenbos and Pruitt, 1975, Hanks, 1983). However due to increasing water scarcity there has been a shift from manipulating environmental factors to maximize yield towards maximizing yield per amount of water used.

2.3.1 Theoretical basis of CWP studies

Water consumption in the form of transpiration occurs as a cost to crop growth. When a plant's stomata open to allow assimilation of CO_2, water is lost and the carbon dioxide gained ultimately results in yield and biomass production.

Earlier work by de Wit in 1958 in which he showed that there is a strong linear correlation between yield and cumulative seasonal transpiration forms the basis of most water yield relationships (Hillel, 1982). For dry climates with high radiation de Wit showed that yield and transpiration were related as follows

$$y = m(T / E_0) \qquad (2.1)$$

Where
y is total dry matter mass per unit area
T is total transpiration per area from emergence to harvest
E_0 is evaporation from a free water surface.
m is a constant governed by crop species mainly and largely independent of soil nutrients and water availability.

When yields are transpiration limited, strong linear correlations can occur between cumulative seasonal dry matter and cumulative seasonal transpiration.

2.3.2 Previous research on crop water productivity

Numerous studies have been conducted on the various aspects of crop yield and water relations from the time of de Wit (1958). There are abundant examples in literature whereby water productivity has been studied. Because of the variation in the definition and dependence on stakeholder, CWP has been studied and documented with numerator ranging from value or amount of grain yield, to aboveground or total biomass yield and the denominator ranging from value or amount of water input to water consumed (Kijne *et al.,* 2003).

Crop water productivity in terms of water applied has been included as part of the research in some studies in Zimbabwe. Water productivity of 0.67 kg yield per m^{-3} of water in maize using conventional fertilizers has been reported in Marondera. The study was under rainfed conditions in the Chihota Communal Lands with predominantly sandy soils (Guzha *et al.,* 2005). Water use efficiency of 1.5 kg m^{-3} was found by found by Pazvakavambwa and van der Zaag (2000) in maize under irrigation for smallholder farmers of Nyanyadzi.

Most crop water productivity studies on water consumed documented utilize actual evapotranspiration (Kijne *et al.,* 2003, Zwart and Bastiaansen, 2004). Transpiration is difficult to measure at field scale so crop water productivity is defined in terms of evapotranspiration rather than transpiration (Kijne *et al.,* 2002). Transpiration and evapotranspiration are strongly correlated particularly after complete plant canopy has been formed.

In a study carried out in Tanzania's Mkoji area CWP was quantified for 3 maize cultivars under irrigation (Igbadun *et al.,* 2005).The CWP reported varied from 0.4-0.7 kg m^{-3} (Igbadun, *et al.,* 2005). The CWP was defined in terms of consumptive use as

$$CWP = \frac{Y(kg)}{SWU(m^3)} \qquad (2.2)$$

Where
CWP is the crop water productivity
SWU is the Seasonal evapotranspiration
Y is the yield

A study under sub-humid conditions of Argentina by Dujnovian *et al.,* (1996) presented one of the few documented examples in literature where evapotranspiration and transpiration were separated in quantifying crop yield water use relationships. In as a study by Dujnovian *et al.,* (1996), evapotranspiraton flux was partitioned into soil evaporation and crop transpiration and reported water use efficiency (grain to transpiration) in maize was 2.33 and 5.86 g m^{-2} mm^{-1} for the two hybrids that were compared.

The range of crop water productivity reported in literature around the world is 0.3 - 2.7 kg m^{-3} (grain yield) for maize (Bastiaanssen *et al.,* 2003). The FAO gives the CWP of maize as 1.6 kg m^{-3} (Doorenbos and Kassam, 1979). Zwart and Bastiaanssen (2004) reviewed relevant literature to develop a database for wheat, rice and maize grain yields versus actual evapotranspiration. It emerged from their review that studies on CWP in terms of water consumed have mainly been concentrated in USA and China with very few studies in African and Latin American continents (Zwart and Bastiaansen, 2004). The review by revealed maize CWP ranging from 0.22 - 3.99 kg m^{-3}. The numerator in this instance was the marketable yield while the denominator was the actual evapotranspiration. The review however excluded data from water balance simulation models and pot experiments. Table 2.1 below summarises some of CWP values for which have been documented

CWP values with respect to evapotranspiration and fresh grain yield at field level

Table 2. 1 CWP values at field level (fresh grain weight to evapotranspiration)

crop	place	range of CWP values (kg/m3)	Reference
		grain yield	
Maize	Texas	1.2-2.2	Rhoads and Bennet (1990)
	Shaanxi, China	3.3	Kang *et al.,* 2000
	Pantnagar, India	1.4-1.5	Mishra *et al.,* 2001
	USA, China, Bangladish & Inc	1.1-2.7	Zwart and Bastiaanssen (2004)
	not given	0.8-1.6	Doorenbos and Kassam, 1979
	Mkoji, Tanzania	0.4-0.7	Igbadun *et al*., 2005
Wheat	Texas	0.6-1.9	Musick and Porter (1990)
	N.Syria	0.8-1.0	Oweis and Hachum (2000)
	Argentina, Austarlia, China , I	0.6-1.7	Zwart and Bastiaanssen (2004)
	not given	0.8-1.0	Doorenbos and Kassam, 1979
Rice	India	0.5-1.1	Toung and Bouman (2002)
	India, China , USA, Malaysia &	0.6-1.6	Zwart and Bastiaanssen (2004)
	not given	0.7-1.1	Doorenbos and Kassam, 1979
Sorghum	Texas	1.1-1.4	Krieg and Lascano (1990)

For this study CWP was determined as the ratio of aboveground biomass to cumulative transpiration.

2.3.3 Factors influencing CWP

The variability of the CWP values reported in literature can be attributed to a number of factors.

2.3.3.1 Crop variety

The CWP is influenced by crop variety (Igbadun *et al.,* 2005). Cultivars differ in their allocation of assimilates to the various plant parts and in relation to physiological development stage. The dry matter partitioning determines the maximum harvest index that can be reached.

Cultivars differ in the length of the growing season and generally a higher yield per unit evapotranspiration can be obtained with shorter growing season under rainfed conditions (Bessembider, *et al.,* 2005). Over the years plant breeding has indirectly contributed to improving CWP because water productivity increased as yields have increased with reduced crop growing period and hence reduced seasonal transpiration.

However, Keller and Seckler (2005) maintain that breeder's efforts have concentrated on increasing harvest index since economic yield can be increased without increasing transpiration, CWP over the years has not changed much. The view is supported by Zwart and Bastiaansten (2004) who have shown that CWP for maize, wheat and rice have not changed appreciably over the last 25 years .

Generally, the low yielding varieties will tend to have a lower CWP in the same environment and the highest CWP will be achieved by the highest yielding variety (van Dam and Malik, 2003). This is because of the linear relationship between yield and ET, i.e. the greater the yield the greater the CWP.

2.3.3.2 Water management

Doreenbos and Kassam (1979) did the most comprehensive international work on crop yield and water relations by relating actual evapotranspiration to actual yield. Doorenbos and Kassam (1979) proposed that the effect on yield could be quantified by a linear function whereby the crop yield response factor, K_y varied with crop growth stage when stress occurred. By introducing K_y the reduction of crop yield could be predicted when there is crop stress due to shortage of soil water according to the following relationship:

$$1-\left({Y_a}/{Y_m} \right) = K_y \left(1 - {ET_a}/{ET_c} \right) \quad (2.3)$$

Where

Y_a = actual crop yield

Y_m = maximum expected or potential yield

ET_c = crop evapotranspiration under standard conditions.

K_y = yield response factor

ET_a =crop evapotranspiration as adjusted to actual conditions under which it occurs.

Many examples in literature describe the influence of water management on CWP (Zwart and Bastianssen, 2004). In a study on maize, Igbadun *et al*., (2005) highlighted that CWP is maximized by withholding water every other week at vegetative and grain filling stages and better water utilization was associated with adequate water application at tasselling to silking stage. Thus, crop yield response to water is dependent on water applied in a particular growth stage rather than to the overall seasonal water applied.

A typical medium maturing grain crop requires 500-800 mm of water depending on climate for maximum production.

2.3.3.3 Vapour pressure gradient (VPG)

For the same crop cultivar and production levels, different maximum CWP can be obtained under different environments partly due to differences in water vapour concentration of the air in the atmosphere (Bessembider, *et al.,* 2005). Lower vapour pressure deficits tend stifle water loss while higher deficits tend to promote evapotranspiration. There is generally a proportionally inverse relationship between vapour pressure deficit of the air and CWP (Zwart and Bastaiannsen, 2004).

2.3.3.4 Soil fertility

The fertility level, especially nitrogen affects the growing conditions and biomass production of a crop. If not taken into account in the modelling equations, the resulting WP values loses robustness and become environment specific (van Halsema, 2003). Nutrients indirectly affect the physiological efficiency of the plant and generally optimum nutrients and irrigation maximize CWP (Zwart and Bastiaanssen, 2004). The soil fertility effect can be taken care of by introducing a fertility stress factor that will reduce the biomass production rate under sub-optimal conditions.

2.3.3.5 Components of the yield used

Whether total or aboveground biomass is used affects the robustness of WP. Taking total biomass which combines aboveground biomass and roots into account significantly improves the robustness of WP. Most crops are able to adapt their root biomass: shoot biomass partitioning ratio to increase and accelerate their root growth in response to water stress so it is vital to include roots into the equation (van Halsema, 2003).

According to Hanks (1983) the relationship between yield and water use for above ground biomass and for grain are different. There is a close relationship between aboveground biomass and transpiration because aboveground biomass accumulation and photosynthesis are also closely related and photosynthesis and transpiration are closely related as well. However grain yield involves the complex interactions among development, assimilate, partitioning and the environment.

2.2.4 Normalization of CWP

The concept of water productivity should be robust enough to yield a unique crop and/or variety specific value for all general climatic and water stress conditions under which the crop can be grown (van Heslema, 2003)**.** Normalization usually takes two approaches; normalization according to vapour pressure gradient or according to reference evapotranspiration (Steduto, *et al.,* 2007). The vapour pressure gradient represents the driving force for transpiration. Tanner and Sinclair (1983) first proposed to normalise the water productivity function by the climatic vapour pressure deficit (VPD), in order to eliminate the component of atmospheric water demand from the equation. According to van Halsema, 2003;

$$B_m = WP.\frac{T_a}{VPD} \tag{2.4}$$

B_m = *total biomass production*

WP = *water productivity*

T_a = *total actual transpiration*

VPD = *vapour pressure deficit*

The second approach uses reference evapotranspiration (ET_o) calculated according to the Penman–Monteith equation (Allen et al.1998, van Halsema, 2003*).* This second approach was used in this study and is adopted after de Wit (1958) who first suggested that to obtain good water productivity values in case of arid and semi arid climates, where water is the limiting factor for assimilation and biomass production, there is need to normalise for the evaporative demand of the atmosphere;

$$B_m = WP.\frac{T_a}{ET_o} \tag{2.5}$$

B_m = total biomass production

WP = water productivity

T_a = total actual transpiration

ET_o = reference evapotranspiration

Research has shown the normalization of water productivity by ET_o to be more robust than the normalization by VPD (Clover *et al.,* 2001, Steduto and Albrizio, 2005). Steduto *et al.,* (2007), indicated that the robustness of WP will increase when normalised for ET_o and the rates of biomass production can then be grouped together in one linear WP expression for a fairly large group of crops (i.e. C3, C4, and some major sub-classes) (van Halsema, 2003). In general good linear WP relations can be established for varying water regimes when WP is not normalised. The values of the WP parameter tend in that case to be crop and/or variety specific. However Hanks (1983) indicated that even with ET_o normalisation the WP will be crop and variety specific.

2.4 Evapotranspiration

Evapotranspiration (ET) includes all water lost by evaporation from soil and vegetation surface and by transpiration from plant tissues (Allen *et al.,* 1998). Various methods can be used to determine crop evapotranspiration which can be direct or indirect.

Evapotranspiration can be measured directly by means of lysimeters. Lysimeters hydrologically isolate soil leading to the reliable estimation of water balance terms and are the most commonly used instrument in measuring actual evapotranspiration in most crop water productivity studies (Zwart and Bastaiansen, 2004). Due to high installation costs and immobility they cannot be used as routine field measuring instruments but primarily a research tool which can be used for checking other ET methods (Allen, *et al*, 1998).

The indirect measurement of evapotranspiration mostly involves the calculation of evapotranspiration from other parameters which are more easily or more accurately measurable.

The energy budget model

The energy budget method estimates ET by applying the principle of conservation of energy. The energy balance components, net radiation, soil heat flux and sensible heat flux are estimated from meteorological data. Once all other components are known ET can be calculated form model. The energy balance equation components can also be measured remotely with sensing technologies or on the ground with Bowen Ratio or Eddy Correlation equipment (Itier and Brunet, 1996).

$$Rn - G - \lambda ET - H = 0 \quad (2.6)$$

Rn – net radiation

λET - latent heat flux

G- Ground heat flux

H – sensible heat

Aerodynamic approach

Evapotranspiration can also be estimated by the aerodynamic approach which is based on the principle that vertical movement of eddies from and towards the evaporating surface is a turbulent process. By assuming steady state conditions and similarity of transfer coefficients for heat, water vapour and momentum ET can be computed (Allen *et al.,* 1998)

These above techniques are not commonly used for agronomic purposes but mainly for micrometeorological and climate studies (Zwart and Bastiansen, 2004). The techniques require sensors, which are sophisticated and expensive with a high response time to sense all turbulent motions responsible for vertical transfer of water vapour (Guyot, 1998).

2.4.1 Estimating ET from Meteorological data

Many methods for estimating ET, based on one or more of the atmospheric parameters which control ET have been developed (Kang *et al.,* 1996). Air temperature, solar radiation and pan evaporation are the most commonly used parameters. Temperature and relative humidity of air affect the rate of diffusion of water molecules while net radiation provides energy for evaporation. Air movement (wind) carries water vapour from the crop surface and maintains a gradient of water potential from leaves to adjacent parts of the atmosphere in addition to importing energy from warmer or drier locations (advection). Hence evapotranspiration can be quantified from weather data using meteorological conditions (Allen *et al.* 1998).

2.4.1.1 The concept of Reference Evapotranspiration

When water is freely available to the crop and the canopy covers most or all of the ground, the rate of water lost depends on evaporative demand of the air which in turn depends on meteorological conditions. There are many empirical methods and physically based ones which have been developed over the years. Based on available research results and recommendations of expert consultations, four ET methods were adopted by Doorenbos and Pruitt (1977) in FAO No. 24 as methods to be used according to availability of climatic data namely the Penman, Blaney Criddle, Pan evaporation and Radiation methods.

The Penman Monteith Equation

Penman (1948) combined the energy balance with the mass transfer method to derive an equation, Penman's combination equation. The equation was further developed by Monteith (1981) to form the Penman–Monteith combination equation. The Penman–Monteith combination equation includes resistance factors accounting for aerodynamic and surface vapour flow resistance at soil and leaf surfaces and through leaf stomata, and allows the method to be used when considering cropped surfaces *(*Blonquist *et al.,* 2006*).*

$$\lambda ET = \frac{\Delta(R_n - G)\rho_a c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + r_s / r_a)} \qquad (2.7)$$

λET is the latent heat flux, R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of vapour pressure curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}), ρ_a is the mean air density (kgm^{-3}), c_p is specific heat capacity (J kg^{-1} K^{-1}), r_s bulk resistance (s m^{-1}), r_a aerodynamic resistance (s m^{-1}).

The FAO Penman Monteith Equation

Advances in research and more accurate assessment of crop water use have revealed weaknesses in the empirical methodologies developed over the years. The FAO Penman was found to frequently over predict ET while the other methods showed variable adherence to crop evapotranspiration estimation. A major study under the American Society of Civil Engineers (ASCE) where more than 20 methods were analyzed based on lysimeter data from 11 locations with variable climate and a parallel study conducted in Europe revealed the superior performance of Penman Monteith equation (Allen *et al.,* 1998). The FAO Expert consultation agreed on the Penmen Monteith combination equation as the best performing method and adopted the concept of a reference surface as a standard method to estimate reference evapotanspiration (Smith *et al.,* 1991).

The reference evapotranspiration is defined as occurring from a hypothetical reference crop with an assumed height of 0.12 m, canopy resistance of 70 m s^{-1} and an albedo of 0.23 closely resembling evapotranspiration from an extensive surface of green grass of uniform height actively growing and not short of water. Assuming standard meteorological observations at 2 m height the Penman Monteith equation becomes;

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2.8)$$

ET_o is the reference evapotranpiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of saturation vapour pressure temperature relationship (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}).

The FAO Penman Monteith equation has received favourable acceptance and application over much of the world and has become the most widely used method of estimating ET (Cassa *et al.,* 2000). It has shown accurate and consistent performance in both arid and humid climates. Through the introduction of an aerodynamic and canopy resistance method, a better simulation of wind and turbulence effects and stomatal behaviour of crop canopy was achieved (Smith, *et al.,* 1996).

The full details for the FAO Penman Monteith method and procedures for estimating the various parameters, algorithms, recommended values and units are included in the FAO Irrigation and Drainage paper 56 (Allen *et al,.* 1998).

2.4.2 Soil water balance method

The soil water balance describes the pathway through which water is lost or gained from the soil water profile. Evapotranspiration can be determined as a residual by measuring components of the soil water balance. The soil water balance method has been widely used to calculate ET on a field scale (Li *et al.,* 2000, Zhang *et al.,* 2003). The soil water balance is based on accounting for losses and gains of water into and out of the root zone. The most commonly used water balance equation is presented by Lal (1991) as:

$$ET = (P + I) - S - D - R \qquad (2.9)$$

ET = evapotranspirtion (evaporation+transpiration).

P = precipitation

I = irrigation

S = change in soil water storage

D = deep drainage/percolation

R = runoff

Various techniques have been applied to measure the components of the water balance equation. The measurement of irrigation and precipitation components is usually simple and direct. However, precipitation measurement is subject to certain errors because of large spatial and temporal variations (Sivakumar, 1991).

2.4.2.1 Soil moisture measurement

The ET term can be estimated from measuring the change in the soil water content contained within the root zone. There are various methodologies for assessing amount of water in the field and regardless of type of method applied, it is essential to determine soil moisture at many test points because of the high spatial variability of soil moisture (WMO, 1994).

Electrical resistance method

Electrical resistance of a block of porous material can be used to measure soil water content. Changes in moisture content cause changes in electrical resistance of two electrodes fixed in the block. The suitability of using such blocks is limited by hysteresis effects and calibration, which depends on density and temperature of the soil.

Dielectric methods

The dielectric constant (permissivity) of a volume of soil varies with moisture contained in the soil. Estimation of water content is based on the ability of sensors to directly measure part of the dielectric permittivity or electromagnetic signal property, which directly relates to volumetric soil water content (θ), (Blonquist, *et al.,* 2006) .Two main methods are used;

<u>The time domain reflectometry</u>

The speed of a microwave pulse between a pair of wave guides placed in the soil is a function of dielectric permissivity of soil water–air mixture. As pulse increases, the permissivity decreases, which indicates a decrease in moisture content of the soil Marshall and Holmes,1988).. The method is fast and measurements are instantaneous and the accuracy is good. Placement of sensors is difficult in deep soils and also the instrument is expensive.

<u>The capacitance method</u>

The capacitance sensor consists of electrodes imbedded in the soil which together with adjacent soil form a capacitor with a capacitance which is a function of permissivity of the soil and of soil moisture content. Measurements are fast and easy (Marshall and Holmes,1988). Its major limitation is that air gaps reduces its accuracy so installation requires special equipment which is expensive and the cost limits depth of tube installation (Payne and Bruck, 1996).

The gravimetric method

The soil water content can be monitored by gravimetric method. Soil water content is determined by finding the mass of water lost upon oven drying a sample at 105^0C to constant mass.

