SIMULATION OF WATER PRODUCTIVITY FOR MAIZE UNDER DRIP IRRIGATION

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BY

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ABSTRACT

Water has become increasingly scarce in most of the countries in the world. To use the available water efficiently in crop production, agricultural water productivity (WP) need to be improved. Drip irrigation systems and deficit irrigation practices are the most efficient methods in improving WP. Availability of soil-water-crop simulation and climatic models can also help in the efforts to improve WP. A study was conducted in Morogoro using CROPWAT model to simulate water productivity of maize under drip irrigation by supplying different water deficits. A completely randomized block design was used with three replications and four treatments. The treatments were T1, T2, T3 and T4 representing 60, 40, 20, 0 percent deficit of ETC (crop evapo-transpiration) respectively. Biomass accumulation (at 45 DAP and 75 DAP), grain yield and harvest index were determined for each treatment and experimental yield reductions were calculated. The CROPWAT simulation was done for each water deficit level and yield reductions were recorded. A comparison was made between experimental and simulated yield reductions. The mean biomass production between the treatments at 45 DAP were not significant different ($P<0.05$). At 75 DAP mean biomass production (0.684, 0.728, 1.049, 1.378 kg/m^2 for T1, T2, T3 and T4 respectively) were highly significant different ($P<0.05$). The mean grain yield between treatments, mean water productivity (1.67, 2.2, 1.78, 1.72 kg/m^3 for T1, T2, T3 and T4 respectively) and harvest index values were significant different ($P<0.01$). Experimental and CROPWAT simulated yield reductions were not significant different ($P<0.01$) at all stages for all the treatments. The CROPWAT model adequately simulated the experimental yield response to water for maize (maize water productivity).

DECLARATION

I, **FESTO RICHARD**, do hereby declare to the Senate of Sokoine University of Agriculture that the work presented here is my own original work, and has not been submitted for a degree award in any other University.

28\01\2011

Festo Richard
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Date

The declaration above has been approved and signed by supervisors;

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DEDICATION

This work is dedicated to my wife **DELFINA THOMAS FESTO,** my two children **GODLOVE FESTO** and **GIAN FESTO** for their patience and moral support that enabled me to complete my work, and to my father **RICHARD SILUNGWE** and mother **SANKANANJI SILUNGWE** for encouraging me in my work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABREVIATIONS AND SYMBOLS

DAP	Days After Planting
ETC	Crop Evapotranspiration
ETo	Reference Evapotranspiration
FAMOGATA	Fanya Morogoro Ghala la Taifa
FAO	Food and Agriculture Organisation of the United Nations
H_1	Alternative Hypothesis
H_o	Null Hypothesis
MGD	Millenium Development Goals
ns	Not Significant
P	Total rainfall
Pe	Effective rainfall
SUA	Sokoine University of Agriculture
T1	Treatment one - 60% water deficit
T2	Treatment two - 40% water deficit
T3	Treatments three - 20% water deficit
T4	Treatment four - optimum irrigation
URT	United Republic of Tanzania
UWTI	United Nations-Water Thematic Initiatives
WP	Water Productivity
GWPA	Ground Water Protection Area

CHAPTER ONE

1.0 INTRODUCTION

Water has become increasingly scarce in most countries in the world due to among other factors the population growth and development of cities, industries and agriculture. Being the largest water user, the agricultural sector is facing a challenge to produce more food with less water, or to produce more crops per drop (Molden *et al.*, 2003). Since scarcity of water is the most severe constraint for development of agriculture, the need to use the available water economically and efficiently is unquestionable (Yenesew and Tilahun, 2009). Globally, there is a general lack of consensus on how the available water resources can be allocated efficiently and equitably among its competing users (Kadigi *et al.*, 2004). But, water accounting and water productivity concepts are useful to evaluate the existing performance and to explore options for real water saving from field to basin scale (Molden, 1997).

New irrigation scheduling approaches aimed at increasing efficient use of the allocated irrigation water, so as to give the highest crop production with the least water use, must be developed (Kirda and Kanber, 1999; Pereira, 1999). To better understand the global water-food relationship, it is necessary to provide accurate crop yield and crop water productivity (WP) which is defined as the ratio of crop yield to actual evapotranspiration (Liu *et al.*, 2007).

To find solutions to water problems already facing many developing countries, we need better understanding of how we have used water to grow food (Molden *et al.*, 2003). The African continent, with its limited water supply and its economy relying on agriculture faces enormous challenges (Giorgis *et al.*, 2004). These challenges include among others:

how to forecast climate change impacts on crop water use and how to raise crop water productivity (Giorgis *et al.*, 2004).