The water content on mass basis :

$$\theta_m = m_w / m_s \tag{2.10}$$

Where

θ_m *is water content on mass basis*

m_w *is the mass of water*

m_s *is the mass of dry soil*

To convert the water content to volume fraction is obtained by

$$\theta_v = \theta_m * \rho_b / \rho_w \tag{2.11}$$

Where

θ_v *is the volumetric water content*

θ_m *is water content on mass basis*

ρ_b *is the bulk density of soil*

ρ_w *is the bulk density of water.*

Technique is laborious and destructive but has the advantage of being more accurate and simple. The gravimetric technique is time consuming and subject to spatial variations (Campbell and Campbell, 1982, Lal, 1991). As such the method is often used as a reference against which other methods can be checked (Guyot, 1998)

The neutron probe

The use of the neutron probe is more acceptable for measuring changes in water content but has risks associated with the radiation. The neutron probe has been extensively used to monitor soil water content in the field (Reichardt *et al.,* 1997). For soil water monitoring the neutron probe was chosen for this study. It has the major advantage that it is non-destructive allowing repeated measurements at the same place. The instrument operates by producing fast neutrons from a radioactive source in the probe. The emitted neutrons are scattered and slowed down by water in the soil. The slowed neutron flux is generated by collision of neutrons and nuclei of hydrogen atoms of water. However other elements found in the soil can scatter and absorb neutrons which can influence the count rate to some extent.

Calibration is therefore often necessary to correct for the presence of bound hydrogen not in the form of water (Dickey, 1990). Calibration is done by establishing the relationship between count rate and water content. This is done by taking soil samples for gravimetric method close to access tube and relating this to readings obtained from access tube by neutron probe .

Relationship is given by a straight-line equation in the form,

$$\theta = m * \left(\frac{R}{R_w} + C \right) \tag{2.12}$$

Where

θ *is the volumetric water content of soil (Volume of water per volume of soil*

S is the gradient of the line

R_w *is the count rate in water standard*

R *is the count rate in the soil*

C is the intercept of the line

Research has shown that calibration equations are site specific and reflect chemical characteristics. The variations in physical and chemical properties require site specific calibrations to obtain reliable water content measurements. In theory every soil has a unique calibration curve.

The use of the neutron probe does not distinguish between layers and can give substantial errors in the short-term estimations of crop water use (Gregory, 1991). The other disadvantages are that of poor estimation of the soil moisture near the soil surface due to the escape of neutrons to the atmosphere. The instrument also looses accuracy near wetting fronts due to large variable sphere of influence. The instrument also poses a radiation health hazard. However, with careful calibration and care the neutron probe remains one of the best tools for monitoring soil moisture content changes.

2.4.2.2 Soil drainage and estimation

Drainage is one of the components of the water balance that is difficult to measure especially in soils containing clays where drainage may occur for long time periods (Gregory, 1991). In deep uniform soil of coarse texture water drains well to almost constant water content within a few days of a rainfall event. In the case of clays, drainage must be estimated to reduce errors in calculation of the crop water use.

As drainage proceeds the water content in a soil layer decreases resulting in a smaller hydraulic conductivity and smaller rates of drainage.

2.4.3 Crop evapotranspiration measurement

The measurement of transpiration at field scale is practically impossible and reliable estimates to separate E and T are difficult to make and time consuming (section 2.3). For most purposes, transpiration is estimated indirectly from the ET (Rosenberg *et al.,* 1983).

Crop evapotranspiration (ET_c)

Crop evapotanspiration is estimated by multiplying the reference evapotranspiration ET_O by the crop coefficient K_c. In the field, crops are affected by a number of factors causing some deviations from the reference crop. K_c is the ratio of ET_c to ET_o and represents the integration of effects of the primary distinguishing characteristics of a specific crop from that of the grass. These include crop height, crop soil surface resistance and albedo of the crop soil surface (Allen *et al.,* 1998).

Crop evapotranspiration under standard conditions and optimal soil water conditions is given by

$$ET_c = K_c * ET_o \qquad (2.13)$$

K_c = *crop coefficient*
ET_o= *reference evapotranspiration rate (mm/day)*

The K_c varies predominantly with specific crop characteristic and with climate to a limited extent. This enables the transfer of standard values of K_c between locations and between climates. As a crop develops its characteristics in terms of height and albedo also change affecting the K_c values. Thus ET_c changes during the growing season as a crop develops from sowing to maturity and increases in leaf area and root development. ET_c decreases from maturity as a crop reaches leaf senescence and harvest time.

Because of the aerodynamic differences between grass reference and many agricultural crops, the K_c increases as wind speed increases and as minimum relative humidity decreases. Adjustments to K_c during mid-season and K_c at the end of the season have to be made where minimum relative humidity differs from 45% and windspeed is larger than 2m/s.
The following equation is used

$$K_c = K_c tab + [0.04(u_2 - 2) - 0.004(RH_{min} - 45](h/3)^{0.3} \qquad (2.14)$$

Where K_c = *K_c at end or mid season*

K_c tab =value of K_c for stage obtained from tables in FAO 56 handbook

u_2 = mean daily value of wind speed at 2m during the mid or late season stage

RH_{min}= mean value of daily relative humidity during mid- season or end season stage

h= the mean plant height during stage.

Alternatively, the basal K_c approach, which involves splitting Kc into two separate coefficients, one for transpiration and one for soil evaporation, can be used. This approach requires more numerical calculations but is useful where effects of day to day variation in soil surface wetness and resulting impact on ET_c are important such as for irrigation scheduling and for soil water balance computations. The equation takes the form

$$K_c = K_s K_{cb} + K_e \qquad (2.15)$$

K_e = soil evaporation coefficient (evaporation from wet soil and is in addition to ET in K_{cb})

K_{cb}= basal crop coefficient ratio of ET_c to ET_o (when soil is dry but average soil water is adequate to sustain transpiration)

K_s = stress reduction coefficient.

2.5 Soil water based models

The reliable simulation of soil evaporation, transpiration, root water uptake, soil water content is without doubt one of the crucial points in any water balance model under cropped field conditions. Given the problems associated with measuring the various components of the field water balance, it is easier to make use of modelling. For this study modelling was undertaken to estimate maize transpiration. In recent decades many complex models have been proposed for analysis and prediction of crop water use (Cassa *et al.,* 2000). The soil water simulation models are grouped based on the degree and complexity of the system modelled. Soil-based models generally use sophisticated numerical solutions of water and solute movement and can predict, also with great detail, soil profile conditions. However, the presence of crop roots in the soil is treated as a simple sink term and plant growth dynamics is generally not considered (Castrignano, *et al.,* 1998)

Most models suffer from limitations to their applicability which stems from a number of factors including considerable variation in soil characteristics in a single field, unavailability of data to input into the model and variability in crop performance for example outbreak of pests. Calibration and validation are always necessary before a model can be used in any environment to ensure accurate simulation of expected conditions in that area. Calibration involves adjustment of the model parameters to make the model work for the specific site while validation is to determine whether the model is capable of performing with reasonable accuracy using a totally independent data set.

2.5.1 The BUDGET model

The BUDGET model is a water balance model that determines the water storage and salt content in the soil profile by keeping track of the incoming and out going water fluxes within the root zone boundaries on a daily basis (Wiyo, 1999). The model consists of several sub-models, which describe the various processes of one dimensional vertical water movement and soil water uptake in a free draining soil (Raes, 2002).

The model estimates the effect of water deficiency on crop yield by computing daily soil water balance. Effects of soil water and atmospheric stress on yield are evaluated and expressed as percentage yield. Yield is calculated on the basis of water stress that occurs during each critical stage of development using K_y factor. The model requires minimum input data on climate, soil and crop parameters and once calibrated and validated for a place it can be used for simulation under different climatic scenarios and soil types (Wiyo, 1999). The major limitation of the model is that capillary rise is ignored and it is not suitable for swelling or cracking soil because these do not wet from surface down.

2.5.1.1 Soil water uptake and retention in the rootzone

The root zone is regarded as a single reservoir with incoming and out-going water fluxes (Fig 2.1). (Source : Raes, 2002)

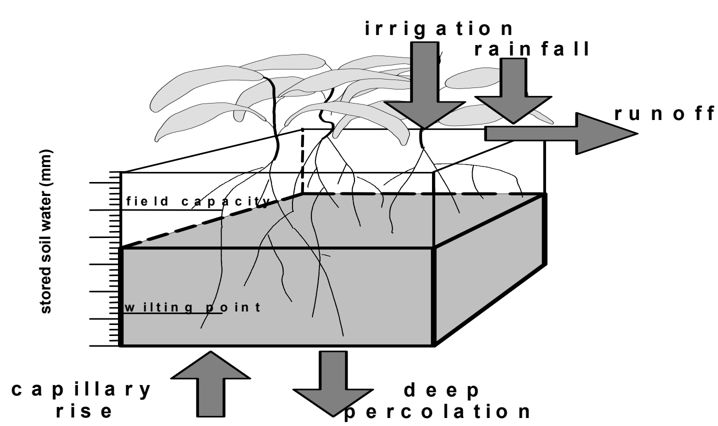

Figure 2. 1 The rootzone water content

Schematically, the root zone can be conceptualized as a box in which the water content fluctuates over time (Figure 2.1). Rainfall, irrigation and capillary rise of groundwater towards the root zone add water to the root zone and decrease the root zone depletion. Soil evaporation, crop transpiration, surface runoff and deep percolation losses remove water from the root zone and increase the depletion.

Water content components

The water content in water balance studies is commonly expressed as an equivalent depth of soil water or depletion. This makes the adding and subtracting of losses and gains straightforward as the various parameters of the soil water budget are usually expressed in terms of water depth (mm) (Raes, 2002).

<u>Field capacity (FC) / Drained upper limit</u>

Field capacity or Drained upper limit is defined as the amount of water that a particular soil holds after drainage has practically ceased or is the amount of water a well drained soil should hold against gravitational forces (Allen, *et al.,* 1998). After rainfall event or irrigation a soil will drain until the drained upper limit is reached. In the heavy clay soils where drainage is inherently slow it may be more logical to refer to a soil being at its upper storage limit than at its drained upper limit.

<u>Permanent wilting point (PWP)/ Lower limit</u>

Wilting point or Lower limit is the water content at which plants will permanently wilt. As water uptake progresses, the remaining water is held to soil particles with greater force until a point is reached where crop can no longer extract the remaining water and it will wilt. Permanent wilting point is referred to as the (LL) lower limit in more recent publications.

<u>Total available water (TAW)</u>

Total available water is the difference between water content at field capacity and wilting point. It is the amount a crop can extract from the root zone.

<u>Depletion factor (p) / First material stress</u>

Depletion factor defines the critical water content where rate of transpiration will drop below the potential transpiration rate. The depletion factor is also known by the term first material stress (FMS).

<u>Readily available water (RAW)</u>

Readily available water is the amount of water a crop can extract from the root zone without suffering any stress. Although water is theoretically available until wilting point, crop uptake is reduced well before wilting point is reached.

$$RAW = p * TAW \tag{2.16}$$

p= the depletion factor

TAW = the total available water (mm)

2.5.1.2 Simulation of soil water balance

The simulation starts with drainage in the soil profile and is simulated by means of a drainage function which takes into account the initial wetness and drainage characteristics of various soil layers (Raes, 2002). The drainage function (τ) describes the amount of water lost by free drainage as a function of time for water content between saturation and field capacity and is exponential (Kipkorir *et al.,* 2002).

The maximum amount of water that can infiltrate into the soil is limited by the maximum infiltration rate of the topsoil (Raes, 2002). Rain that falls on unsaturated soil infiltrates, increasing soil water content until the soil becomes saturated after which additional rainfall becomes runoff. Surface runoff is estimated based on the curve number method of US Soil conservation service (Raes, 2002).

Soil evaporation is derived from the soil wetness and crop cover (Ritchie, 1972, Belmans *et al.,* 1983, Raes *et al.,* 2005). The actual water uptake by the plant roots is described by means of a sink term that takes into account the soil depth (root distribution and soil water content in the soil profile). The evaporation rate and crop transpiration are calculated by means of a dual crop coefficient. The effects of water logging and water shortage are described by means of a water stress factor K_s.

In BUDGET ET_c is the sum of maximum amount of water that can be lost by soil evaporation E_{pot} and by crop through transpiration (T_{pot})

$$ET_c = E_{pot} + T_{pot} \qquad (2.17)$$

ET_c is crop evapotranspiration
E_{pot} is potential soil evaporation
T_{pot} is potential transpiration

The maximum amount of water that can be lost through soil evaporation is estimated by the equation below (Belmans, *et al.,* 1983)

$$E_{pot} = f.e^{-cLAI}.ET_c \qquad (2.18)$$

Where
LAI = leaf area index (m^2m^{-2})
f and c = regression coefficients with values f= 1.0 and c = 0.6-0.7 to obtain acceptable estimates of potential evaporation.

Actual evaporation is determined by the following equation;

$$E_{act} = \int \alpha . fw_z . E_{pot} . dz \tag{2.19}$$

α *= fraction of extractable water*

fw_z *= weighing factor which depends on soil depth*

dz = soil depth

Actual transpiration is determined by means of a sink term which expresses the amount of water extracted by roots per unit volume of soil per unit time (Raes, 2002). The sink term is dependent on water stress factor K_s

$$T_{act} = \int S_{i.} dz \tag{2.20}$$

S_i is a sink term in $m^3 m^{-3} day^{-1}$ given by $S_i = K_s . S_{max}$

S_{max} is the maximum sink term in $m^3 m^{-3} day^{-1}$

2.6 Irrigation scheduling

Irrigation scheduling deals with how much and when to irrigate a crop. Irrigation scheduling methods are based on three approaches, namely, crop monitoring, soil monitoring and water balance technique (Blonquist *et al.,* 2006).

2.6.1 Approaches to irrigation scheduling

Plant water based methods

Recently the monitoring of plant water has been advocated and techniques involving plant water measurement as a response to soil water especially water stress (Jones, 2004). The major drawback of this method is that the decision to irrigate is made after the plant has suffered some amount of moisture stress, which may adversely affect the crop yield. Calibration is often necessary to determine the control threshold at which irrigation should commence (Jones, 2004).

Soil water content or potential based methods

Irrigation scheduling can be based on soil water content measurement where soil moisture status, water content or potential is measured directly to determine the need for irrigation. Measurements and estimates of water content for use in irrigation scheduling can be performed via gravimetric, neutron scattering, gypsum block and tensiometer methods. In recent years, water content estimates have advanced to include electromagnetic (EM) techniques such as time domain reflectometry (TDR) (Topp *et al.,* 2001, Robinson *et al.,* 2003).

Evaporation pan

The use of the evaporation pans provide a practical tool for accurate scheduling in the field. The evaporation measured from the pan (E pan) is multiplied by the pan coefficient (K_{pan}) to obtain the ET_o (reference evapotranspiration). Multiplying ET_o by crop water use coefficient K_c for the specific crop, stage and cultural conditions to obtain the crop water requirement. The pans require proper recording, maintenance and management (Allen *et al.,* 1998).

Soil water balance method

Alternatively the soil water balance method can be used. Soil water balance based irrigation scheduling models use soil water budgeting in the root zone. A number of computerized simulation models for crop water requirements have been developed using this approach. (Kincaid and Heermann, 1974; Smith, 1991) .

2.6.2 FAO CROPWAT Model

CROPWAT was used for this study. CROPWAT is a computer model developed by FAO (Allen *et al.,* 1998). The model is based on the soil water balance method. The crop water and irrigation requirements are calculated based on climate, soil and crop data (Savva, 2002). The updated versions use the FAO Penman Monteith method to estimate ET_0. Climatic data for temperature, relative humidity, sunshine hours and rainfall can be used as input into the model to calculate ET_o. Once rainfall has been input, the model can calculate effective dependable rainfall using the USDA conservation method (Savva, 2002).

CHAPTER 3

MATERIALS AND METHODS

3.1 Study area

Field data for this study was collected between October 2006 and April 2007 season at the University of Zimbabwe farm, Harare (17.42^0 S, 31.07 ^{0}E and 1479 m above sea level). Harare is in agroecological zone IIa and has a semi-arid climate with rainfall generally starting between October and December. On average, the area receives mean annual rainfall ranging between 750-1000 mm (Vincent and Thomas, 1961). Harare has a mean annual temperature of 19 ^{0}C while the maximum mean temperature is about 27^0 C in summer.

3.2 Soil characterization

A soil study was conducted to characterize the site for soil physical properties, bulk density, water retention and hydraulic properties. The soil characterization was conducted by the Department of Agriculture Research and Extension (AREX).

Soil characterization was done by sinking 10 auger holes on a plot measuring one and half hectares. This was done to group soils of similar morphological properties such as depth, colour, texture and surface stoniness. Only one soil category was identified. A representative pit was dug from which soil profile description and sampling was made. Soil profiles were described according to FAO/ISRIC Guidelines for soil description and field soil and site description in Zimbabwe. These are guidelines for standard reporting in soil profile description to facilitate cross reference and comparison of soils between sites (Bennet, 1985).

3.2.1 Field capacity (FC) and bulk density determination

The Field capacity and bulk density were determined according to the guidelines by Landon, (1984).Undisturbed core samples were taken from each soil horizon in triplicates to a 60cm depth. The samples were then saturated for 24 hours and after saturation the samples were taken into a sand bath at a pressure of 5k Pa to determine the field capacity for medium to heavy textured soils. The samples were left for a week before weight measurements were taken at two-day intervals until equilibration. Equilibrated samples were put in an oven at 105 ºC for 24 hours. The weights were then recorded and used in calculating bulk density and field capacity.

3.2.2 Permanent Wilting Point (PWP) Determination

A cellulose membrane was first saturated in water and then put in a pressure chamber. Retention rings and samples were also put into the chamber. The samples were then saturated with water by capillarity before the chamber was mounted. The amount of water collected was then measured and the volume determined for the time period. The chamber was then connected to a pressure of 1500 kPa (15 bars) and burette readings were taken at hourly intervals after 24 hours. The chamber was dismounted after no changes were recorded on the burette. The samples were oven dried and weights recorded for the calculation of permanent wilting point (Landon, 1984).

Calculations were as follows:

$$\text{Bulk Density (BD)} = \frac{\text{Mass of dry soil}}{\text{Volume of core}} \quad (3.1)$$

$$\text{Gravimetric moisture } \theta g = \frac{\text{Mass moist soil} - \text{Mass of dry soil}}{\text{Mass of dry soil}} \quad (3.2)$$

Volumetric moisture at field capacity/ permanent wilting point $\theta v = \theta g * BD$

$$AWC = FC - PWP \quad (3.3)$$

Where

AWC is available water capacity
FC is the field capacity
PWP is the permanent wilting point

Volumetric moisture content were used for AWC and PWP

3.2.3 Particle size determination

Soil samples of 50 g were taken and put in large beakers. 15 ml of calgon and distilled water were added to cover the soil and the solutions were left overnight. The solutions were stirred for 4 minutes using a stirrer. The solutions were sieved through a 500 µm and 180 µm sieve into 1litre measuring cylinders. The sieved soil was oven dried and weighed for fine, medium and coarse sand. Coarse sand (2-0.5mm) and medium sand (0.5-0.2mm) were separated by sieving and fine sand (0.2 – 0.02) was calculated by difference. The solutions were then filled to the mark (1L) with distilled water and shaken with a spindle mixer. A hygrometer was immersed to read silt content. The solution was left to settle for 2 hours before being read for clay.

3.2.4 Infiltration rate

The double ring method was used for the infiltration test, in which two concentric rings of diameters 28 cm for the inner ring and 53 cm for the outer ring were driven vertically into the soil surface to approximately 8 cm depth to prevent lateral movement of water. Both rings were filled with water to the depth of 15 cm to 20 cm recording the time and height of water in the inner cylinder using a floating scale in the still well. The levels of water in the still well were measured after 1, 5, 10, 20, 30, 45 minutes and after each hour depending on the rate of infiltration until a steady state was reached (after 3-5 hrs). Once the values of the infiltration rate were constant the final infiltration rate had been reached. The recordings were made on a standard form and rates calculated.

3.3 Experimental Setup and Management

3.3.1 Experimental design

The experimental design was a randomized complete block design with 4 replications. The treatments comprised three cultivars or varieties of SeedCo, SC403, SC635 and SC719. Each treatment was randomly allocated to a plot. The trial had a total of 12 plots each measuring 10 x 10 m with pathways of 0.5 m to separate the plots and 1 m to separate the blocks. The net plot area harvested at the end of the season for final biomass and grain yield data analysis comprised of 4 rows per plot (2.7 x 10 m). The field layout for the experiment is presented in Figure 3.1.