The need for irrigation which aims to provide the amount of water that a crop requires during the growing season, which is not supplied by natural rainfall is essential (Schahbazian *et al.*, 2007). Since the water to be applied is scarce (Yenesew and Tilahun, 2009) the amount available must be used efficiently. The concepts of water accounting and water productivity are necessary for efficient water use. However, a complete understanding of the existing water use pattern and the interaction of different water balance components which are complex at different spatial and temporal scales is required (Schahbazian *et al.*, 2007). Soil - water and crop models can be used to increase the understanding on how to efficiently use irrigation water (Schahbazian *et al.*, 2007). At district and national level, simulation models can be the best estimators of crop yields compared to traditional survey methods (Tumbo *et al.*, 2005).

In Tanzania various estimates have indicated that the country has a potential total arable area of about 40 million hectares (URT, 2010). Of this total figure only some 6.3 million hectares are currently under crop production, 5.2 million hectares by smallholders with the remaining being used by parastatals and private sectors (URT, 2010). Expanding the agricultural sector is currently the core aim of the Government of Tanzania and the strategies include shifting from rainfed agriculture to expansion of irrigated agriculture. Several goals have been put forward for increasing crop production in the country. Among these is the production of 5 million tonnes of food crops in Morogoro Region per year by the year 2015. Another goal is the expansion of irrigated agriculture from the current 8,804 hectares to 114,700 hectares by 2015 (FAMOGATA, 2009). The amount of water for irrigation is probably going to be compromised. This brings a challenge that the increased water demand can be met either by developing new water resources or using the available water resources efficiently (George *et al*., 2000).

Nevertheless increasing water productivity in agriculture will play a vital role in easing competition for water (Molden *et al.,* 2003). This can only be achieved if water productivity is improved. However, the profit maximizing strategies call for significantly less water than maximum yield strategies (Schahbazian *et al*., 2007).

1.1 Problem Statement and Justification

Water scarcity problems do not exclude Tanzania. Drought problems and inconsistent rainfalls have made agriculture a very unreliable investment in Tanzania. It has been stated by the Government that only irrigation can change and improve agriculture. However reliable irrigation water is not available all over the country and where it is available there are many conflicts erupting as a result of it not being enough to support all farmers around the areas. It may be true that the famer's water conflicts that arise in many schemes in Tanzania are due to water scarcity. However the most serious problem is how the available water has been used by these farmers. Poor water use has lead to low water productivity as a result it has increased the water scarcity problem. The lack of knowledge on how to improve water productivity through best scheduling practices is one of the core factors that need to be addressed in order to minimize the poor usage of water. Soil water and crop models in combination with deficit irrigation can be used to increase efficient use of the available irrigation water and reduce the extent of the problem. However this has not been put into practice.

The CROPWAT model is a very useful tool in scheduling irrigation and estimating yield reductions under different water stress conditions. The use of this model has improved water use in several countries that has adopted it. In Tanzania there are very limited studies and inadequate information about the use of this model. The fact that CROPWAT model has shown good results in other countries cannot justify its adoption in Tanzania. There is therefore a need to investigate whether the model can be adopted in Tanzania or not, and if the model is adoptable where exactly can it be useful and what will be its advantages and disadvantages when compared to other available models. This study is intended to highlight the reliability of the CROPWAT model and whether it can be transferable to other locations in Tanzania for use. Given the condition that Morogoro has been earmarked as the National Food Reserve centre and the need to increase crop production in the region, it was worth to undertake the study in Morogoro to simulate water productivity of maize under drip irrigation using the CROPWAT model. A comparison of the field based results and the results simulated from CROPWAT model was used to judge if the model can adequately simulate water productivity of drip irrigated maize at different water deficit levels. This helped to decide whether the model can be adopted or not. In addition the field results of this research can help farmers in adoption of the best irrigation practices to improve water productivity and save water while increasing crop production. This is because the optimal water application point was determined; the point at which water deficit stress cannot have significant influence on the yield reduction of maize under drip irrigation in Morogoro Region.

1.3 Objectives of the Study

The general objective of the proposed study was to simulate crop water productivity for maize under drip irrigation in Morogoro District using CROPWAT model.

The specific objectives were:

i. To assess water productivity for drip irrigated maize under different levels of water stress.
ii. To calibrate and validate CROPWAT model.
iii. To apply CROPWAT to extrapolate field based results across smallholder farmers.

1.4 Research Hypothesis

The following research hypotheses were tested:

Ho: There is no significant difference between average maize water productivity under different management allowable deficits.

H1: There is significant difference between average maize water productivity under different management allowable deficits.

H_o: CROPWAT model adequately simulates crop water requirements for maize.

H_1: CROPWAT model is inadequate in simulating crop water requirements for maize.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Scheduling Strategies for Saving Water

Irrigation schedules are designed to either fully or partially provide the irrigation water requirements of a crop (Kihupi, 2008). Full irrigation involves providing the entire irrigation water requirements and results in maximum production in accordance with the respective production function for a given crop. On the other hand exceeding full irrigation reduces crop yield by reducing soil aeration and restricting gas exchange between the soil and atmosphere (Schahbazian *et al*., 2007).

Partially supplying the irrigation water requirements, a practice that has been called deficit irrigation, reduces yield as smaller amount of water, energy, and other production inputs are used to irrigate the crop (Kihupi, 2008; Ismail and Depeweg, 2005). Although the aim of irrigation is to provide the amount of water that a crop requires during the growing season, which is not supplied by natural rainfall (Schahbazian *et al.*2007), under conditions of scarce water supply and drought, deficit irrigation can lead to greater economic gain by maximizing water use efficiency (Yenesew and Tilahun, 2009). The methods for determining both the timing and depth of water to be applied to the crop can generally be classified as crop based, soil based and climatic measurement based or a combination of these methods (Steele *et al*., 1994).

2.2 Soil - plant Water Relationship

2.2.1 Soil water relation

From agricultural point of view, soil is defined as the natural medium for plant growth (Thadei, 2009). The role of soil in the soil-plant-atmosphere continuum is unique. It has been demonstrated that soil is not essential for plant growth and indeed plants can be grown hydroponically (in a liquid culture). However, usually plants are grown in the soil and soil properties directly affect the availability of water and nutrients to plants. Soil water affects plant growth directly through its controlling effect on plant water status and indirectly through its effect on aeration, temperature, and nutrient transport, uptake and transformation. The understanding of these properties is helpful in good irrigation design and management (Haman and Izuno, 2009).

The soil system is composed of three major components: solid particles (minerals and organic matter), water with various dissolved chemicals, and air. The percentage of these components varies greatly with soil texture and structure. An active root system requires a delicate balance between the three soil components; but the balance between the liquid and gas phases is most critical, since it regulates root activity and plant growth process (Jamierson *et al*., 2002; Haman and Izuno, 2009). The amount of soil water is usually measured in terms of water content as percentage by volume or mass, or as soil water potential. Water content does not necessarily describe the availability of the water to the plants, nor indicates how the water moves within the soil profile. The only information provided by water content is the relative amount of water in the soil. The type of soil and climatic conditions have a significant effect on the main practical aspects of irrigation, which are the determination of how much water should be applied and when it should be applied to a given crop (FAO, 2000). For instance the amount of rainwater retained in the root zone called effective rainfall (Pe), should be deducted from the total irrigation water requirements calculated (Balaghi, 2010).

2.2.2 Plant water relation

Water is essential in the plant environment for a number of reasons. Water transports minerals through the soil to the roots where they are absorbed by the plant (Haman and

Izuno, 2009). Water is also the principal medium for the chemical and biochemical processes that support plant metabolism. Under pressure within plant cells, water provides physical support for plants. It also acts as a solvent for dissolved sugars and minerals transported throughout the plant. In addition, evaporation within intercellular spaces provides the cooling mechanism that allows plants to maintain the favourable temperatures necessary for metabolic processes (Haman and Izuno, 2009). It is necessary to monitor plant water stress but atechnique to measure plant water stress should provide nondestructive, rapid, and reliable estimates of plant water status. Infrared thermometers can rapidly measure canopy temperatures over large areas (Irmak *et al.*, 2000).

2.3 Evapotranspiration

Evapotranspiration (ET) or consumptive use is evaporation from all water, soil, snow, ice, vegetative, and other surfaces, plus transpiration (Farias *et al.,* 2009; UCCE-GWPA, 2005; Mahoo, 2008; Keller and Seckler, 2005). Its value is largely determined by climate factors, such as solar radiation, temperature, humidity and wind, and by the environment (FAO, 2000). In addition to the climatic factors, both soil and vegetation factors govern the evapotranspiration from an area (Farias *et al.,* 2009; Mahoo, 2008; Keller and Seckler, 2005).

Reference evapotranspiration (ET_o) is defined as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m (4.72 in), a fixed surface resistance of 70 sec m^{-1} (70 sec $3.2ft^{-1}$) and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground" (Irmak and Haman, 2009). Crop Coefficient, Kc, is the ratio between the maximum water losses (evapotranpiration) of the cultivated species at a given stage in its growth and either the potential water loss or some reference (United Nations, 1992). The reference evapotranpiration, ETo, and Kc approach provides a simple and convenient way to estimate crop water requirements for a variety of crops and climatic conditions (Farias *et al.*, 2009).Crop water requirements encompasses the total amount of water used in evapotranspiration. The crop evapotranspiration can be calculated using Equation 1.