3.3.2 General management of the trial

The crop was managed according to the guidelines in the SeedCo Agronomy Manual (2004). The maize was sown on the 27th October 2006. Land was first prepared by conventional tillage. Planting was done by placing two seeds per sowing station and thinning was done at 4 weeks after sowing to leave one seedling per station. The maize was sown in rows measuring 0.9 x 0.40 m. At sowing a basal fertilizer compound D (Nitrogen; Phosphorus; Potassium, NPK=7: 16:5) was applied at the rate of 400kg /ha. Top dressing was done at 5 weeks using Ammonium nitrate (34, 5% N) at the rate of 250 kg /ha. Thionex granules were applied in the maize funnels at 5 weeks as a preventative measure against maize stalk borer. Weed control was done manually at 4 weeks and at 8 weeks.

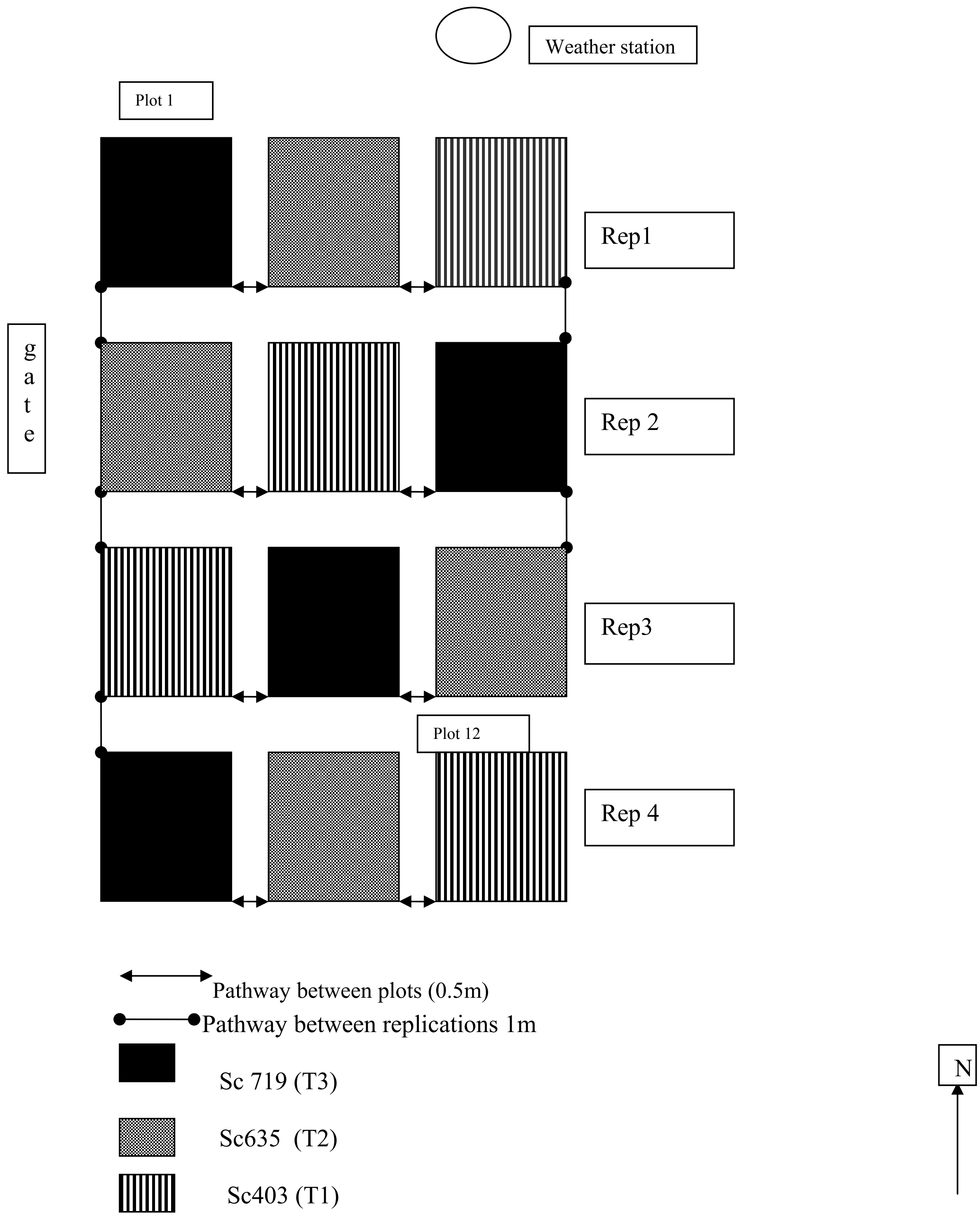

Figure 3. 1The field layout of the trial

The three cultivars of maize were selected on the basis of length of the growing season (short , medium and long season varieties). The exact variety chosen under each category was influenced by availability. Table 3.1 summarizes the characteristics of the selected varieties

Table 3. 1Characteristics of maize varieties grown.

(*Source: Adapted after SeedCo Manual, 2005.)*

Class	Variety	Growing period (days)	Potential yield (t/ha)	Days to silking
Short season	SC403	140	4-8	61
Medium season	SC 635	150	5-10	67
Long season	SC719	165	7-13	73

3.3.3 Water management

A sprinkler irrigation system was used in this trial. The application rate for the sprinkler system was determined using the catch can method (Fig 3.2). As a means of checking the application rate buckets were placed around the experimental area and water was applied for 70 minutes. The amount of water collected was then measured and the volume determined for the time period.

Application rate = average depth of water applied /time (3.4)

The application rate determined this way was 3.2 mm / hour and this was used in the irrigation schedules. Appendix B (Table B1) provides the irrigation schedule using CROPWAT .

CROPWAT model (§2.6) was used to calculate crop water and irrigation requirements. The reference evapotranspiration was calculated according to FAO Penmen Monteith equation (equation 2.1) using weather data. The weather data was obtained from an automatic weather station at the site Figure 3.3. The rainfall was obtained from the rain gauge installed at the site. The soil characteristics determined for the site (§3.2) were used and the initial soil water content was calculated from the soil moisture measurements taken before the planting. The crop parameters of crop stage, length of growing season, K_c (crop coefficient), K_y (yield response factor), rooting depth and depletion fraction were taken from the guidelines provided by FAO and the SeedCo manual (2004). Once the crop data, climatic data and soil data were entered the crop water requirements were generated on a ten day basis.

Figure 3. 2 The determination of the application rate using catch can method

The Schedules projected from CROPWAT and the determined application rate were used to derive the date and the amount of hours of irrigation. Table 3.2 presents the date and irrigation hours recorded at the site

Table 3. 2 Summary irrigation applied at the site

date	hours	amount(mm)
25-Okt	4	12.8
26-Okt	6	19.2
27-Okt	6	19.2
29-Okt	6	19.2
30-Okt	9	28.8
06-Nov	8	25.6
17-Nov	8	25.6
29-Nov	10	32
07-Des	12	38.4
27-Des	8	25.6
total		246.4

3.4 Field Measurements

3.4.1 Measurements for the Model

3.4.1.1 Climatic data

The weather data of maximum and minimum daily temperature, solar radiation, relative humidity, net radiation and horizontal wind speed at 2 m were recorded from an automatic weather station installed at the site at 30 minute intervals by means of a data logger. The weather data was processed into daily values EXCEL. These weather parameters were used to calculate ET_O using the FAO Penman-Monteith equation (equation 2.1) (Allen *et al.,* 1998) by means of ET_o calculator. Rainfall was measured by means of a tipping rain gauge connected to the same datalogger.

Figure 3.3 The automatic weather station used to collect daily weather data for the computation of the FAO Penmen -Monteith equation.

3.4.1.2 Soil water content

Soil water content was measured every 2 weeks at 10 cm depth intervals up to 1 m. The gravimetric method was used for measuring soil water content in the top 10 cm layer by means of augering. The Wallingford neutron probe (MK II type) was used to measure soil water content in the lower layers. Soil water content readings using the neutron probe were taken from aluminium access tubes which were installed in the field to a depth of 1.2 m. The positioning of the access tubes was random.

The samples for the 10 cm depth obtained from the site were weighed and oven dried at 105 °C for at least 24 hours. The gravimetric soil water content was converted to the volumetric water content using the equation 2.9 (section 2.3.2.1).

Calibration of the Neutron Probe

Calibration of the neutron probe (Fig 3.4) was carried out by the regression of the volumetric water content determined using the gravimetric technique against the count ratio (R/R_w) given by the count rate in the soil profile at different depths in the field (R) and that of standard count determined in a drum of water (R_w). The site was first flooded and samples and neutron probe readings made after 3 days. Thereafter the readings were taken following guidelines provided by Evett and Steiner (1995. Four gravimetric samples were obtained near the access tubes at different soil depths. Figure 3.5 illustrates how gravimetric samples were collected.

Figure 3. 4 The Wallingford neutron probe used for soil moisture measurement

Figure 3. 5 Collection of soil samples around the access tube for neutron probe calibration.

The soil samples collected around the access tube for calibration of the probe (Fig 3.5) were oven dried and volumetric water content was obtained using equation 2.8 and 2.9. The data obtained over the period was split into 2 data sets to enable the calibration and validation of the determined equations. Validation was therefore done using independent data from that used to calibrate the equation. As pointed out by Jaywardare *et al.,* (1983) for accurate field soil water measurement, separate calibration equations are required to account for different soil densities and textural changes in different layers. The first soil data was pooled (taken as one layer for the whole root zone) and a calibration line was determined. Later separate regressions were done for the different soil layers identified during the characterization of the soil layers.

3.4.2 Aboveground biomass

Destructive sampling at regular intervals was used in this project for obtaining biomass yield. The sampling was at two weekly intervals from approximately the end of the establishment phase of the crop (30 days after sowing) to biological maturity (Raes *et al.,* 2004). At harvest aboveground biomass was also determined for the computation of the harvest index. Plant samples from each plot were selected randomly for biomass measurement from the two rows outside the net plot area. The outer rows of every plot were left intact and the net plot was guarded by one inner row, which was not harvested for biomass to cater for the edge effect. The samples were oven dried at 80 ^{0}C for at least 48 hours. The dry weight of each sample was obtained by weighing with a digital scale balance.

3.4.3 Maximum rooting depth

Immediately after harvesting the maize crop, the maximum rooting depth was determined by digging three pits up to 1.5m near the three varieties so as to inspect of the pits for maximum rooting depth. The profile was wetted with water to facilitate the inspection where roots were not readily visible.

Figure 3. 6 The soil profile exposed to inspect for maximum rooting depth

3.4.4 Grain yield

The four central lines (net plot) were harvested in each plot for yield measurement. Each net plot had an area of 27 m^2. The grain was weighed fresh and a crop moisture metre was used to measure the moisture content of the grain at harvest. The fresh weight was standardized by adjusting to 12.5% moisture content by calculating the equivalent mass at standard moisture using equation 3.5 The harvest index was calculated as the ratio of standardized grain yield to the dry above ground biomass at harvest

$$m_{std} = \frac{m_f(100 - M\%)}{100 - 12.5\%} \qquad (3.5)$$

where;

m_{std} = the grain mass at 12.5% moisture content

m_f = the measured mass of grain at M% moisture content wet basis at harvest.

3.5 Validation of the BUDGET Model

Crop transpiration was determined using the BUDGET model. The model is described in detail in §2.5. To estimate actual transpiration a simple water budget to account for inputs and outputs into the root zone was carried out using the model. After specifying the climate, soil and crop parameters and setting the initial soil water conditions at the soil moisture content measured prior to planting, simulation was started. Soil water content in the top 60 cm was considered. This is because the 60cm was given as the effective depth due to the presence of gravel layer.

To validate the BUDGET model, the simulated root zone water content was compared to root zone water content measured by means of a neutron probe (Raes *et al.,* 2005). The observed water content was monitored at regular intervals using the neutron probe. The soil moisture measurements were carried out for the 1.2 m depth but for model validation the first 60cm of the soil profile was considered. To assess how well the budget model predicted observed soil moisture a regression of observed and simulated soil water content was done and statistical parameters (RSME, R^2 value , slope and SE) were used to analyze the validation. Table 3.3 shows the inputs used in validating the model.

Table 3. 3 Inputs used to validate the BUDGET model:

input	value	units
crop parameters		
length of growing season	*SC719(165)*	days
allowable depletion	0.5 (default)	
growth stages	25(i) 40(d) 65(m) 35 ((l)	days
kc	0.17-1.1(0-25) 1.20(65-130) 0.35(131-165)	
sowing date	27 october	
harvesting date	april 5th, 2007	
rooting depth	0.3(0-25) 0.30-1.0(26-65) 1.0(66-165)	metres
soil data		
saturation water content	45.3 vol %(1st) 47 vol %(2nd) 50.0(3rd) soil layer	
field capacity	32.1 vol %(1st) 35.5 vol %(2nd) 39.0(3rd) soil layer	
wilting point	15.0 vol %(1st) 26.0 vol %(2nd) 26.0(3rd) soil layer	
drainage factor (tau)	0.45; 0.42; 0.40	cm^3cm^{-3}
infiltriation rate ksat	150;75;100	mm dy^{-1}
curve no.	75(CN)	
climatological parameters		
daily ET_0	daily input	mm
daily rainfall	daily input	mm
daily irrigation	daily input	mm

3.6 Modelling maize transpiration

To simulate transpiration in the different varieties the following parameters were used as inputs into the BUDGET model. The similar data to for soil and climate parameters to validation was used in running the model to determine maize transpiration, only the crop parameters distinguished the runs for the 3 models the crop parameter input for the 3 varieties is shown below;

Table 3. 4 Crop parameters used in the model to simulate transpiration

Crop parameter	**SC 719**	**SC 635**	**SC 403**
Length of growing season	165	150	140
K_c	***0.17-1.10 (I); 1.10-1.20(M);1.20-0.35(L)***	***0.17-1.10 (I); 1.10-1.18 (M);1.18-0.31(L)***	***0.17-1.10 (I); 1.10-1.15 (M);1.15-0.30(L)***
Sowing date	27 October	27 October	27 October
Rooting depth	1.00	0.70	0.60
Growth stages	*I (25) CD (40) M(65) L(35)*	*I (20) CD (40) M(60) L(30*	*I (20) CD (35) M(55) L(30)*
Harvesting date	9 April	25 March	15 April

Table 3. 5 Soil parameters used to simulate transpiration

Soil parameter	1st layer	2nd layer	3rd layer
Saturation water content (vol %)	45.3	47	50
Field capacity (vol %)	32.1	35.5	39
Wilting point (vol %)	15	26	26
Drainage factor (cm^3 cm^{-3})	0.45	0.42	0.40
Infiltration rate mm dy^{-1}	150	75	100
Curve no.	75		

The daily weather input and irrigation input are shown in table of the appendix

3.7 Determination of maize water productivity

Water productivity in this study was defined as the ratio of above ground biomass to cumulative transpiration. The validated BUDGET model was used to simulate daily actual crop transpiration for each variety which differed in terms of the crop parameters that were input into the model as shown in table 3.4. Aboveground biomass collected at two-week intervals was plotted against the cumulative transpiration. In this case, the difficult of extracting all roots in this type of soil at the site was a contributing factor to the choice of numerator as above ground biomass.

3.8 Normalization of CWP

Normalization was carried out to enable WP to account adequately for the climatic differences that govern crop growth, yield production and water productivity (van Heslema, 2003.The normalized water productivity WP* in this case was obtained by plotting above ground biomass against sum (actual transpiration/ ET_o) .

3.9 Prediction of maize yield at a different site (ART farm)

The determined water productivity yield equations were applied to ART farm yield data to evaluate how the predicted and observed yield would compare. To allow the comparison of predicted and observed grain yield, the determined WP* was converted to grain yield by means of the harvest index This was done by using the Harvest Index (HI) and Normalized water productivity to predict yield for maize 3 seasons (2000-2001; 2002-2003 and 2004-2005) (section 3.8) For 400, 600 , 700 series which are the early maturing varieties, medium maturing varieties and late maturing varieties (Seed Co , 2004) the following assumptions were made;

- Each series had similar yield potential thus where the exact variety was not available the yield of the close member in the series was used.
- Transpiration and growth characteristics were assumed to be the same for all members in a series and hence the input and output in the BUDGET model was the same for all members in one series.

The cultivar specific values for inputting into the BUDGET model were therefore the same as those given for the different cultivars in table 3.4. The crop was rainfed and the actual weather input data is given in appendices J

Data on the following parameters was collected from ART farm for 3 seasons (2000/01; 2002/03 and 2004/05).

- Historical daily rainfall data
- Daily ET_o for the site
- previous maize yield

BUDGET model was run to simulate crop transpiration. Aboveground biomass was calculated using equation 3.6 and the harvest index (equation 3.7) below were applied to determine the expected yield. Expected with observed yields were compared. Transpiration for the maize varieties was simulated by BUDGET model using input data on crop, soil and climate parameters provided for the site. Weather data input on rainfall and ET_o were provided for the site

$$WP^* = AB \Big/ Sum(T_{act} / ET_o) \qquad (3.6)$$

$$HI = E.yield \Big/ TB \qquad (3.7)$$

Where

WP is normalized water productivity*

AB is aboveground biomass

B_m is total biomass

E.yield is economic yield

HI is the harvest index

3.10 Statistical Analysis

GENSTAT statistical package was used for regression analysis and analysis of variance in this study. The package was also used to carry out regression analysis of neutron probe count against volumetric water content and observed versus simulated water content in model calibration and validation.

Regression analysis was also carried out for the above ground biomass and cumulative transpiration in determining water productivities and aboveground biomass and sum (actual transpiration/reference ETo) for normalized water productivity. The statistical parameters of R^2, RMSE, CRM and slope standard errors were used to compare simulated and measured root zone water content.

Statistical analysis of water productivity and yield data was done by means of Analysis of variance (ANOVA) and separation and comparison of the means was done using the least significant differences using GENSTAT statistical package. The results were said to be significant if the probability of obtaining this result or a more extreme one when the hypothesis being tested was true was less than 0.05.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Rainfall and Reference Evapotranspiration for the season.

The BUDGET model requires as input daily rainfall and reference evapotranspiration. The reference evapotranspiration was calculated using the FAO Penman Monteith Equation (§3.4.1.1 and §2.4.1). Meteorological parameters of temperature, relative humidity, wind speed and solar radiation required to calculate $ET_{o,}$ were recorded daily on site by means of an automatic weather station. Daily meteorological values were summarized into dekadal meteorological data for the season and presented in Appendix A, table A1.

The rainfall and reference evapotranspiration observed at the university farm during the season 2006/7 per dekad is presented in Figure 4.1.