ETc = Kc x ETo...(1)

Where:

ETc = Crop evapotranspiration

Kc = Crop constant

ETo = Reference evapotranspiration (Kassam and Smith, 2001; Keller and Seckler, 2005; Allen *et al.*, 1998).

2.4 Regulated Deficit Irrigation

Regulated deficit irrigation provides a means of reducing water consumption while minimizing adverse effects on yield. In applying regulated deficit irrigation, irrigation models can play a useful role in developing practical recommendations for optimizing crop production under conditions of scarce water supply (Smith and Kivumbi, 2002).

Water deficits in crops, and the resulting water stress in the plants, have a direct effect on actual crop transpiration and crop yield. When the full crop water requirements are not met, water deficit in the plants will develop to a point where crop growth and yield are affected. The manner in which the water deficit affects crop growth and yield varies with the crop species and crop growth stage (Ismail and Depeweg, 2005). Under conditions of scarce water supply and drought, deficit irrigation can lead to greater economic gain by maximizing water use efficiency (Yenesew and Tilahun, 2009).

2.5 Harvest Index and Biomass

Richard *et al.*, (1993) reported that in almost all crops, the greater grain yield is not due to an increase in biomass but to an improved ratio of the grain to biomass (harvest index). As the potential ceiling value for the harvest index is rapidly approaching in many crops, the only way to maintain increase in yield will be to increase biomass (Richard *et al.*, 1993). In a study by Worku and Zelleke, (2009) to compare improved maize varieties released in Ethiopia for their harvest index and other important agronomic traits; twelve improved maize varieties which were released from 1970s to 1990s in Ethiopia and 8 breeding populations were tested in a randomized complete block design at Bako Agricultural Research Centre under sub-optimum and optimum soil fertility conditions in 1997 and 1998. The results indicated that the varieties released in the 1990s had a better harvest index than the old maize composites, indicating that the breeding progress made was successful for both grain yield and harvest index (Worku and Zelleke, 2009).

2.6 Water Productivity

Water productivity (WP) is defined as crop yield per cubic metre of water consumption (Cai and Rosegrant, 2003). It may also be defined as yield per unit of water (Kijine, 2003). Increasing WP is particularly important where water is a scarce (Molden *et al.*, 2003). The growing scarcity and rising value of water in a basin calls for both farmers and irrigation organizations to seek various ways to increase WP, economic efficiency and net returns (Barker *et al.*, 2003).

The Millennium Development Goals (MDGs) present a formidable challenge in realizing the target to halve hunger by 2015. UN-Water Thematic Initiatives (UWTI), (2006) reported that agriculture accounts for 70 percent of all water use globally, and up to 95 percent in several developing countries. To keep pace with the growing demand for food, it is estimated that 14 percent more freshwater will need to be withdrawn for agricultural purposes in the next 30 years. This indicates that more water will be used for agriculture. Therefore the need to improve crop water productivity is unquestionable (Molden *et al.*, 2003; Yenesew and Tilahun, 2009; Kijine, 2003). The use of efficient irrigation systems especially drip systems have been reported as one of the best way to increase water productivity (Yenesew and Tilahun, 2009; Kijine, 2003).According to Schahbazian *et al.* (2007), soil water and crop models can be used to increase efficient use of the allocated irrigation water.

Increasing the productivity of water in agriculture will play a vital role in easing competition, prevention of environmental degradation and provision of food security (Molden *et al.*, 2003). If water requirements for agriculture increase, competition for the resource may limit supply (Neilsen *et al.*, 2001). Liu and Yang, (2009) reported that challenges of availability of irrigation water supply may be influenced by global climate change; although the impacts of climate change on irrigation water demand is still not well studied.

Falkenmark and Rockström (2004) using year 2000 as a baseline estimated that an additional 5,600 km ^{3} per year of consumptive green water use would be required by 2050 in order to feed an additional three billion world inhabitants and to eradicate malnourishment. This is comparable to current global consumptive water use in irrigation of approximately 1,800 km^3 per year (Shiklomanov, 2000) and the current total estimated consumptive water use in agriculture of 6,800 km^3 per year (Rockström, 2003).

Furthermore, it has been reported the average WP of the developed world (0.47 kg m $^{-3}$) is higher than that for developing world of 0.39 kg m $^{-3}$ (Cai and Rosegrand, 2003) indicating the need for improving WP (Bennet, 2003).

2.7 Application of CROPWAT Model

The CROPWAT model, developed by FAO Land and Water Management Division (FAO, 1992), is an irrigation management tool to evaluate the crop water requirements and irrigation needs. The latest version of CROPWAT model, namely CROPWAT 4W, uses a windows interface and includes a simple water balance model. The model allows the simulation of crop water stress conditions and estimations of yield reductions based on well established methodologies for determination of crop evapotranspiration (FAO, 1998) and yield responses to water (FAO, 1979). The application of seasonal weather forecasts together with CROPWAT model allows the estimation of soil water supply conditions with 3-6 months ahead. When a skilful weather forecast is done, it can help farmers and decision makers to minimize negative consequences of unfavourable weather conditions or take advantages of favourable conditions (Marica, 2005).

The use of soil, plant and crop models together with climatic models will help in studying the impact of climate change on irrigation water demand. The CROPWAT model has been used for maize simulation in different countries such as Spain (Cavero *et al.*, 2000), Ethiopia (Georgis, 2004; Yenesew and Tilahun, 2009) and Egypt (Ismail and Dewpeg, 2005) and it has produced positive results. The application of regulated deficit irrigation and CROPWAT model can play an important role in developing practical recommendations for optimizing crop water productivity under conditions of scarce water supply (Yenesew and Tilahun, 2009; Smith and Kivumbi, 2002; Georgis, 2004; Cavero *et al.*, 2000; Ismail and Dewpeg, 2005; Schahbazian *et al.*, 2007).

The CROPWAT model calculates effective rainfall (Pe) based on Equations 2 and 3:

$$Pe = 0.8\,P \quad \text{.......................} (2)$$

Where; $P > 75$ mm/month; and

$$Pe = 0.6\,P \quad \text{.......................} (3)$$

Where; $P < 75$ mm/month.

In general, the efficiency of rainfall will decrease with increasing rainfall intensity. This is because of runoff created when the intensity exceeds the soil infiltration rate. For most rainfall values below 100 mm/month, the efficiency will be approximately 80%. Unless more detailed information is available for local conditions, it is suggested to select the Option "Fixed percentage" and give 80% as requested value when using CROPWAT model (Balaghi, 2010).

2.9 Synthesis of the Literature Review

In general water scarcity has been reported as an increasing problem in many countries. It is due to this reason that improving crop water use and productivity has become a concern of many countries in the world. The problem is reported to be more severe in developing countries than in developed countries. This has been due to lack of simple and straight away methods of managing irrigation water. Soil based irrigation scheduling has largely been used in scheduling irrigation although it is time consuming compared to for example the leaf temperature method which has not been used by many researches.

Several measures have been suggested to tackle the problem of poor water use and low water productivity. Some findings have suggested that the use of simulation models such as CROPWAT in irrigation scheduling can help to improve water productivity. Others have suggested that deficit irrigation can provide a significance increase in water productivity. The use of efficient irrigation systems especially drip systems have been reported in literatures as one of the best ways to increase water productivity.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Location, Climate and Soils

3.1.1 Location

The experiments were conducted at Sokoine University of Agriculture (SUA) in Morogoro Region. The site is located at Latitude -6.85^0 and Longitude 37.65^0. The average elevation is about 526m above mean sea level. The research was conducted at the crop museum of the Department of Crop Science-SUA (Fig. 1).

3.1.2 Climate

The area has bimodal rainfall distribution. The average annual rainfall is between 900mm and 1000mm with erratic distribution. The short rainy season (locally called Vuli) occurs between November and January and long rainy season (locally called Masika) occurs in March to June. A dry spell is experienced in February. Table 1 shows the summary of climatic parameters as provided by FAO CLIMWAT, (2006). The CLIMWAT database includes data from a total of 3262 meteorological stations from 144 countries.