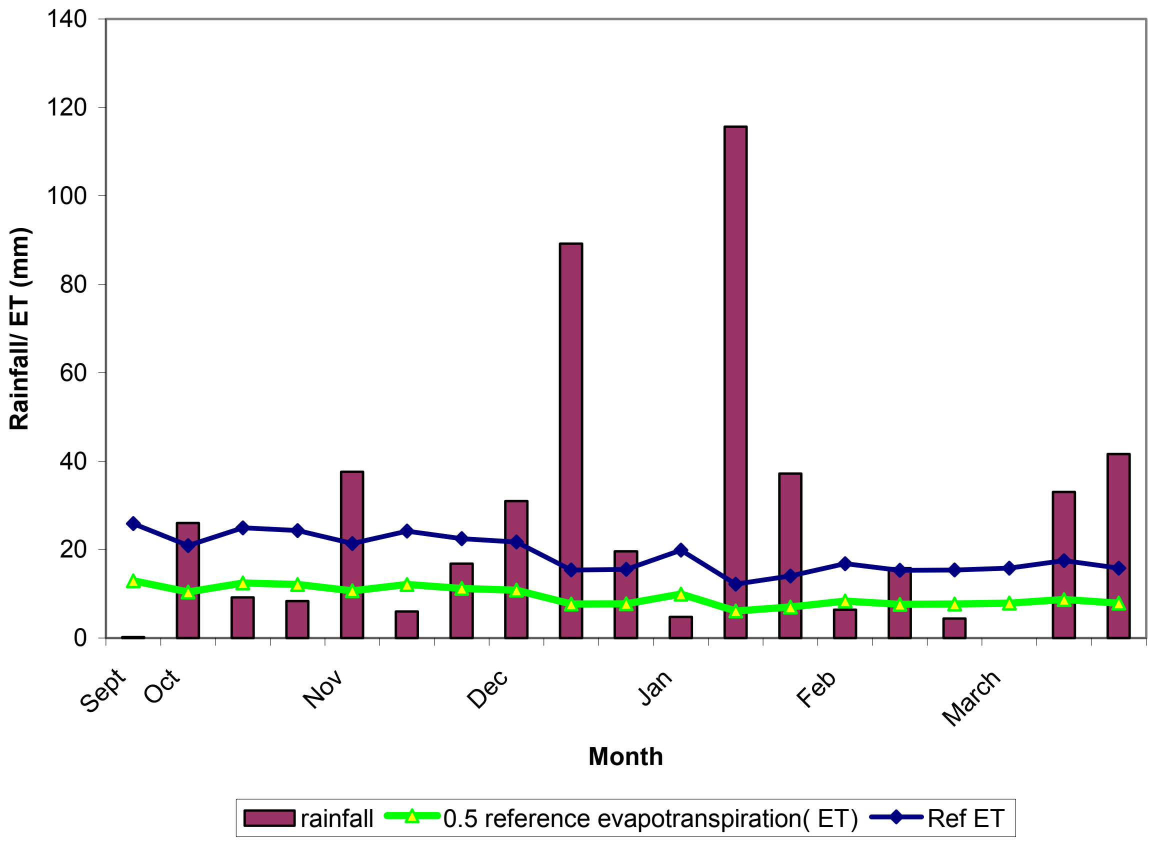

Figure 4. 1 Dekadal observed rainfall and calculated ET_0 during the growing season (October 2006 to March 2007)

A total amount of 505.2 mm was received during the 2006/7 growing season. Some dekads of the season had very little or no rainfall while some received substantial amounts. The most wet dekad was second dekad of January with 115 mm of rainfall. About half of the dekads were dry (rainfall less than 0.5 ET_o).

The observations indicated the poor distribution of rainfall which often characterises areas in semi - arid climates. The growing season was a dry one as a total of 505 mm were received in an area which receives on average 750 to 1000 mm (Vincent and Thomas, 1961).

4.2 Soil characterization

The soil characterization for textural and water retention properties was done so as to use as input into the BUDGET model (§2.5.1 and §3.5.1). The textural properties of the soils on the site are presented in Table 4.1. The soil profile was not uniform and 3 layers could be distinguished. The soil particle composition changed with depth. The soils for the site were generally sandy loam in texture. The detailed soil profile description is given in Appendix C, table C1.

Table 4. 1 Soil textural properties determined for the research site

depth (cm)	clay %	Silt %	Sand %
0-20	27	18	56
20-39	31	19	49
39-60	34	21	45

The water retention properties of the soil are presented in Table 4.2.

Table 4. 2 Soil water relations at UZ research site, UZ farm

Depth	**Bulk density**	**Field capacity**	**Permanent wilting point**	**AWC**	**Available water in horizon**
(mm)	*g cm^{-3}*	*mm /10 cm*	*mm /10 cm*	*mm /10 cm*	*mm*
0-20	1.34	34.4	26.7	7.7	15.4
20-39	1.45	32.1	20.2	11.9	22.6
39-54	1.59	35.1	18.4	16.7	25.1

The bulk density and water retention characteristics changed with depth. The bulk density ranged between 1.34 and 1.59 g cm^{-3}. The top 60 cm of the soil profile will hold about 63 mm. The changes in the bulk density and water retention properties can be linked to the changes in the clay content with depth.

4.3 Neutron probe calibration

Soil moisture measurements were taken by means of the neutron probe (§3.4.1.2). Calibration of the neutron probe is always necessary to correct for the presence of bound hydrogen not in the form of water and research has shown that calibration equations are always site specific and reflect textural properties (Dickey, 1990).

Soil data was first pooled and calibration equation was determined (§3.5.3). Pooling refers to averaging for the whole root zone and separation by layers to take into consideration the different soil layers within the root zone. Separation of soil data into different layers was done as soil characterization revealed that the soil profile was not uniform and therefore to account for different textural changes and density changes ((§3.4.1.2).

The regression analysis of the mean volumetric water content against the count ratio for pooled data was able to account for 84% of the variance.

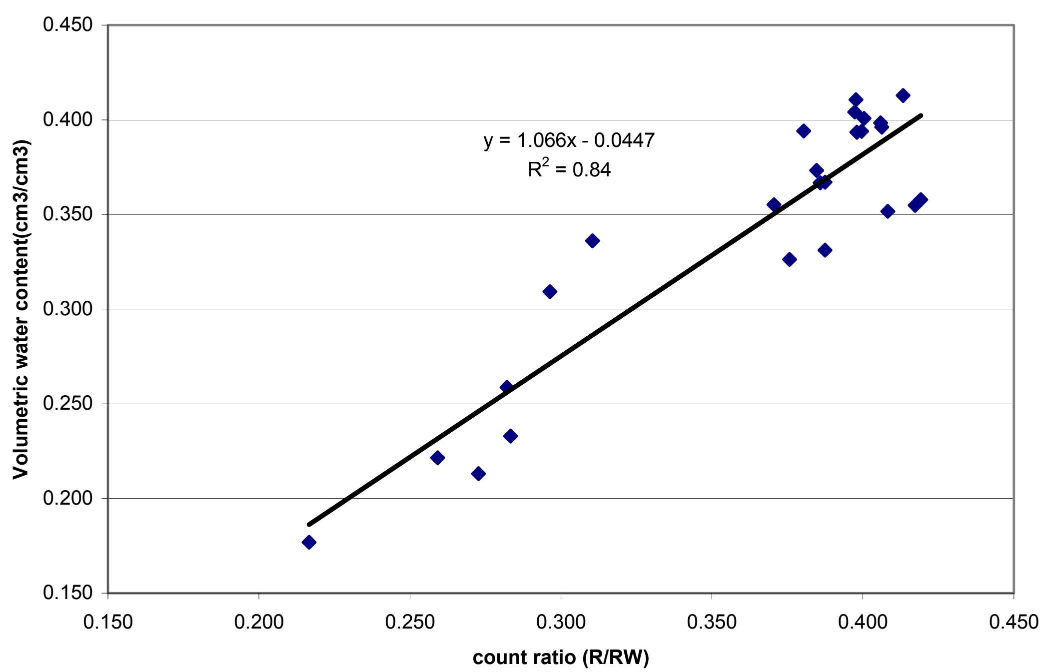

Figure 4.2 The relationship between count ratio and volumetric water content for the site using pooled (averaged for the whole rooting zone) data.

Table 4.3 shows regression analysis results for the separate soil layers and the regression graphs are shown in Appendix D, Figures D1-D4.

Table 4.3 Calibration equations determined for the site using separate soil layers

Depth (cm)	Slope	Intercept	Regression coefficient	SE
0-20	0.92	-0.02	0.99	0.004
20-40	0.99	-0.04	0.95	0.010
40-60	1.10	-0.065	0.86	0.029
60-100	0.90	+0.03	0.80	0.021
Pooled data (0-60cm)	1.07	-0.04	0.84	0.027

The table shows that there was a very good relationship between volumetric water content and count ratio (R^2 between 0.80-0.99) for separate soil while pooling data gave an R^2 value of 0.84.In the calibration of the neutron probe, inclusion of different equations for each soil layer improved the regression relationship as the variance explained by determined equations is much higher ($R^2 > 0.84$) with the exception of the 60-100 cm layer with an R^2 of 0.80 as shown in Table 4.3. The lower R^2 in the 60-100 cm can be explained by the fact that the soil characterization considered the upper 60 cm which was the effective depth and hence lower layers were not properly defined.

The standard errors obtained for separating soil layers are much smaller than for pooling data (except the 40-60 cm layer, SE of 0.029) showing that using separate calibration equation for each layer can give a better estimate of the volumetric water content. The standard errors of soil water content for neutron probe calibration ranging from 0.4 to 2.9 % compare favourably with other reported values of 1.5-3.2 % (Parkes and Siam, 1979), 1% (Everett and Steiner, 1995) and 5% (McGowan and Williams, 1980).

4.4 Crop performance

4.4.1 Biomass

The aboveground biomass dry weight was used to assess the performance of the different varieties as presented in figure 4.3. Variety SC 719 yielded the most biomass (2368 g/m^2), at the end of the season than the other 2 varieties, followed by SC 635 (2206 g/m^2) and lastly SC 403 (2026 g/m^2). During the first 8 weeks the biomass accumulation for the three varieties was comparable with an almost linear increase in biomass between the 6th and 13th week however from the 10th January, marked differences in varieties were observed.

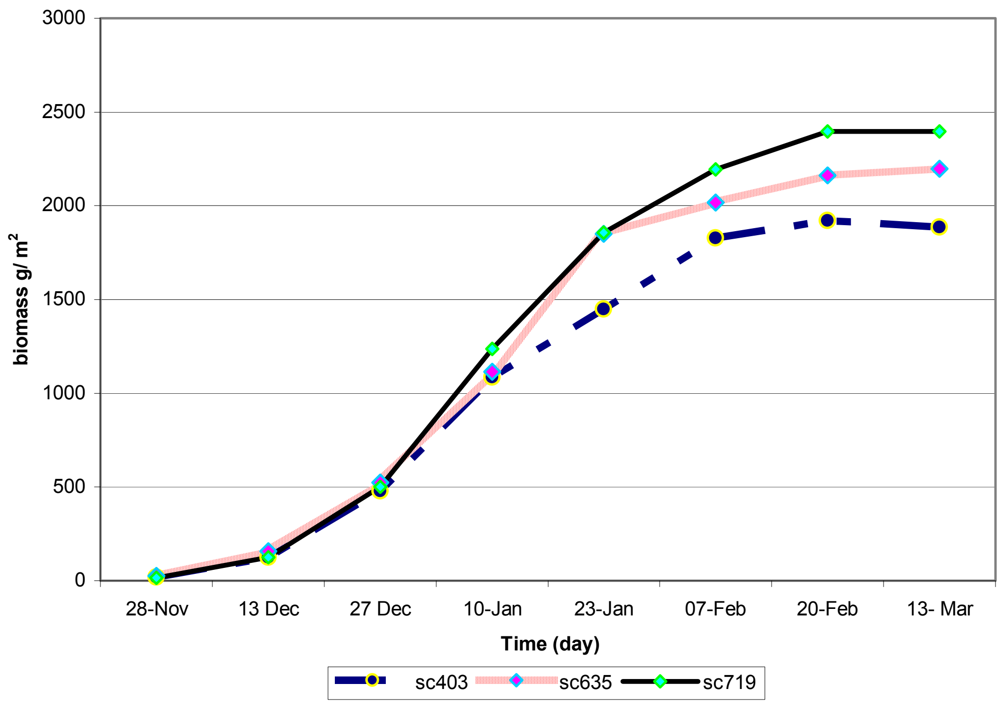

Figure 4. 3 Biomass production performance for the 3 varieties

The observed biomass production pattern can be attributed to the fact that after an initial lag , leaf area production increases rapidly upto flowering when maximum LAI is attained after which leas area production decreased as senescencing starts to occur until harvesting.

SC 719 had more vegetative mass and grow taller than the other varieties because of the length of its growth season and inherent yield potential it tends to grow taller and accumulate more biomass before entering the reproductive stage compared to shorter season varieties (Seedco manual, 2005).

4.4.2 Crop yield

Figure 4.4 summarize the yield results for the 3varieties.

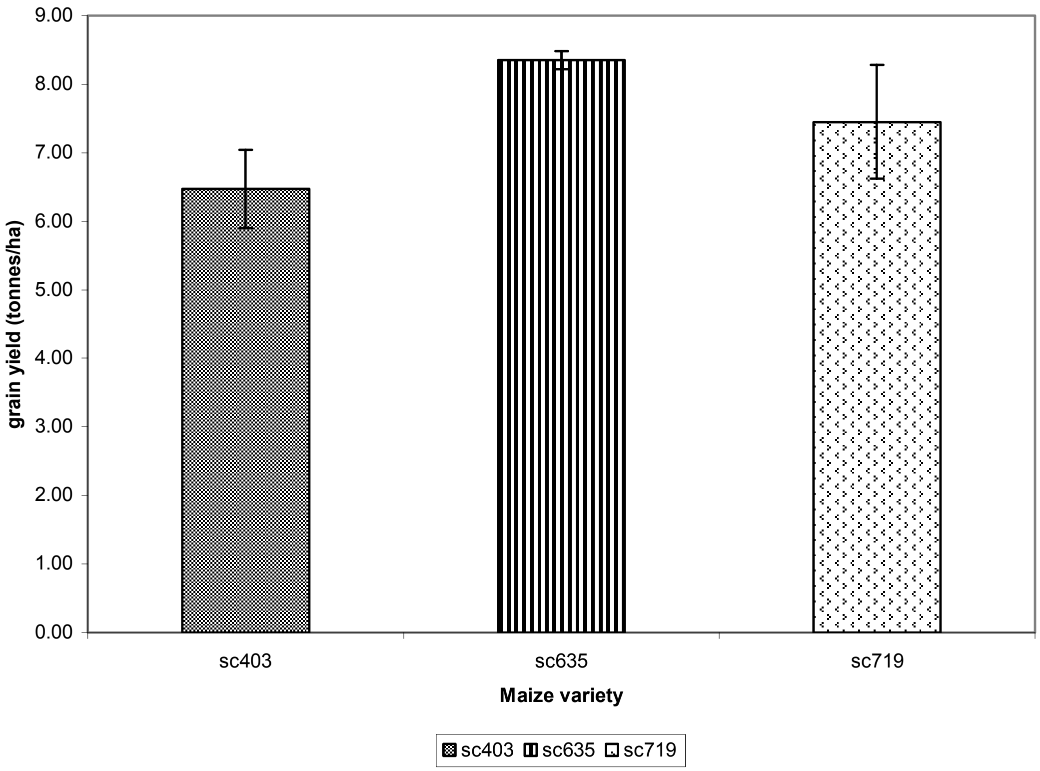

Figure 4.4 Grain yield of the 3 maize varieties

The grain yield obtained ranged between 6.47-8.35 Tonnes /hectare. The highest yield was produced by SC 635 yielding highest 8.35 t ha^{-1} followed by SC719 had 7.45 t ha^{-1} while SC 403 yielded average of 6.7 t ha^{-1}. There was much variation in the yield of cultivar SC 719 while minimal variation was observed in SC 635.

Summary of the statistical analysis for yield variation is presented in Table 4.4 below. And the ANOVA tables are in Appendix F.

Table 4. 4 Summary of the analysis of mean yield differences between the 3 varieties

Treatment	**Mean yield**	**Standard Deviation**
SC 719	7.45_a	0.83
SC 635	8.35_b	0.13
SC 403	6.47_c	0.57
SE	0.291	
LSD	0.712	

Subscripts $_{a, b, c}$ represent significant and non significant differences in mean yield- varieties with yield followed by the same subscript do not differ significantly in the mean yield.

The analysis showed that the yield differences were significant at the 10 and 5% level. Further analysis of the differences of the means showed that the mean yield for SC719 was different from that of SC625 and SC403.

The observed yields fall within the expected range of potential yields in the region as provided by SeedCO Product manual (2005), SC 403 (4-8 t ha^{-1}); SC 635 (5-10 t ha^{-1}); SC719 (7-13 t ha^{-1}). SC719 did not do well, as it was expected to out perform SC 407 and SC635. This was probably as a result of water stress at the beginning of the yield formation stage. SC 403 and SC 635, which mature earlier than SC 719, seem to have accumulated more assimilates when the crop could not be irrigated as the irrigation pump had broken down and hence their yield formation was not severely restricted as in SC 719.

4.5 Model validation

Model validation was done by comparing the measured and simulated root zone water content in the top 60 cm of the soil profile as detailed in Chapter 3 (Raes et al ,2005) For model validation only SC 719 was taken into consideration, inputs into the model for validation are given in Table 3.3 in Chapter 3 of this thesis. The soil water content was measured by means of a calibrated neutron probe. The soil moisture measurements used to compare against the simulated water content are given in appendix , E, table E1. At least two plots were measured each time to give the mean water content. Following the method used by Raes et *al.,* 2005 the model simulated water content was also checked to see how it performed around the range of measured soil water content.

The simulated and observed root zone water content is shown in Figure 4.5. The simulated water content generally agrees with the observed water content as shown by the fact that the simulated water content is within (+/-) standard deviation ranges of the observed water content. The points in the graph where water fell almost to wilting point (DOY 47-68) occurred during the time when the irrigation pump was down.

To assess how well the BUDGET simulated root zone water content, simulated water content was plotted against the observed content (Figure 4.6). Further statistical analysis to assess the performance was done using (RSME, CRM, R^2 value, slope and intercept). The statistical analysis showed, RSME = 5.84%, CRM=0.46, R^2 = 0.85, Slope= 1.06

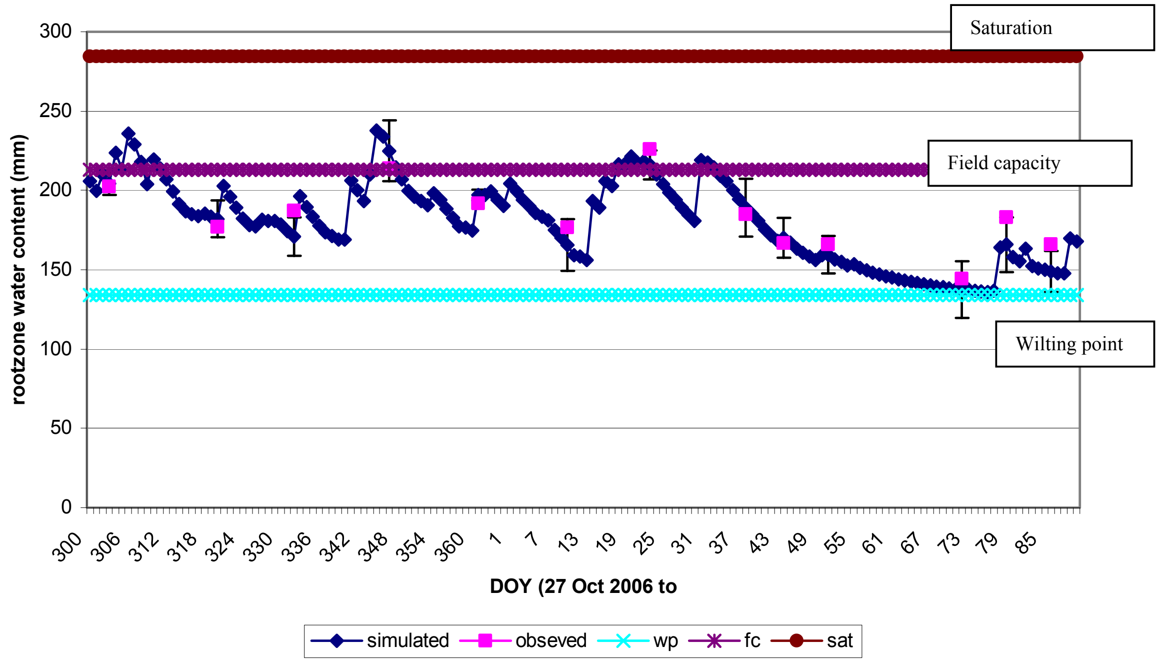

Figure 4. 5 Validation graph - Simulated and measured soil water content in the root zone water content.