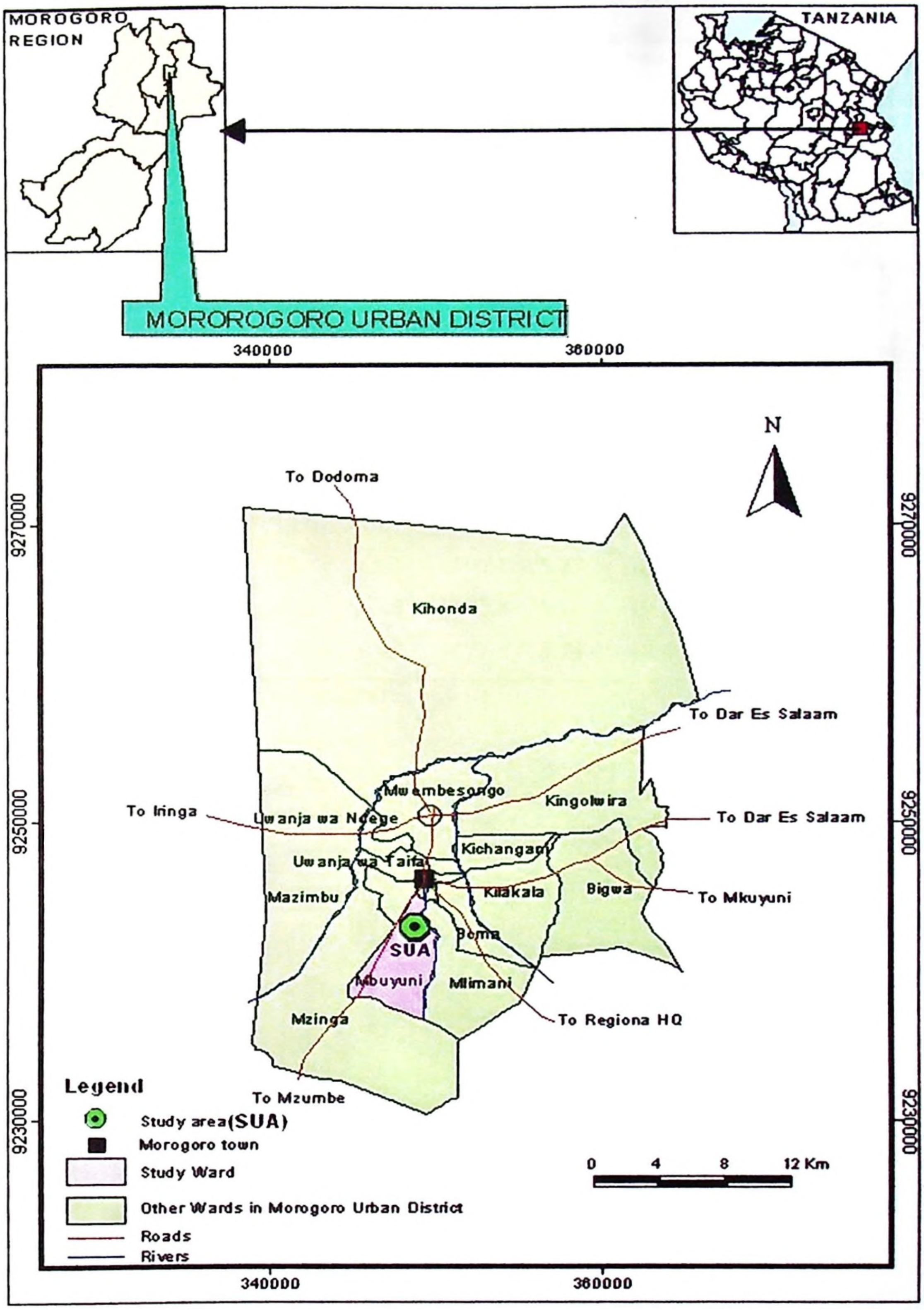

Figure 1: Location of Morogoro Region

Table 1: Mean Monthly Climatic data of Morogoro for the period of 1971 – 2000

Month	Maximum Temp	Minimum Temp	Relative Humi	Wind Speed	Sunshine Hours	Solar (Global) Radiatio	ET0(mm /day)	Precipitation (mm)
January	31.5	21	71.4	129.6	5.73	18.62	4.23	105
February	31.7	20.8	72.7	121	5.9	19.1	4.24	97
March	31.5	20.8	76.3	121	5.96	18.83	4.09	133
April	29.6	20.4	83	103	4.58	15.64	3.28	198
May	28.2	18.8	82.3	112.3	4.22	13.92	2.88	79
June	27.3	15.9	78	129.6	4.46	13.55	2.75	19
July	27.2	15	74.1	129.6	4.36	13.67	2.79	13
August	28.3	15.8	69.2	129.6	4.41	14.77	3.17	11
September	29.8	16.6	66.9	155.5	4.89	16.61	3.75	20
October	31.2	18	65.1	190.1	5.77	18.63	4.42	43
November	31.8	19.5	67.8	172.8	6.14	19.23	4.48	98
December	31.8	21	69.2	172.8	5.74	18.46	4.43	119

Source: FAO CLIMWAT, (2006)

3.1.3 Soils

Soils at the research site are *Ultic Haplustalfs* with six different layers at 200cm depth (ReACCT, 2009). As described by ReACCT (2009), the top soil from 0-30 cm depth is clay loam, dark brown (7.5YR 3/4) when dry and very dark brown (7.5YR 2.5/2) when moist. It consists of coarse strong granular particles which are slightly hard when dry and very friable when moist. The soils are slightly sticky and slightly plastic when wet, consisting of many fine to coarse pores with fine to medium roots in it. At this 0-30cm depth the soils did not react with HCl, this behaviour was common across all depths indicating that the soils were non-saline. However the burrows of animals and termites activities were common.

At depth 30-55 cm, the soil was silt clay loam red (2.5YR 4/6) when moist with no gravel fragments. It was characterised with coarse strong granular particles, firm when moist, slightly sticky and slightly plastic when wet. It also consisted of common distinct clay and sesquioxides cutans and common fine to medium pores. Roots (very fine to fine) were also observed in it. These characteristics continued to be gradual with smooth boundary throughout this depth. The characteristics of the soil particles changed when a depth of 55-77 cm was attained.