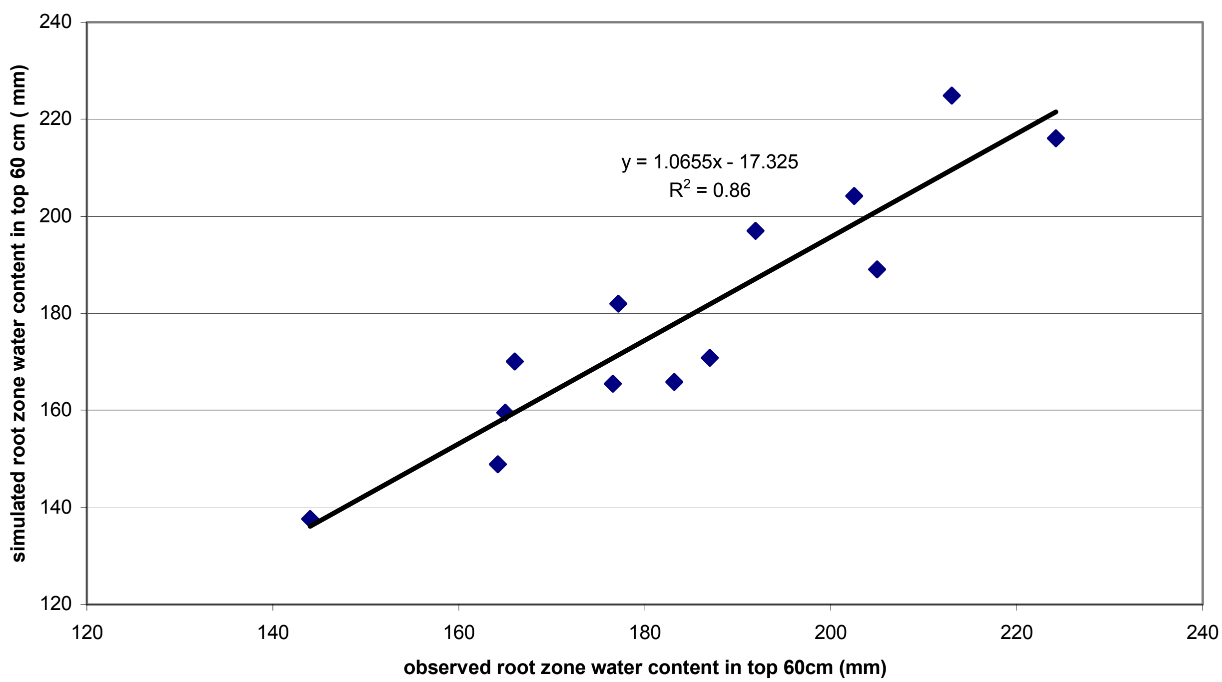

Figure 4. 6 The regression graph of the validation of BUDGET simulated water content versus measured values using SC 719 during 2006/7 season.

The simulated soil water content in the soil profile showed a good agreement with observed data. The model was able to match the sharp increases and decreases in water content and closely predict soil water content within the standard deviation range of the observed values (Fig 4.5).

An R^2 value of 86 % found by validation of the BUDGET model, indicates the strength of BUDGET in simulating root zone water content. The slope of the correlation between observed and simulated water content is close to 1 suggesting a close relationship between observed and simulated root zone water content. The model tends to under estimate the mean observed soil water content by 5.8 % (RSME). The CRM (The coefficient of mass residual) expresses the relative size and nature of the error. The CRM of 0.5 was close to zero (optimal) but positive, showing that the model tends to some extent to under estimate the soil water content measurements.

4.6 Crop transpiration

The cumulative transpiration for the 3 varieties is presented in figure 4.7

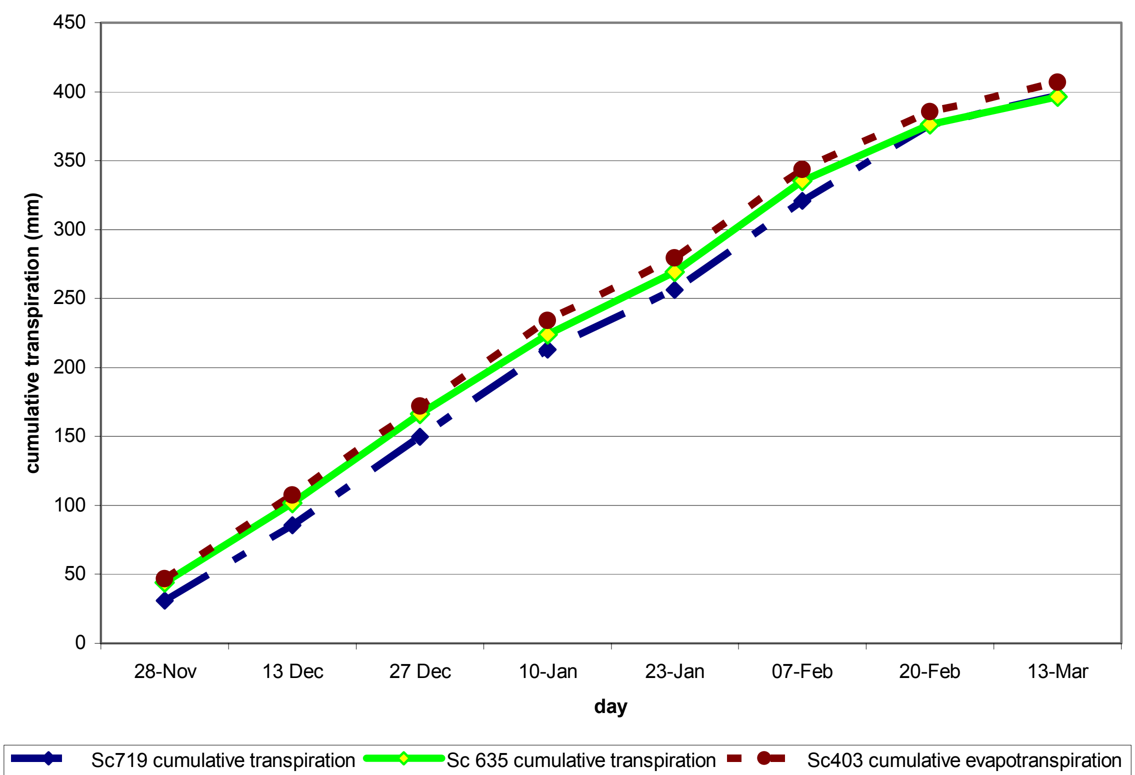

Figure 4. 7 Cumulative actual transpiration for the 3 varieties

The inputs into the BUDGET for simulating transpiration for the different varieties differed in terms of the crop parameter used to simulate transpiration for each variety as shown in Table 3.4. The soil and climatic parameters inputs into the model were the same. The output of the simulation for the 3 varieties is summarized in Appendix G, table G2.

Variety SC 403, on any given day, tended to transpire more than SC 635 and SC 719. This can be explained by the fact that this is a short season variety and hence morphological (leaf area) and physiological development is faster (SeedCO manual, 2004). For the same reason the medium maturing variety SC 635 transpired more on any given day than SC719.

4.7 Water productivity

Water productivity for maize was determined by plotting aboveground biomass against calculated cumulative transpiration.

4.7.1 Water productivity for the 3 varieties

Plotting aboveground biomass to cumulative transpiration for the whole season gives an S shaped curve rather than straight line as shown in figure 4.8. The trend observed here is for a non linear response at the beginning and towards the end of the season while a linear response can be observed in the middle of the growing season.

Aboveground biomass is not linearly related to transpiration over the entire growth season. The non linear response observed can be attributed during the first 5 weeks more water was being lost without a corresponding increase in biomass yield and at the end of the season when the response is no longer linear this can be attributed to senescencing of the plant. Thus the stage of rapid crop development tend to plot a linear biomass to transpiration line(Stewart and Musick, 1982). Also grain formation appears to affect the linearity of the relationship suggesting that there is little increase in cumulative transpiration at high levels of resource use as hypothesised by Purcell et al. in their study of yield response to transpiration in soyabean.

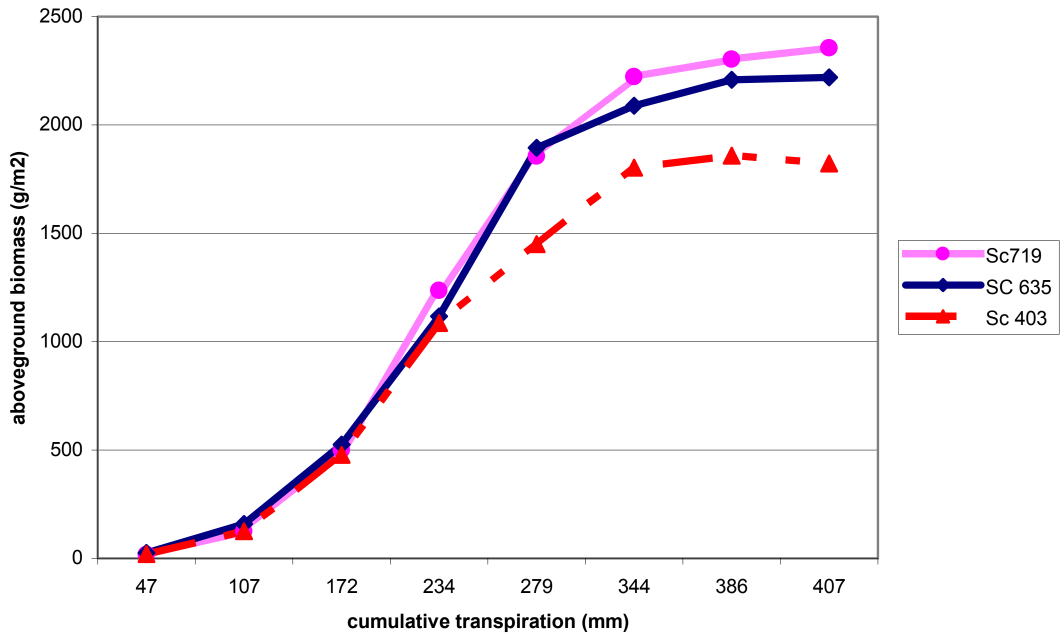

Figure 4. 8 Graph of aboveground biomass versus cumulative transpiration for the growing season

The slope of this linear response of aboveground biomass to transpiration was taken to indicate crop water productivity. The water productivity of SC719, SC635 and SC403 are shown in Figures 4.9 and Appendix H shows the water productivity values for individual varieties and plots.

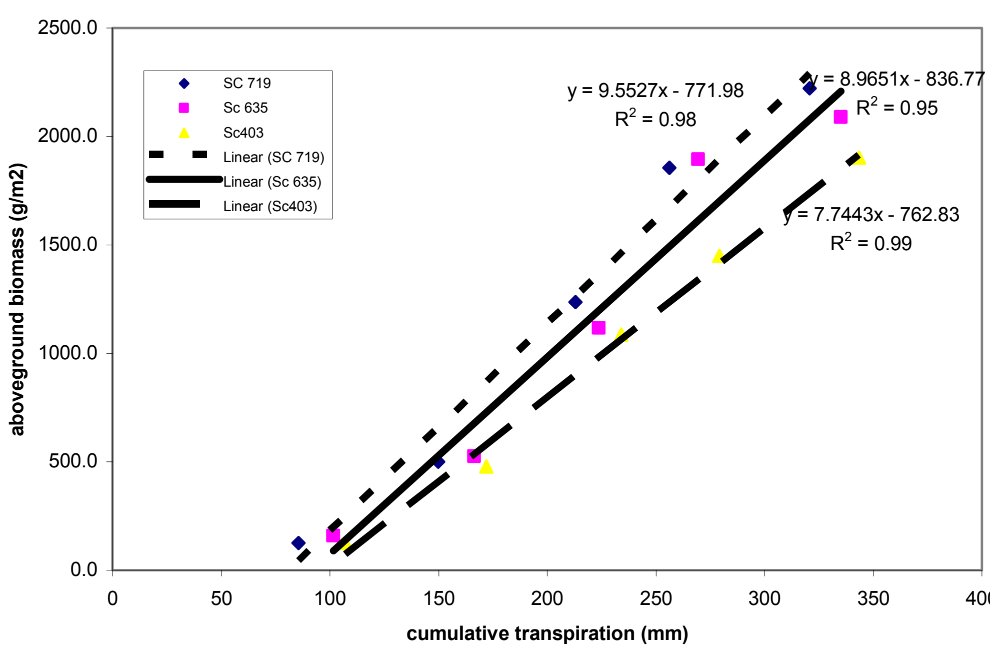

Figure 4. 9 Water productivity for the three varieties.

The determined water productivity was in the range of 7.7 to 9.5 g/m^2 per mm. SC 719 had the highest WP and SC403 had the lowest value.

The high R^2 (0.95- 0.99) values obtained support the strength of the relationship between aboveground biomass and cumulative transpiration. Statistical analysis of the water productivity values for each plot showed that there were no significant differences in water productivity among the varieties, ANOVA table in Appendix H, ($p > 0.05$). The mean water productivity values for the 3 varieties is shown in Table 4.5

Table 4. 5 Mean values for maize water productivity for the 3 varieties (WP)

treatment	**Mean WP**
SC 719	9.57
SC 635	8.96
SC 403	7.74
SE	0.475

The linearity of the relationship between aboveground biomass and cumulative transpiration can be explained by that both transpiration and biomass share the same transport pathway and are driven both by solar radiation thus they tend to be closely related ((Steduto, 2006).

Most crop water productivities reported in literature are based on grain yield and on evapotranspiration because of the challenges involved in measuring actual transpiration. From such studies it is expected that the trend will be for aboveground biomass and cumulative transpiration relationship to remain linear as transpiration and evapotranspiration are closely correlated. Comparison of the actual figures however is not possible as evaporation losses from soil surface are not included and the ratio of grain to biomass is about half.

4.7.2 Normalized water productivity

Water productivity was normalized using reference evapotranspiration (§2.3.4 and §3.7). The normalized water productivity (WP*) was obtained by plotting aboveground biomass against sum of (transpiration/ET_O). Normalization allows the WP to be used among different environments.

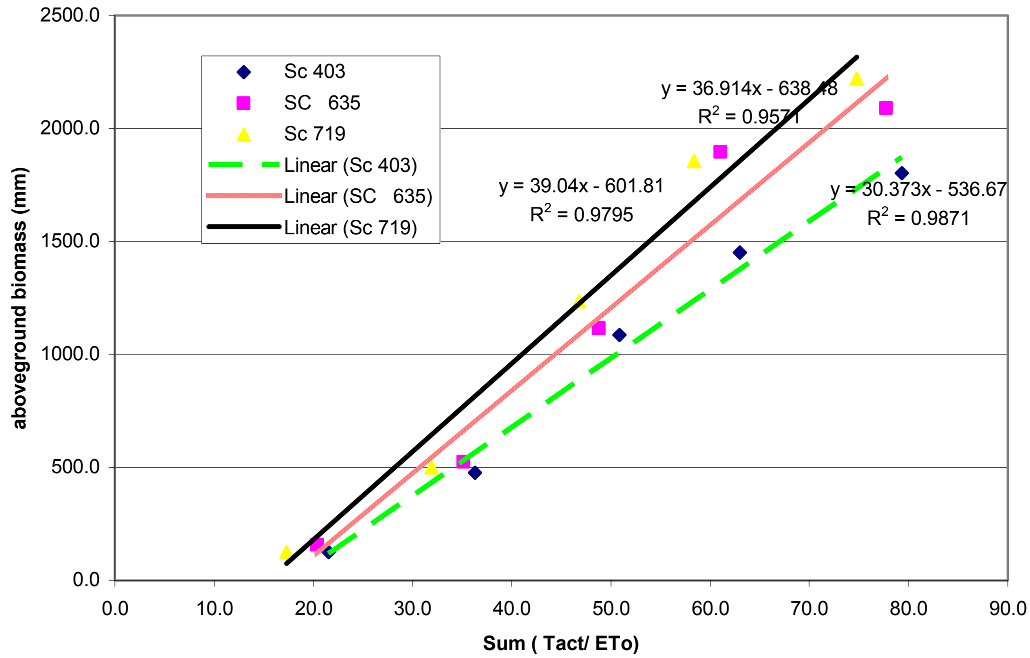

Figure 4. 10 Normalized water productivity for SC403

The normalized water productivity ranged from 30.4 and 39 g/m^2. Normalization of the obtained water productivity values resulted in a positive and linear relationship between aboveground biomass and cumulative transpiration.

The statistical analysis of the of normalized water productivity are shown in table 4.6

Table 4. 6 The Mean values for normalized water productivities for maize varieties

treatment	**Mean WP***
SC 719	39.0
SC 635	36.9
SC 403	30.3
SED (+/-)	1.95

The statistical analysis of data revealed no significant differences between varieties at 5 % level (p> 0.05). The lack of apparent differences in normalized among the varieties was predicted by Steduto *et* *al.,* (2007) and van Halsema, (2003) who also state that varieties with similar rates of biomass production can then be grouped together in one linear WP expression for a fairly large group of crops.

4.8 Prediction of maize yield at ART Farm for 3 seasons

The determined water productivity yield equations were applied to ART farm yield data to evaluate how the predicted and observed yield would compare. The crop was rainfed and the cultivar specific values for inputting into the BUDGET model were therefore the same as those given for the different cultivars in table 3.4 and the weather input is shown in appendix I. In line with the stated objectives in this paper WP and WP* in terms of above ground biomass were used to determine grain yield was predicted from WP* using equations 3.6 and 3.7

To allow the comparison of predicted and observed grain yield, some assumptions were made . For 400, 600 , 700 series which are the early maturing varieties, medium maturing varieties and late maturing varieties (Seed Co , 2004) the following assumptions were made;

- Each series had similar yield potential thus where the exact variety was not available the yield of the close member in the series was used.
- Transpiration and growth characteristics were assumed to be the same for all members in a series and hence the input and output in the BUDGET model was the same for all members in one series.

The output application of the determined WP* and HI to predict yield at ART farm for 3 seasons is shown in table 4.

Table 4. 7 The observed and simulated yield for the 3 varieties for 3 seasons at ART farm

variety	wp*	sumTact/Eto	est abv .biomas g/m2	Harvest index	Simulated yield (T/Ha)	Observed yield(T/Ha)
2000-2001						
SC 713	39	111.14	4334.5	0.31	13.44	9.81
SC 633	36.9	123.90	4571.9	0.38	17.37	13.538
SC 403	30.3	113.40	3436.0	0.35	12.03	8.865
2002-2003						
SC713	39	94.84	3698.8	0.31	11.47	8.96
SC627	36.9	85.53	3156.1	0.38	11.99	9.21
SC405	30.3	75.03	2273.4	0.35	7.96	5.865
2004-2005						
SC719	39	102.43	3994.8	0.31	12.38	9.46
SC627	36.9	101.82	3757.2	0.38	14.28	10.93
SC403	30.3	114.70	3475.4	0.35	12.16	8.967

The resulting regression analysis for the combined seasons is shown in figure in Figure 4.11 .

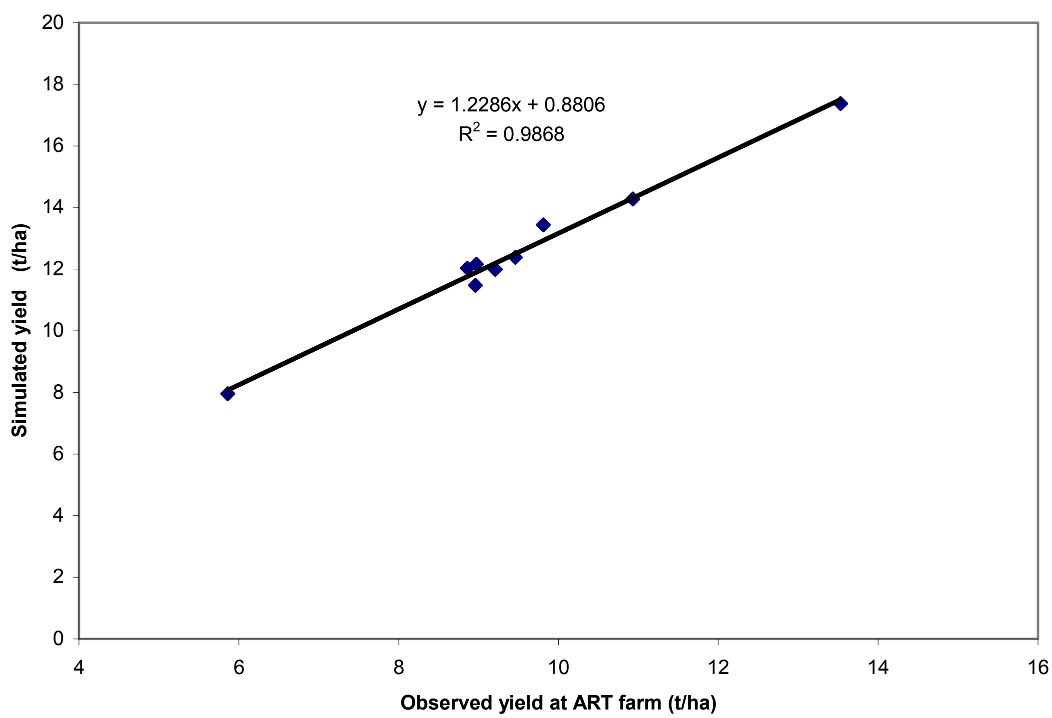

Figure 4. 11 Regression of Simulated against observed yields at ART farm

The regression analysis obtained was highly positive with an R^2 value of 0.98. The yields predicted for ART farm for the 3 seasons are comparable to the observed yield and the regression analysis of the predicted yields against the simulated yield showed a highly positive and linear relationship with an R^2 value of 0.98. Clearly the coinciding of planting date with that used in determining the initial WP* values improved the accuracy of the results. The high management level at the ART farm (Personal communication with Research manager- Mr Mutemeri) meant that management was good thus removing the element like pest and diseases and nutrition which can affect the robustness of the water productivity. The effect of water components on yield was taken into account using the BUDGET model to predict yield.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The strong relationship between simulated and measured root zone water content (R^2 of 0.85) using variety SC 719 indicated that the BUDGET model can be used to predict transpiration.