Silt clay loam with dark red colour (2.5YR 3/6) when moist was observed between 55-77 cm depth. This depth consists of strong medium to coarse granular particles; very friable when moist; slight sticky and slightly plastic when wet; common distinct clay and sesquioxides cutans; fine to medium pore; very fine to fine roots.

At a depth of 77-100 cm, it was observed that the soils were characterised with dark red moist (2.5YR 3/6) particles with silt clay loam to sand clay loam being dominant having moderate medium to coarse granular particles and very friable when moist. Also the soil was observed to be slightly sticky and slightly plastic when wet with common distinct clay and sesquioxides cutans, it had fine to medium particles, very fine to fine roots and the soil did not react with HCl.

At 100-130 cm depth, the soil was observed to be yellowish red moist (5YR 4/6); silt clay loam to sand clay loam and weak medium to coarse granular. Soil particles were very friable when moist, slight sticky and slightly plastic when wet, common distinct clay and sesquioxides cutans. Also it was observed to have very fine to fine particles with very few fine to fine roots seen in it.

From 130-190+ cm depth, the soil was observed to be yellowish red (5YR 5/8) moist; sand clay loam, weak medium to coarse granular. Soil particles were very friable when moist, slightly sticky and slightly plastic when wet, common distinct clay and sesquioxides cutans. There were very fine to fine soil particles and few very fine to fine roots.

3.2 Experimental Design and Treatments

The experimental layout consisted of three blocks each with four sub-blocks arranged in a completely randomized block design (CRBD) (Fig. 2). Four treatments were randomly assigned in a block containing four sub blocks such that each sub block had an equal chance of receiving one treatment. The treatments were T1 (60% irrigation water deficit), T2 (40% irrigation water deficit), T3 (20% irrigation water deficit) and T4 (No deficit or called optimum irrigation). The experiment consisted of three replication hence forming a completely randomized block design CRBD with three blocks and four treatments. In each sub block a diviner access tube was installed for volumetric soil moisture measurements. The installation involved the use auger unit to make holes (profiles) of the same diameter as the diviner access tube. The access tube was forced to enter and fit into a hole by hammering slowly using a plastic hammer. This was important to make sure that the access tube was in contact with the soil. Soil profiles were created with the default calibration equation as explained in Sentek sensors technologies manual (SST, 2009). The drip system for irrigating the maize was installed following the layout of the block (Fig. 2) with emitters at 30cm apart and the lines at 75 cm apart. Each sub-main had a flow control valve for allowing and disallowing water to flow into the field lines. For easy access of data, an automatic weather station was installed just after entrance of the trial site (Fig.2).