Although yield- water use has been widely reported as linear especially under water limited conditions, in this study plotting of aboveground biomass to cumulative transpiration for the whole season gave a non linear relationship. By plotting aboveground biomass and cumulative transpiration for part of the season a highly linear relationship was obtained between aboveground biomass and cumulative transpiration (R^2 between 095-0.99) The determined water productivity ranged between 7.7 to 9.6 g m^{-2} m^{-1} The results imply that 7.7 -9.5 g/m^2 are produced per mm of water consumed.

From the findings in this study indicate that the linearity of biomass yield response to transpiration widely reported over the entire growing season and for an irrigated crop cannot be assumed. Clearly the water stress experienced by the crop may have played a part in shaping the nature of the curve of yield response to transpiration for the irrigated crop. The lack of significant differences among the varieties imply that no variety can be conclude to have had better water biomass yield –water relationship.

Literature tends to concentrate on grain yield to evapotranspiration, the range of crop water productivity reported around the world is 0.3 - 2.7 kg m^{-3} (grain yield) for maize (Bastiaanssen *et al.,* 2003) while FAO gives the CWP of maize as 1.6 kg m^{-3}. Comparison of the actual figures however is not possible as evaporation losses from soil surface are not included and the ratio of grain to biomass is about half. The inclusion of non grain component part as biomass will likely give higher WP values so the observed WP values are within the expected range.

The normalized water productivity also did not showed variety differences ($p>0.05$). Normalization of water productivity gave values in the range 30.3 and 39.0 g m^{-2}. The lack of significant differences among the varieties suggest that varieties of same crop can be grouped together in one linear WP expression for a fairly large group of crops (van Halsema, 2003).

Application of the determined water productivity and harvest index for ART farm data to predict yield revealed a strong agreement between simulated and observed yield (R^2 of 0.98). The results imply that water productivity with aid of BUDGET can be used to predict yield.

5.2 Recommendations

Based on the findings from the research the following recommendations are made for future research;

There is need to explore the sensitivity of water productivity to variety by further investigation on measured quantitative values for crop water productivity evaluated for different varieties over a longer time period (more than in one season).

The same study should also be evaluated under farmer managed conditions as indicated by the yield data, the research conditions might give higher water productivity values than obtained practically by the farmer on farm situations.

It is strongly recommended that the effect of water regime on water productivity be investigated, as this will shed more light on the crop yield to water use relationship. Since crop water productivity was investigated under optimal irrigation for this study it might be worthwhile to investigate the range of CWP for the same varieties under Deficit and Full irrigation.

Another calibration and validation of BUDGET model is needed before for the site the model can be used with confidence to predict transpiration which is critical for such a study.

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APPENDIX A

Meteorological Data

Table A1. Average Dekadal meteorological parameters recorded during the growing season.

Month	Dekad	T max oC	Tmin oC	T mean oC	RS MJ/m2.day	Wind spee m/sec	RH (max) %	RH (min) %
Sept	III	27.1	14.3	20.8	36.850	2.9	67.93	25.28
Oct	I	28.7	13.4	19.8	25.925	2.3	81.68	22.95
	II	27.1	15.4	20.3	31.075	3.0	87.68	35.38
	III	28.6	16.0	22.5	18.600	3.3	68.78	27.63
Nov	I	27.9	12.8	21.0	16.875	3.0	74.38	25.90
	II	28.1	16.5	22.2	22.100	3.8	89.35	33.40
	III	26.6	13.5	20.4	24.825	2.3	84.70	28.10
Dec	I	28.6	16.8	22.6	21.025	2.3	85.98	31.33
	II	27.2	17.1	21.2	16.600	1.3	93.28	48.70
	III	26.2	18.1	21.1	16.725	2.0	95.18	57.58
Jan	I	27.1	16.7	21.2	22.825	1.7	94.50	41.05
	II	23.9	17.0	19.5	13.700	1.6	95.68	67.50
	III	24.0	16.7	20.0	16.675	1.4	94.38	62.45
Feb	I	27.2	17.0	21.3	20.200	1.1	94.28	52.15
	II	25.3	14.3	19.6	19.100	1.0	95.33	50.08
	III	25.8	15.6	19.8	18.475	1.4	93.10	53.75
March	I	24.6	14.8	19.1	19.150	1.8	91.98	53.05
	II	28.3	13.4	20.3	22.225	1.1	95.15	37.75
	III	26.9	14.3	19.7	19.950	1.1	95.38	42.98

Table A2.Climatic data used to simulate transpiration

Day	Month	Year	ETo	rainfall)
			mm/day	mm
27	9	2006	7.4	0.0
28	9	2006	6.7	0.0
29	9	2006	6	0.0
30	9	2006	5.8	0.2
1	10	2006	6.2	0.0
2	10	2006	6.1	0.0
3	10	2006	6.3	13.2
4	10	2006	5.8	12.8
5	10	2006	7.6	0.0
6	10	2006	6.9	0.0
7	10	2006	6.5	0.0
8	10	2006	4.8	0.0
9	10	2006	3.4	0.0
10	10	2006	6.2	0.0
11	10	2006	5.9	0.0
12	10	2006	6	0.0
13	10	2006	6.3	0.0
14	10	2006	6.4	0.0
15	10	2006	6.6	0.0
16	10	2006	6.9	0.0
17	10	2006	5.9	1.4
18	10	2006	6.5	2.0
19	10	2006	6.2	5.8
20	10	2006	6.3	0.0
21	10	2006	7	0.2
22	10	2006	7.5	0.0
23	10	2006	7.8	8.4
24	10	2006	6.9	0.0
25	10	2006	7.8	0.0
26	10	2006	8.3	0.0
27	10	2006	8.5	0.0
28	10	2006	5.2	0.0
29	10	2006	5.3	0.0
30	10	2006	5.4	0.0
31	10	2006	8.4	0.0
1	11	2006	9.2	0.0
2	11	2006	6.9	35.4
3	11	2006	6.5	1.2
4	11	2006	5.9	1.0
5	11	2006	8	0.0
6	11	2006	6.2	0.0
7	11	2006	3.2	0.0
8	11	2006	5	0.0
9	11	2006	6.4	0.0
10	11	2006	6.8	0.0
11	11	2006	6.2	0.0
12	11	2006	9.7	0.0
13	11	2006	6.2	0.2
14	11	2006	2.9	4.8
15	11	2006	2.2	0.4
16	11	2006	3.1	0.0
17	11	2006	4.9	0.4

Day	Month	Year	ETo	rainfall)
			mm/day	mm
27	9	2006	7.4	0.0
28	9	2006	6.7	0.0
29	9	2006	6	0.0
30	9	2006	5.8	0.2
1	10	2006	6.2	0.0
2	10	2006	6.1	0.0
3	10	2006	6.3	13.2
4	10	2006	5.8	12.8
5	10	2006	7.6	0.0
6	10	2006	6.9	0.0
7	10	2006	6.5	0.0
8	10	2006	4.8	0.0
9	10	2006	3.4	0.0
10	10	2006	6.2	0.0
11	10	2006	5.9	0.0
12	10	2006	6	0.0
13	10	2006	6.3	0.0
14	10	2006	6.4	0.0
15	10	2006	6.6	0.0
16	10	2006	6.9	0.0
17	10	2006	5.9	1.4
18	10	2006	6.5	2.0
19	10	2006	6.2	5.8
20	10	2006	6.3	0.0
21	10	2006	7	0.2
22	10	2006	7.5	0.0
23	10	2006	7.8	8.4
24	10	2006	6.9	0.0
25	10	2006	7.8	0.0
26	10	2006	8.3	0.0
27	10	2006	8.5	0.0
28	10	2006	5.2	0.0
29	10	2006	5.3	0.0
30	10	2006	5.4	0.0
31	10	2006	8.4	0.0
1	11	2006	9.2	0.0
2	11	2006	6.9	35.4
3	11	2006	6.5	1.2
4	11	2006	5.9	1.0
5	11	2006	8	0.0
6	11	2006	6.2	0.0
7	11	2006	3.2	0.0
8	11	2006	5	0.0
9	11	2006	6.4	0.0

Day	Month	Year	ETo	rainfall)
			mm/day	mm
1	1	2007		0.0
2	1	2007		0.0
3	1	2007		0.0
4	1	2007	3.5	1.4
5	1	2007	3.8	3.2
6	1	2007	3.3	0.2
7	1	2007	4.5	0.0
8	1	2007	5.4	0.0
9	1	2007	5.2	0.0
10	1	2007	4.8	0.0
11	1	2007	5.1	2.4
12	1	2007	5.2	0.2
13	1	2007	4.5	42.6
14	1	2007	3.8	0.4
15	1	2007	4.4	33.4
16	1	2007	4	0.4
17	1	2007	4.5	20.6
18	1	2007	3.1	3.8
19	1	2007	2.7	7.0
20	1	2007	1.9	4.8
21	1	2007	3.4	2.4
22	1	2007	3.5	0.0
23	1	2007	4.1	0.0
24	1	2007	5.2	17.0
25	1	2007	5.1	14.4
26	1	2007	4.3	0.0
27	1	2007	3.7	0.0
28	1	2007	3.8	0.0
29	1	2007	4.2	4.2
30	1	2007	3.1	1.6
31	1	2007	2.9	0.0
1	2	2007	2.8	0.0
2	2	2007	2.6	0.0
3	2	2007	4.1	0.0
4	2	2007	2.8	0.4
5	2	2007	4.6	0.0
6	2	2007	5.1	0.0
7	2	2007	4.7	0.2
8	2	2007	3.7	0.0
9	2	2007	3.7	0.2
10	2	2007	4.7	0.6
11	2	2007	3.5	5.0
12	2	2007	3.4	0.2
13	2	2007	2.8	0.2
14	2	2007	2.8	0.2
15	2	2007	4.2	0.2
16	2	2007	4	0.0
17	2	2007	4.8	6.2
18	2	2007	4.2	3.4
19	2	2007	3.3	0.2
20	2	2007	3	0.2

Day	Month	Year	ETo	rainfall)
			mm/day	mm
21	2	2007	4.3	1.2
22	2	2007	5.5	2.6
23	2	2007	3.2	0.2
24	2	2007	2.7	0.0
25	2	2007	4.1	0.0
26	2	2007	3.2	0.0
27	2	2007	4.1	0.0
28	2	2007	4	0.0
1	3	2007	4.3	0.0
2	3	2007	4.4	0.0
3	3	2007	4.6	0.0
4	3	2007	4.7	0.0
5	3	2007	3.6	0.0
6	3	2007	5	0.0
7	3	2007	4.1	0.0
8	3	2007	3.7	0.0
9	3	2007	3.8	0.0
10	3	2007	4.2	0.0
11	3	2007	4.4	0.4
12	3	2007	4.4	0.2
13	3	2007	3.7	0.0
14	3	2007	4.1	0.2
15	3	2007	3.9	0.0
16	3	2007	4.5	1.4
17	3	2007	5	30.2
18	3	2007	4.3	0.2
19	3	2007	3.6	0.2
20	3	2007	4.6	0.2
21	3	2007	4.4	0.0
22	3	2007	4.5	0.4
23	3	2007	4.2	0.2
24	3	2007	3.8	0.2
25	3	2007	3.9	0.2
26	3	2007	2.6	0.2
27	3	2007	3.7	0.0
28	3	2007	4.3	25.4
29	3	2007	3.7	7.6
30	3	2007	4	4.4
31	3	2007	3.8	3.0
1	4	2007	2.3	0.2
2	4	2007	3.1	0.0
3	4	2007	3.3	0.0
4	4	2007	2.8	2.2
5	4	2007	3.7	0
6	4	2007	3.2	0

APPENDIX B

Irrigation schedule determined by CROPWAT

Table B1 CROPWATschedule

Date	ETo Area (mm/perio(	Planted Kc (%)	Crop (ETm) ----------	CWR Rain (mm/period)	Total Rain ----------	Effect. Req. (l/s/ha)	Irr.
--							
27-Okt	70.2	100	0.3	21.1	0	0	21.1
11-Jun	69.3	100	0.3	20.8	37.6	35.8	-15.0
16-Nov	54.8	100	0.3	16.4	5.4	5.1	11.3
26-Nov	48.5	100	0.33	16.0	17.2	16.4	-0.4
12-Jun	52.7	100	0.51	26.9	3.8	3.6	23.3
16-Des	44.3	100	0.71	31.5	102.2	97.3	-65.9
26-Des	43	100	0.91	39.1	22.8	21.7	17.4
01-Mei	45.6	100	1.11	50.6	35.8	34.1	16.5
15-Jan	45.6	100	1.2	54.7	7.4	7.0	47.7
25-Jan	36.8	100	1.2	44.2	115.4	109.9	-65.7
02-Apr	36.6	100	1.2	43.9	37.2	35.4	8.5
14-Feb	39	100	1.2	46.8	6.6	6.3	40.5
24-Feb	39.3	100	1.17	46.0	14.4	13.7	32.3
03-Jun	39.7	100	0.99	39.3	0.2	0.2	39.1
16-Mar	41.3	100	0.79	32.6	0.8	0.8	31.9
26-Mar	42.8	100	0.59	25.3	33	31.4	-6.2
--							
Total	700.2	536.69	530.62	431.24	124.25	[0.13]	
--							

Table B2: Irrigation depth collected in catch cans

Can no	Depth (ml)1	Depth(ml) 2
1	155	172
2	375	386
3	368	347
4	283	261
5	244	247
6	545	538
7	528	534
8	750	721
total	3248	3206

Determination of the application rate.

$1000l = 1m^3$

$3.227l = 0.003227m^3$

The orifice of the bucket is

Πr^2

$= \left(33/2\right)^2 * \Pi$

33

$= 855.3 * 10^{-4}$

$= 0.08553 m^2$

The depth of water applied =
$0.003227 / 0.08553$

$= 0.038m$

$= 3.8mm$

The amount of water applied in 70 minutes=3.8
The amount of water applied in 60 minutes **= 3.2mm/hr**

APPENDIX C

Soil profile

Co-ordinates : S17°42.266` E031°00.546`

Location	: University of Zimbabwe Farm – Physics Research Site
Elevation	: 1506 m
Rainfall	: 800 - 1000 mm
Landscape (form)	: Pediplain
Landscape (shape)	: Flat/ almost flat
Capping	: Nil
Surface stones	: Small common stones
Slope (%)	: 1-2%
Erosion	: Slight sheet
Landuse	: Fallow
Effective depth	: 60 cm
Parent material	
	(A) Metabasalt - E
	(B) Phyllite- I

Classification

Zimbabwe

Group : 5 - Fersialitic

Family : 5EI

FAO: Haplic lixisols

DESCRIPTION :

0 - 20 cms: Dark reddish brown (2.5YR 3/3 d,m); coarse sandy clay loam; slightly dry hard, moist friable, plastic, sticky consistence; moderate medium subangular blocky breaking to granular structure; good permeability; well drained; fairly numerous medium roots; clear smooth transition to :

20 - 39 cms: Dark reddish brown (2.5YR 3/4 d,m) coarse sandy clay loam; dry hard; moist friable, very plastic, very sticky consistence; moderate medium subangular blocky breaking to granular structure; good permeability; well drained; few fine roots; clear smooth transition to :

39 - 54 cms: Dark reddish brown (2.5YR 3/4 d,m) coarse sandy clay loam; dry hard; moist friable,very plastic, very sticky consistence; moderate medium subangular blocky structure; good permeability; well drained; few fine roots; clear smooth transition to :

54 - 60 cms: Loosely packed small quartz stones (stoneline); clear smooth transition to:

60 - 100 cms: Gravelly; common small quartz stones and soft weathering

100cms+ Soft weathering rock

APPENDIX D

Neutron probe calibration- Regression equations and statistical analysis

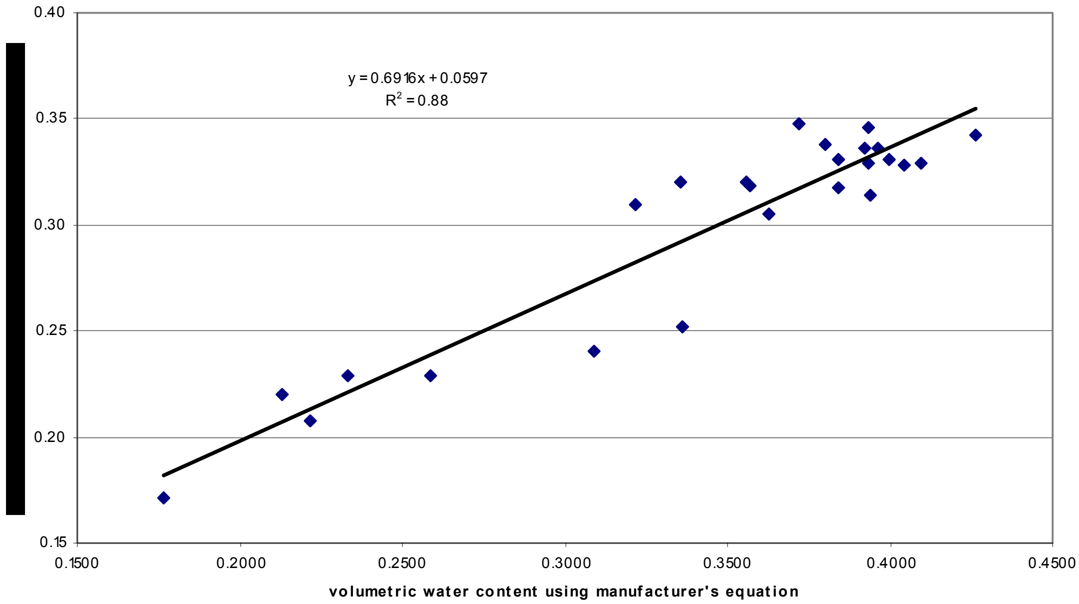

Figure D1 Comparison of the volumetric water content as determined by un calibrated neutron probe using manufacturer's equation and gravimetric methods

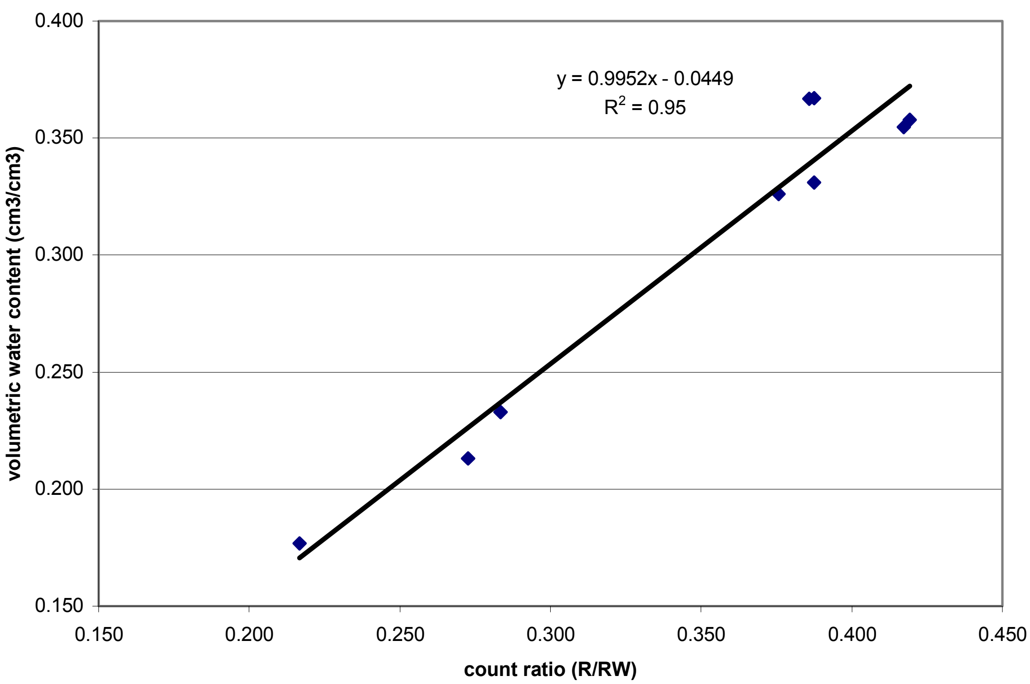

Figure D2 Regression of volumetric water content against the count ratio for the 20-40cm soil layer

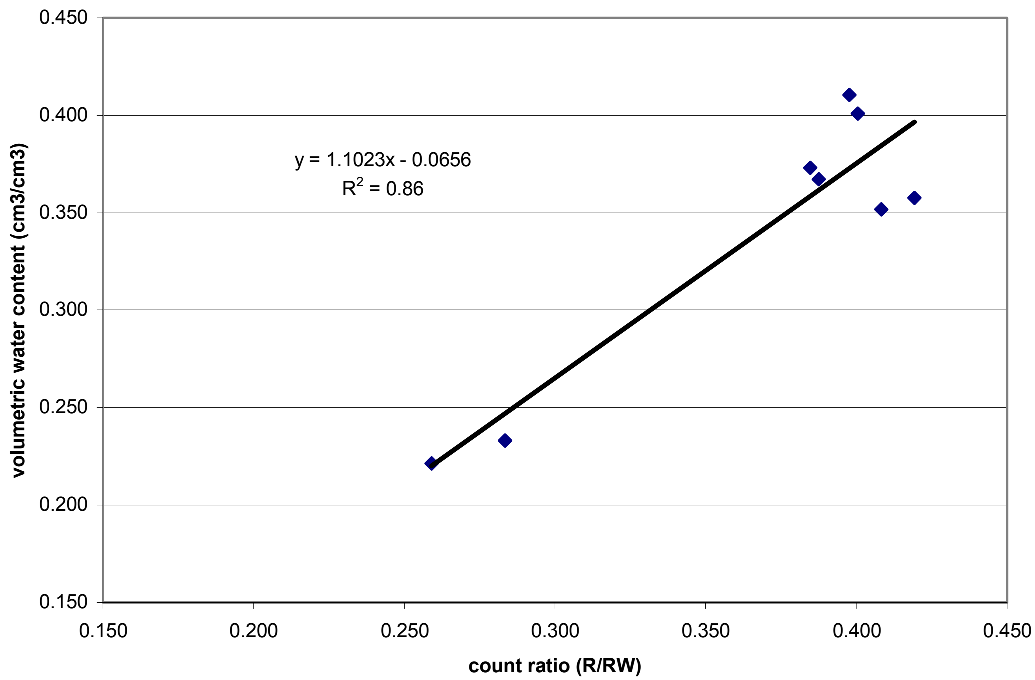

Figure D3 Regression of volumetric water content against the count ratio for the 40-60 cm soil layer

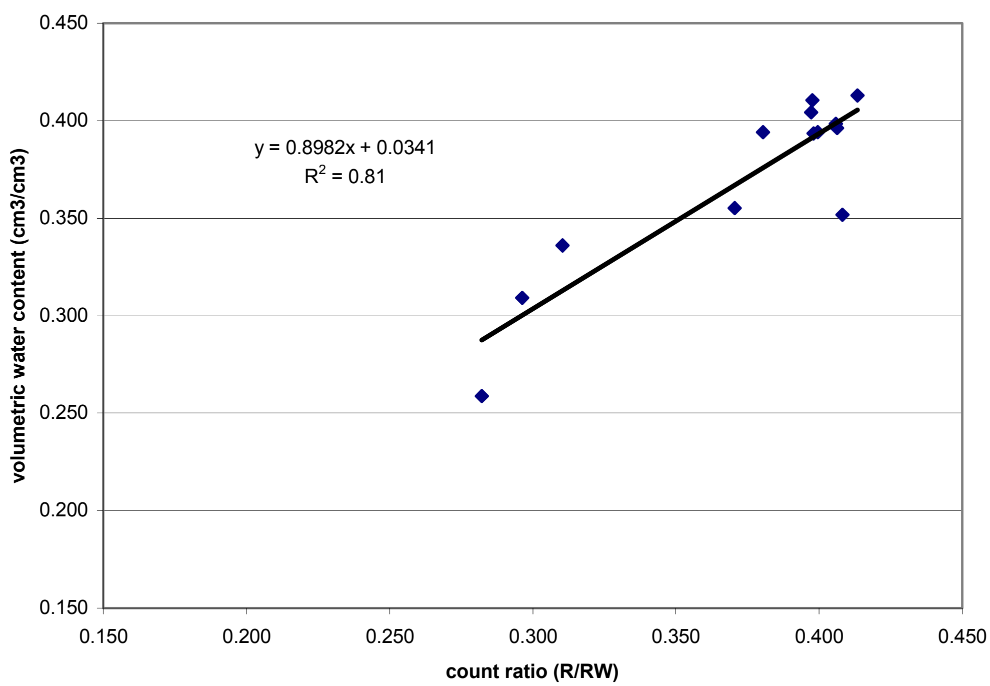

Figure D4 Regression of volumetric water content against the count ratio for the 60-100 cm soil layer

Table D1 Validation using obtained equations and independent data

Data	intercept	slope	R	R^2	SE
using pooled data	-0.04	1.04	0.91	0.83	0.030
different soil layers	-0.01	0.99	0.90	0.81	0.032

APPENDIX E

Soil water content data

Table E 1. Soil water content in the top 60cm

Soil moisture measuremnts during the growing season									
	Depth (cm)	**10**	**20**	**30**	**40**	**50**	**60**		total water content (mm)
30 Oct		***0.23***	0.37	0.37	0.38	0.37	0.36	2.08	207.50
		0.20	0.29	0.34	0.35	0.36	0.43	1.97	197.43
	mean	*0.22*	*0.33*	*0.36*	*0.36*	*0.36*	*0.40*	*2.02*	*202.47*
	sd	*0.02*	*0.05*	*0.02*	*0.02*	*0.01*	*0.05*	*0.07*	**7.12**
16-Nov									
		0.31	0.27	0.25	0.27	0.23	0.44	1.77	177.16
28-Nov		0.16	*0.27*	*0.32*	*0.33*	*0.36*	*0.42*	1.86	186.05
		0.21	0.27	0.32	0.33	0.35	0.43	1.90	189.87
	mean	*0.19*	*0.27*	*0.32*	*0.33*	*0.35*	*0.42*	*1.88*	*187.96*
	sd	*0.04*	*0.00*	*0.00*	*0.00*	*0.01*	*0.01*	*0.03*	**2.70**
13 dec	plot 1	0.29	0.35	0.38	0.37	0.35	0.41	2.15	215.17
	plot 5	0.25	0.38	0.40	0.43	0.45	0.45	2.37	236.65
	plot8	0.26	0.33	0.34	0.33	0.29	0.30	1.85	185.26
	plot9	0.25	0.30	0.35	0.38	0.40	0.38	2.07	207.47
	plot12	0.25	0.33	0.39	0.41	0.42	0.43	2.24	224.03
	mean	*0.26*	*0.34*	*0.37*	*0.39*	*0.38*	*0.40*	*2.14*	*213.72*
	sd	*0.02*	*0.03*	*0.03*	*0.04*	*0.06*	*0.06*	*0.19*	*19.25*
27 dec									
	plot1	*0.31*	*0.16*	*0.35*	*0.37*	*0.36*	*0.38*	*1.92*	*191.94*
	plot 8	0.29	0.34	0.34	0.33	0.30	0.29	1.90	190.02
	mean	*0.30*	*0.16*	*0.35*	*0.37*	*0.36*	*0.38*	*1.92*	***191.94***
	sd	*0.01*	*0.13*	*0.00*	*0.03*	*0.04*	*0.06*	*0.01*	*1.36*
23-Jan									
	plot1	*0.35*	*0.37*	*0.37*	*0.36*	*0.38*	*0.40*	*2.22*	*222.44*
		0.37	*0.37*	*0.37*	*0.38*	*0.39*	*0.41*	*2.30*	*229.51*
	mean	*0.36*	*0.37*	*0.37*	*0.37*	*0.38*	*0.40*	*2.26*	*225.97*
	sd	*0.01*	*0.00*	*0.00*	*0.02*	*0.01*	*0.01*	*0.05*	***5.00***
07-Feb	*plot1*	*0.30*	*0.26*	*0.29*	*0.27*	*0.28*	*0.32*	*1.72*	*172.19*
	plot12	*0.34*	*0.32*	*0.31*	*0.31*	*0.34*	*0.36*	*1.98*	*197.83*
	mean	*0.32*	*0.29*	*0.30*	*0.29*	*0.31*	*0.34*	*1.85*	*185.01*
	sd	*0.03*	*0.04*	*0.01*	*0.03*	*0.05*	*0.03*	*0.18*	***18.13***
13-Feb	plot1	*0.27*	*0.23*	*0.27*	*0.26*	*0.27*	*0.29*	*1.58*	*157.88*
	plot12	*0.23*	*0.28*	*0.29*	*0.31*	*0.33*	*0.33*	*1.76*	*175.54*
	mean	*0.25*	*0.25*	*0.28*	*0.28*	*0.30*	*0.31*	*1.67*	*166.71*
	sd	*0.03*	*0.03*	*0.02*	*0.04*	*0.04*	*0.03*	*0.12*	**12.48**
20-Feb	*plot1*	*0.24*	0.24	0.25	0.24	0.28	0.32	1.58	157.58
	plot12	*0.29*	*0.26*	*0.28*	*0.28*	*0.31*	*0.32*	*1.74*	*174.28*
	mean	*0.27*	*0.25*	*0.27*	*0.26*	*0.29*	*0.32*	*1.66*	*165.93*
	sd	*0.04*	*0.01*	*0.02*	*0.02*	*0.02*	*0.00*	*0.12*	**11.81**
13 march	plot1	*0.18*	*0.19*	*0.22*	*0.22*	*0.23*	*0.27*	*1.32*	*131.61*
	plot12	*0.20*	*0.21*	*0.27*	*0.28*	*0.29*	*0.31*	*1.57*	*156.87*
	mean	*0.19*	*0.20*	*0.24*	*0.25*	*0.26*	*0.29*	*1.44*	*144.24*
	sd	*0.01*	*0.01*	*0.03*	*0.04*	*0.04*	*0.03*	*0.18*	**17.86**
20 march	*plot1*	*0.33*	*0.31*	*0.32*	*0.31*	*0.32*	*0.35*	*1.95*	*195.37*
	plot5	*0.33*	0.24	0.23	0.25	0.31	0.34	*1.71*	*171.00*
	mean	*0.33*	*0.28*	*0.28*	*0.28*	*0.32*	*0.35*	*1.83*	*183.19*
	sd	*0.00*	*0.05*	*0.06*	*0.05*	*0.01*	*0.01*	*0.17*	**17.23**
	plot1	*0.17*	*0.18*	*0.21*	*0.33*	*0.33*	*0.34*	*1.57*	*156.95*
27 march	*plot5*	*0.25*	*0.31*	*0.32*	*0.30*	*0.29*	*0.28*	*1.75*	*175.12*
	mean	*0.21*	*0.25*	*0.26*	*0.32*	*0.31*	*0.31*	*1.66*	*166.00*
	sd	*0.05*	*0.09*	*0.07*	*0.02*	*0.03*	*0.04*	*0.13*	**12.85**

APPENDIX F

Analysis of variance

Table F1 Analysis of variance for grain yield

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
rep stratum	3	2.1071	0.7024	4.14	
treatment	2	7.0871	3.5435	20.90	0.002
Residual	6	1.0174	0.1696		
Total	11	10.2116			

******* Tables of means *******

Grand mean 7.43

trt	1.00	2.00	3.00
	6.47	8.35	7.45

*** Standard errors of means ***

Table	trt
rep.	4
d.f.	6
e.s.e.	0.206

***** Standard errors of differences of means *****

Table	treatmentt
rep.	4
d.f.	6
s.e.d.	0.291

*** **Least significant differences of means** ***

Table	trt
rep.	4
d.f.	6
l.s.d.	0.712

******* Stratum standard errors and coefficients of variation *******

Stratum	***d.f.***	***s.e.***	***cv%***
rep	3	0.484	6.5
rep.*Units*	6	0.412	5.5

APPENDIX G

Biomass and cumulative transpiration data

Table G1 The biomass accumulation during growing season for varieties by plot

Plot	1	2	3	4	5	6	7	8	9	10	11	12
Variety	*sc719*	*SC635*	*SC403*	*SC635*	*SC403*	*SC 719*	*SC 403*	*SC 719*	*SC 635*	*SC 719*	*SC 635*	*SC 403*
28-Nov	11.1	19.0	12.1	22.8	15.2	20.1	23.7	20.8	26.2	18.2	29.1	26.2
13 Dec	78.1	72.0	111.6	207.0	101.9	142.7	158.3	148.2	132.1	129.7	219.1	127.4
27 Dec	408.4	393.2	277.0	467.0	544.3	507.5	546.8	627.0	654.6	458.6	579.8	541.6
10-Jan	740.4	1152.0	1197.5	1193.6	1035.4	1664.5	1215.7	1534.1	1306.8	1005.5	810.4	893.2
23-Jan	1739.5	2127.9	1581.8	1902.9	1508.2	1891.4	1340.7	1961.8	1633.8	1828.4	1916.4	1369.1
07-Feb	2411.3	2145.5	1982.9	2013.6	1637.1	1976.4	2180.9	2073.4	1980.7	2422.9	2221.3	1809.3
20-Feb	2645.4	2192.0	1957.1	2549.8	1936.8	2286.1	1933.0	2187.3	2182.9	2088.8	1904.1	1610.0
13Mar	2622.9	2199.5	1829.3	2348.4	1701.4	2256.1	2176.1	2853.9	2155.5	2482.1	2176.4	1583.9

Table G2 Average Biomass and transpiration data

	SC719			SC635			SC403		
	biomass	cum Tact	Sum(ETo/Tact)	biomass	cum Tact	Sum(ETo/Ta	biomass	cum Tact	Sum(ETo/Ta
28-Nov	17.6	31.2	6.1	24.3	44.3	8.7	19.3	46.5	9.2
13 Dec	124.7	85.6	17.3	157.6	101.8	20.4	124.8	107.2	21.5
27 Dec	500.4	149.8	31.9	523.7	166.5	20.4	477.4	172.1	36.3
10-Jan	1236.1	213.1	46.8	1115.7	223.9	20.4	1085.4	234	50.9
23-Jan	1855.3	256.3	58.4	1895.2	269.5	20.4	1450.0	279.2	63.0
7-Feb	2298.0	320.8	74.8	2090.3	335.2	20.4	1802.0	343.5	79.3
20-Feb	2395.9	375.8	89.6	2207.2	376.4	20.4	1859.2	385.6	90.8
13 Mar	2403.8	397.2	95.1	2220.0	396.4	20.4	1822.7	407	96.1

APPENDIX H

Water Productivity

Table H.1 Analysis of variance for water productivity

Anova Table

source of var	**df**	**ss**	**m.s**	**vr**	**Fpr**
rep	3	0.8058	0.2686	0.29	
treat	2	6.5618	3.2809	3.6	0.094
residual	6	5.4707	0.9118		
total	11	12.8383			

Table of means

Grand mean 8.77

treat	1	2	3
	7.79	8.96	9.57

Standard error of the means

table	treat
rep	4
d.f	6
sed	0.477

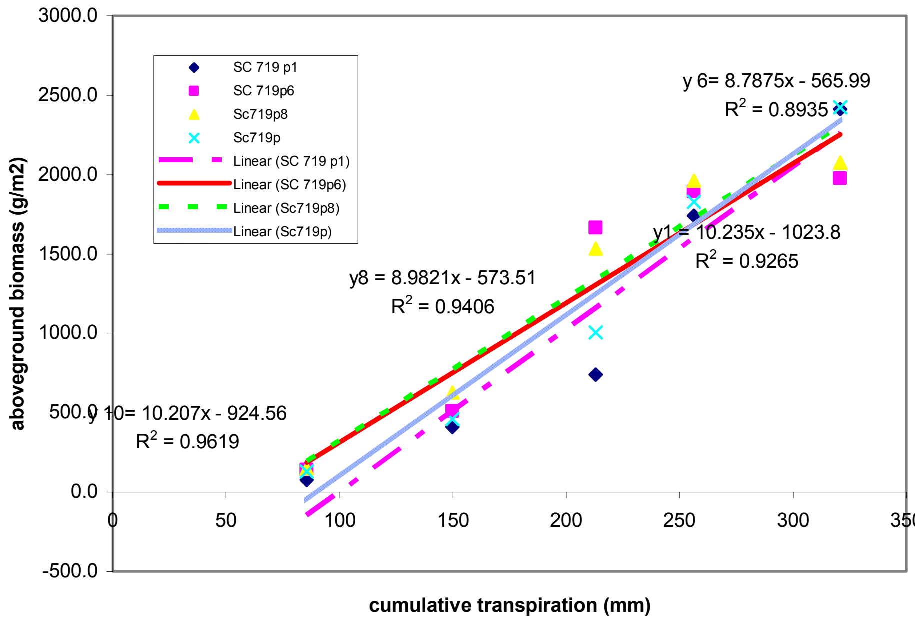

Figure H1- Water productivity for SC719 for different plots

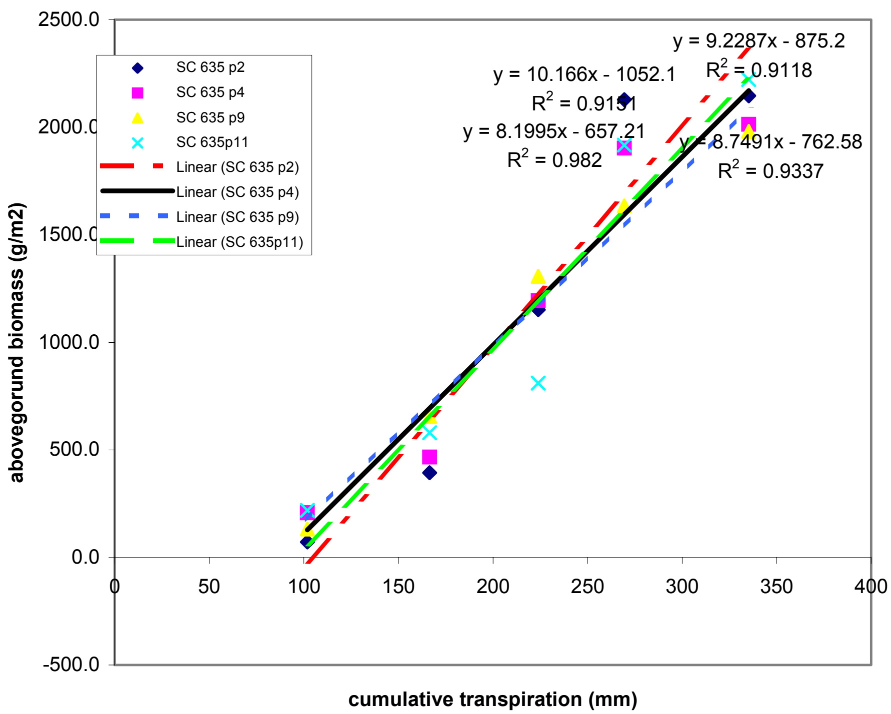

Figure H2- Water productivity for SC 635

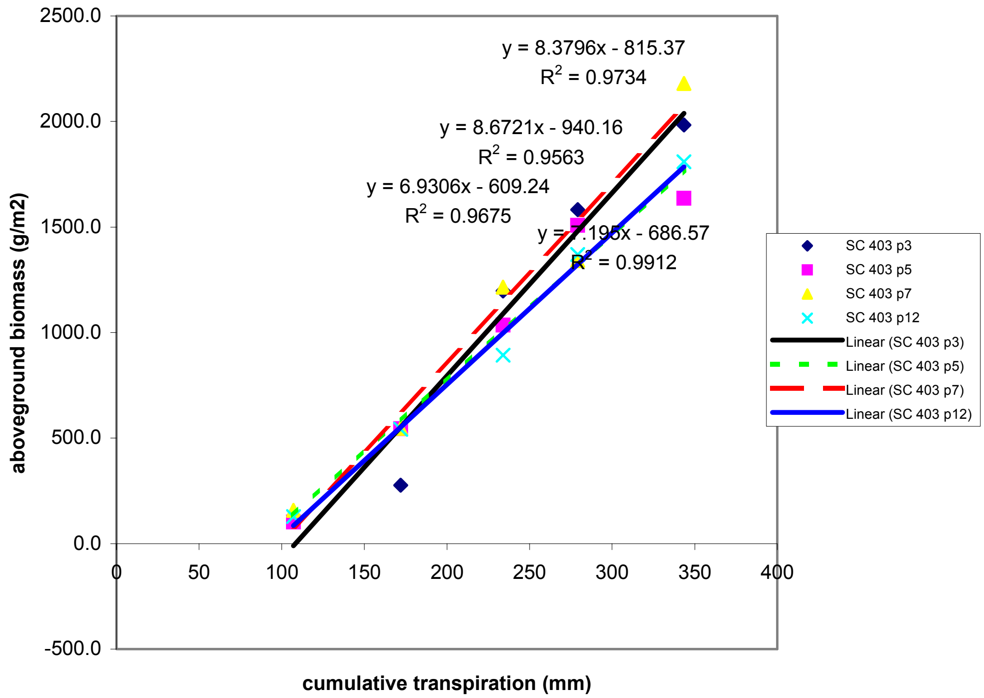

Figure H3- Water productivity for SC 403

Table G 2. Analysis of variance for Normalized water productivity

Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep	3	18.98	6.33	0.41	
treat	2	109.11	54.56	3.58	0.095
Residual	6	91.57	15.26		
Total	11	219.66			

Tables of means

Grand mean 35.9

treat	1	2	3
	31.8	37.1	38.8

Standard errors of means

Table	treat
rep.	4
d.f.	6
e.s.e.	1.95

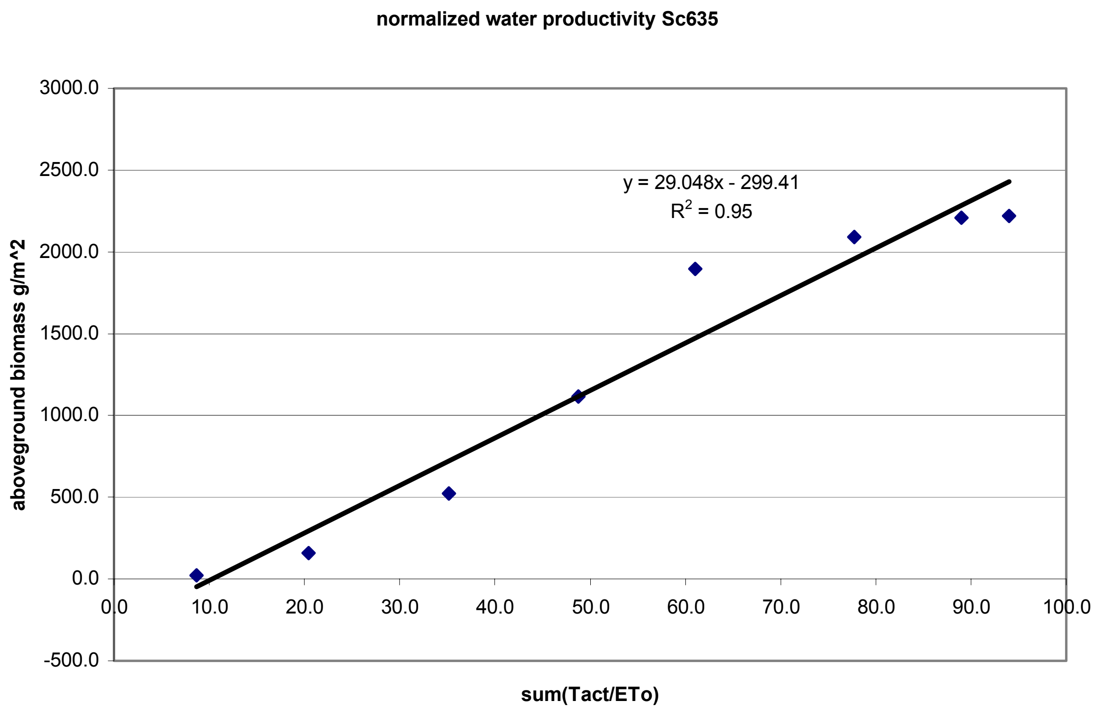

Figure H4- Normalized Water productivity for SC 635

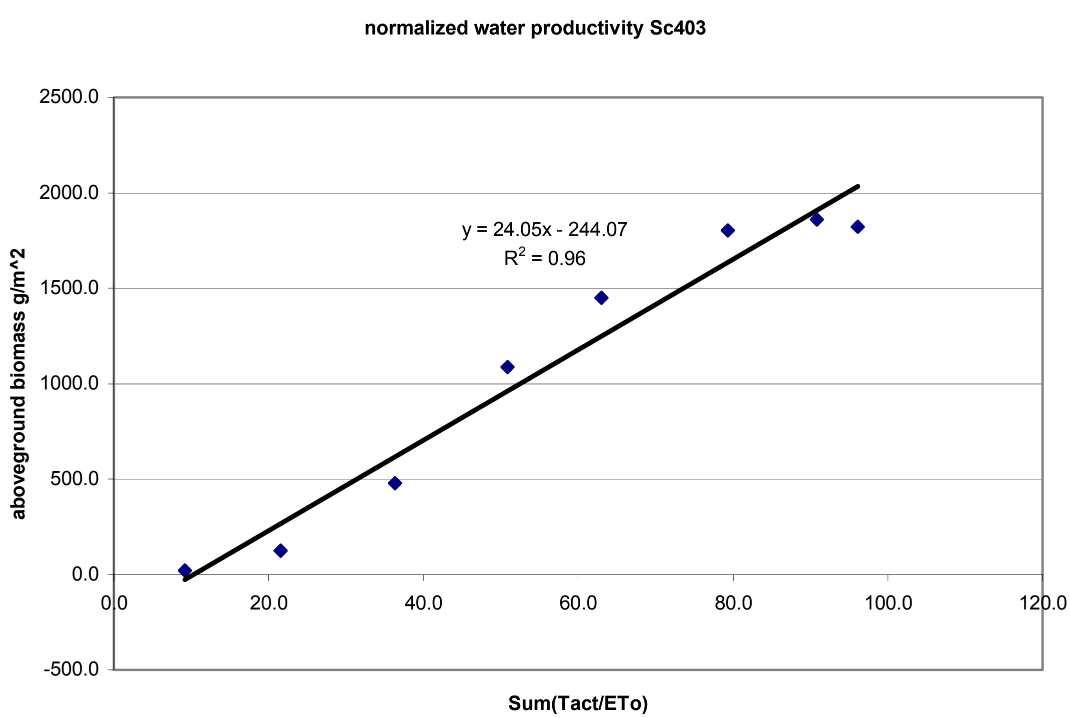

Figure H5- Normalized Water productivity for SC 403

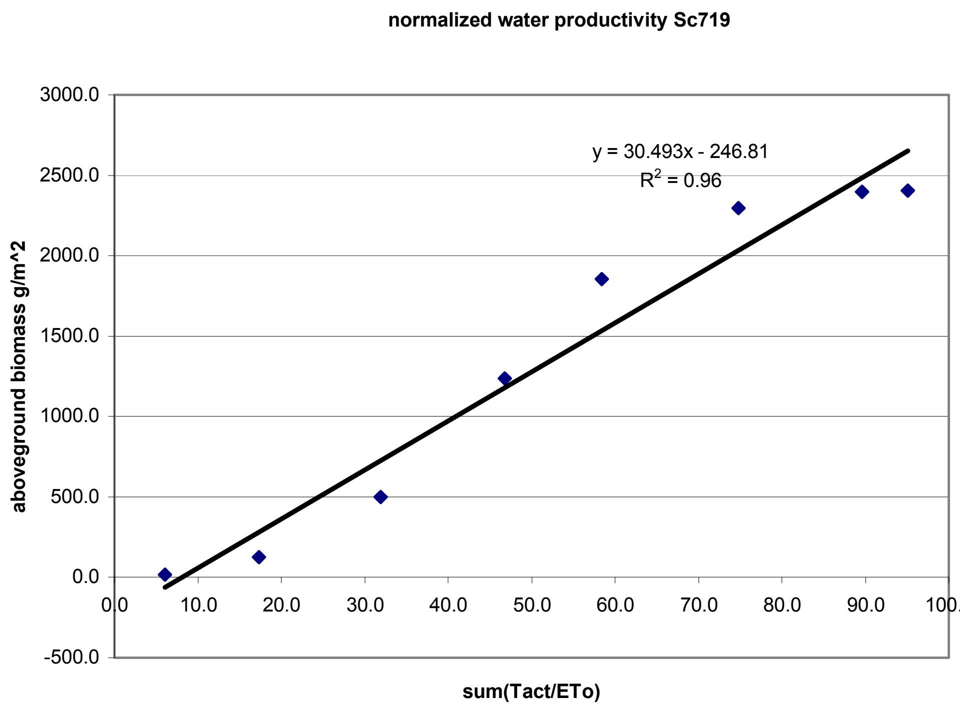

Figure H6- Normalized Water productivity for SC 403

APPENDIX I

Weather data input for ART Farm

		2000-2001	2002-2003	2004-2005	2000-2001	2002-2003	2004-2005
Day	**Month**	**ETo**			**rainfall**		
27	10	5.6	6	5.6	0	0	0
28	10	6.3	5.3	6.3	0	2	0
29	10	6.4	5.4	5.6	0	0	0
30	10	6.7	4.8	5.5	0	0	0
31	10	6	2.7	5.9	0	0	0
1	11	6.1	4.6	5.8	0	0	0
2	11	6	4.3	6.4	0	0	0
3	11	6.2	4.7	5.7	0	0	0
4	11	6.2	5.1	5.7	0	7	2
5	11	6	5.6	6	0	0	36
6	11	6.2	1.3	5.7	0	0	4
7	11	4.9	3.5	6.1	0	0	2
8	11	5.1	4.7	5.7	0	0	0
9	11	5.6	4.9	5.9	0	0	0
10	11	5.6	5.9	5.2	0	0	14
11	11	5.7	5.1	6	0	0	3
12	11	5.6	5.5	5.7	0	0	0
13	11	6.2	6.1	6.4	0	0	0
14	11	6.1	6.2	6.2	4	0	0
15	11	6.3	5.9	6.2	0	0	0
16	11	5.6	6	6	18	0	0
17	11	5.5	6.2	6.2	0	0	0
18	11	4.4	5.6	6	0	0	0
19	11	5.1	5.9	5.5	0	0	0
20	11	5.1	6.5	5.2	0	3	0
21	11	4.7	6.1	5.9	0	0	2
22	11	4.6	6.2	5.2	0	0	3
23	11	3.8	5.6	4.8	0	0	0
24	11	3.9	4.6	4.9	0	34	0
25	11	4	5	6.1	0	39	5
26	11	5.5	5.8	5.4	0	6	0
27	11	5.5	5.4	5.2	0	0	0
28	11	4.9	6.1	5.5	0	0	0
29	11	4.9	6.4	6.1	0	0	0
30	11	4.5	5.4	6	0	0	0
1	12	4.6	6	5.4	0	24	0
2	12	3.5	6.1	5.4	0	18	0
3	12	2	6.4	5	0	3	2.5
4	12	3.3	6	4.2	0	0	0
5	12	4.2	5.7	3.8	0	3	0
6	12	4.5	6.4	3.9	0	0	0
7	12	5.1	6.3	3.4	0	0	0
8	12	4.6	6	3.8	0	0	0
9	12	4.9	5	3.8	0	0	0
10	12	4.9	2.6	3.8	0	0	0
11	12	4.1	3.7	4.2	24	0	0
12	12	5.1	5.6	4.3	0	0	0
13	12	4.5	5	4.1	38	0	0
14	12	4.9	4.8	3.6	1	0	0
15	12	5.1	5.3	5.2	13	0	0

		2000-2001	2002-2003	2004-2005	2000-2001	2002-2003	2004-2005
Day	**Month**	**ETo**			**rainfall**		
16	12	5.3	6	4.6	8	0	7.5
17	12	4.8	5.8	5.7	1.5	0	0.5
18	12	5.3	5.1	5.7	2.5	0	13.5
19	12	4.5	5	5.4	0.5	0	0
20	12	5.2	4.6	5.6	0	12	36
21	12	4.9	5.4	5.5	5	14	0
22	12	5.3	6	5.3	6	0	0
23	12	4	5.7	4.7	42	0	2
24	12	4.8	4.5	4	20	0	0
25	12	4.7	4.4	5.2	0	0	0
26	12	4.4	5.2	4.2	0	0	0
27	12	4.7	5.3	4.4	0	0	0
28	12	4.7	5.7	4.5	9.5	0	0
29	12	4.9	5.6	4.4	0	0	25
30	12	5.3	5.6	5.2	3	0	40
31	12	4.8	5.9	5.6	0	0	0
1	1	4.9	6	5	0	0	9
2	1	4.9	4.9	5.6	2	5	24
3	1	4.8	5.6	5.6	13	4	4
4	1	4.5	5.7	6.1	0	1	3
5	1	4.7	5	5.7	4	14	26
6	1	4.1	7	6	11	4	1.5
7	1	4	6.9	6	22	0	14
8	1	4.1	6.8	5.2	22	2	13
9	1	4.9	5.9	5.7	36	0	4.5
10	1	4.5	5.4	5.7	8	8	0
11	1	4.7	4.1	5.8	20	0	0
12	1	4.9	5	5.8	1	7	0
13	1	4	5.8	5.4	15	1	0
14	1	5	6.4	4.8	0	1	0
15	1	4.5	6.4	4.3	15	4	0
16	1	4.4	6.4	4.5	11	0	0
17	1	5.2	7.1	4.3	7	1	5
18	1	4.8	6.4	4.4	6	7	0.5
19	1	5	6.2	5	13	14	60
20	1	4.8	5.7	4.4	2	9	8
21	1	4.9	5.8	4.8	3	0	7
22	1	4.8	5.9	5	41	0	4
23	1	5.3	5.5	4.8	11	0	22
24	1	5.4	6.2	4.6	15	0	3.5
25	1	5.3	3.9	4.1	12	0	
26	1	5.3	6.6	3.9	0	0	
27	1	4.9	4.8	4.4	8	5	0
28	1	5	5.4	3.2	1	2	0
29	1	5.5	4.8	4.6	25	0	0
30	1	4.6	4.7	5	6	0	0
31	1	4.5	5.6	5.1	10	0	0
1	2	4.5	5	5.3	26	0	0
2	2	3.6	6	5.9	5	0	0
3	2	3.9	6.3	5.7	0	0	0
4	2	4.3	6.4	5.7	32	16	0
5	2	4	6	5.3	3	1	4
6	2	3.6	6.1	5.2	10	0	0
7	2	4.2	6	5.8	40	12	0
8	2	5.1	5.8	5.6	34	0	0
9	2	3.6	5.6	4.9	1	0	2.5
10	2	3.9	5.6	5.7	0	0	12

		2000-2001	2002-2003	2004-2005	2000-2001	2002-2003	2004-2005
Day	**Month**	**ETo**			**rainfall**		
11	2	5.4	4.8	6.1	0	0	90
12	2	5.5	5.7	5.7	16	0	4
13	2	5.6	5.5	5.5	18	0	0.5
14	2	4.9	5.6	5.4	38	0	3
15	2	4.5	5.6	5.5	1.5	0	0
16	2	4.9	6	5.2	10	22	0
17	2	4.7	5	5.6	0	0	7
18	2	5.1	5.5	5.9	22	1	5
19	2	4.8	6.1	5.6	32	54	30
20	2	5	5.3	5.7	4	0	0.5
21	2	4.8	5.4	5.2	0	1.5	1.5
22	2	4.8	4.1	4.2	0	65	0
23	2	4.4	4.2	4.7	21	6	3
24	2	4.7	3.7	5.4	0	2.5	3
25	2	4.3	4.3	5.3	23	0	0
26	2	4.4	3.9	4.6	17.5	1	0
27	2	4.8	4.9	4.3	5	0	0
28	2	5.1	5.5	3.8	6	0	0
1	3	4.6	5.6	4.5	15	0	0
2	3	5.3	4.1	4.5	10	0	0
3	3	4.9	5.1	5.1	30	6	0
4	3	5.1	2.1	4.8	15	0	1.5
5	3	4.9	3.9	4.6	21	0	0
6	3	4.4	2.7	4.9	0	14	0.5
7	3	4.4	2.7	5.5	7	0	0
8	3	5	2.9	5.1	0	0	0
9	3	4.5	3.2	5.9	0	1	0
10	3	4.7	3.2	5.7	0	6	0
11	3	5.1	3.6	5.3	0	0	0
12	3	5	3.6	4.4	7	0	0
13	3	4.7	2.8	4.3	0	0	0
14	3	4.6	5.2	4.4	0	0	0
15	3	4.7	5.3	4.4	0	14	12
16	3	5.1	5.5	4.5	37	5	2
17	3	4.8	5.2	5.6	42	4	9
18	3	5	4.7	5.7	8	0	16
19	3	4.8	5.1	5.2	0	11	55
20	3	4.8	4.9	4.2	2.5	24	0
21	3	4.4	3.6	4.7	55	14	20
22	3	4.7	4.5	5.4	0	20	0
23	3	4.3	5.1	5.3	0	55	0
24	3	4.4	4.5	4.6	0	12	2
25	3	4.8	4	4.3	14	1	4
26	3	5.1	4.3	3.8	0.5	0	0
27	3	4.6	3.9	4.5	7	0	3.5
28	3	5.3	3.9	4.5	0	0	0
29	3	4.9	4.3	5.1	1	3	0
30	3	5.1	4.6	4.8	0	9	0
31	3	4.9	4.9	4.6	4	21	0

		2000-2001	*2002-2003*	*2004-2005*	*2000-2001*	*2002-2003*	*2004-2005*
Day	**Month**	**ETo**			**rainfall**		
1	4	4.4	5.2	4.9	1	12	0
2	4	4.4	5.4	5.5	0	10	0
3	4	5	4.1	5.1	0	8	0
4	4	4.5	4.7	5.9	0	24	0
5	4	4.7	4.1	5.7	3	7	0
6	4	5.1	4.3	5.3	0	2	0
7	4	5	5.7	4.4	7	5	0
8	4	4.7	5.5	4.3	0	3	0
9	4	4.6	5.6	4.4	7	0	0
10	4	4.7	5.2	4.4	18	0	0
11	4	5	4.3	4.5	10	0	0
12	4	4.3	4.4	4.9	12	0	0
13	4	4.4	4.6	5.1	8	0	0
14	4	4.6	4.6	4.8	44	0	0
15	4	4.1	4.5	4.9	12	0	9
16	4	3.8		4.5	5	5	8
17	4	4.2	4.5	4.8	5	12	0
18	4	4.4	5.1	5.2	36	0	0
19	4	4.9	4.5	4.9	16	1	0
20	4	3.8	4	4.5	1	4.5	1.5
21	4	4.5	4.3	4.6	0	1	4
22	4	4.8	3.9	4.2	0	4	0
23	4	4.3	3.9	5	0	7	6
24	4	3.9	4.3	3.1	2	4	32
25	4	3.9	4.6	4	0	0	20
26	4	4.8	4.9	4	0	4	5
27	4	4.4	5.2	4.5	0	0	0
28	4	4.6	5.4	4.8	0	0	0
29	4	4.4	4.1	4.7	1	2	0
30	4	4.2	4.7	4.5	0	1	0