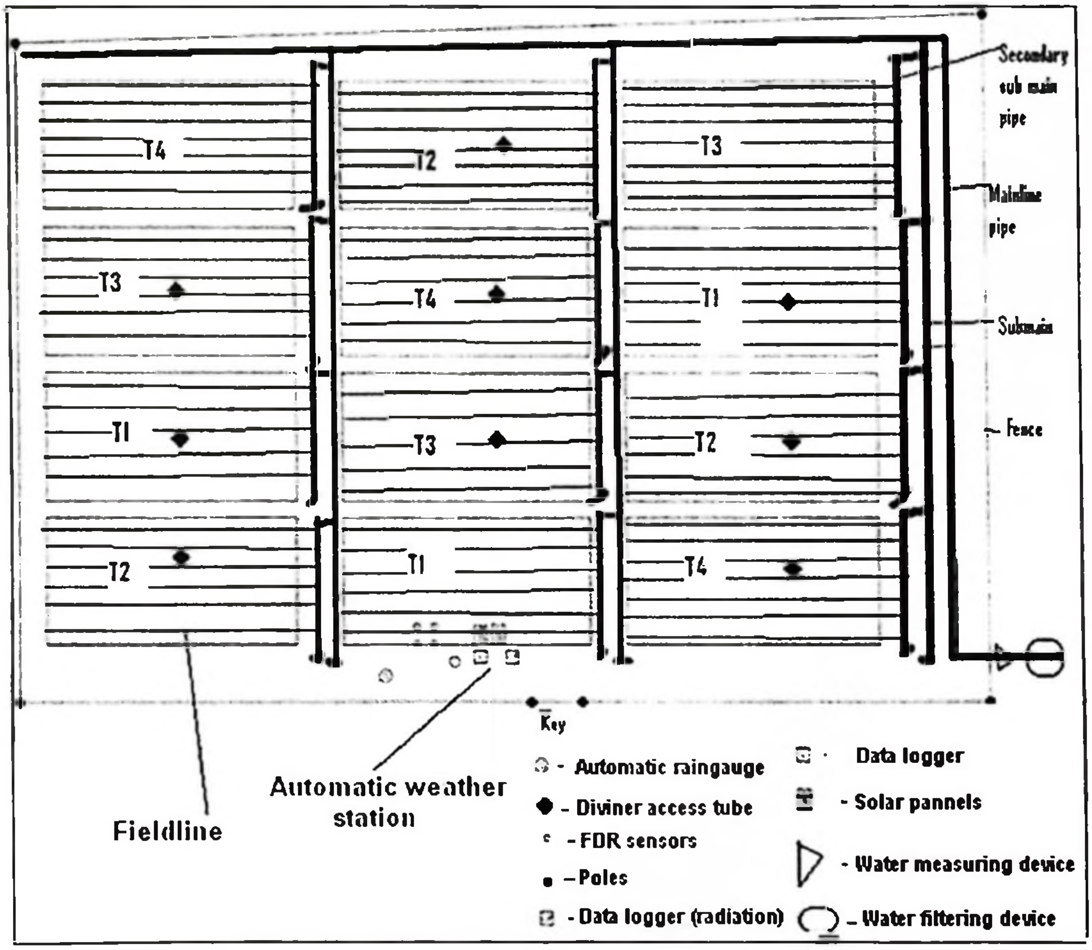

Figure 2: Experimental Layout

3.3 Data Collection

3.3.1 Soil moisture data

The diviner 2000 unit was used to collect the volumetric moisture content of the soil. Tensiometers were used to get estimates of the soil matric potential in each subplot in the initial stages of the growing period. The matric potentials which were monitored were those at field capacity (FC) and permanent wilting point (PWP).

3.3.2 Crop data

The planting date (26th October 2009), emergence date (3th November 2009) and development stages were recorded. The development stages were recorded at 15, 30, 45, 75 and 90 days after planting (DAP). The number of leaves fully developed was counted by randomly picking 10 different plants in each sub-block on weekly basis. The plant height was measured on weekly basis using a ruler on a random sample of 10 plants and averaging their heights. Leaf temperature of crops in each subplot was measured on daily basis using infrared (Laser jet) thermometer to monitor stress development in the crops (Irmak *et al.*, 2000). The grain yield in kilogram was measured after harvest using a digital weigh balance. Fig. 3 shows maize crop at 15 DAP.

Figure 3: Maize under deficit drip irrigation 15 DAP

3.3.3 Biomass sampling and harvest index

Three biomass samples were collected at three different stages (development, mid-season and maturity) in each sub-block to analyse the effect of water stress on biomass production. One square meter of plants from each sub-block was cut down in each sampling day. Wet samples and oven dried samples of stem, leaves and cobs from each sub-block were weighed and recorded. A comparative analysis was done to observe if there existed any significant difference in biomass production among different treatments. For each sub-block harvest index value was calculated by taking one square metre sample of plants from each sub-block, measure the weight of biomass and grain then take the ratio of grain to biomass weight (Richard *et al.*, 1993; FAO, 2009).

3.3.4 Crop water requirement and irrigation scheduling

Crop water requirements were calculated based on ETo adapted from FAO CLIMWAT program and Kc values adapted from FAO Irrigation and drainage paper 56 (FAO, 1998).

The schedules of irrigation were conducted based on Kihupi, (2008) by combining crop based and soil based irrigation schedules through observing appearance and growth, measuring leaf temperatures and measuring the soil volumetric moisture content. The amount of water depth applied per each sub-block was measured using a scale hydrological water meter. A measuring cylinder was used to measure the amount of water dripping per plant hole. Rainfall was recorded using an automatic rain gage which was available at the station. During irrigation, the recorded rainfall was deducted from the total amount of irrigation water in successive irrigation.

3.3.5 Model simulation data

The following data were collected for inputting into the CROPWAT simulation model:

Weather data: Monthly average temperature, radiation, wind speed, humidity and rainfall (Appendix 11 and 12).

Management data: cropping pattern, cropping calendar, planting date.

Crop characteristics data: crop coefficient values (kc), accumulation of dry matter, yield response factor ky, number of days to maturity (Appendix 14).

Soil properties: soil layers, infiltration rate, textural characteristics, field capacity and permanent wilting point. (Appendix 15).

The CROPWAT model was run to determine the ET_C and irrigation scheduling for the growth period (Appendix 15), daily soil moisture balance and yield reductions.

3.4 Data Analysis

3.4.1 Crop data analysis

The biomass, grain yield and harvest index data obtained in all the treatments (sub-plots) were analyzed using GenStat Discovery Edition 3 program to determine if there exist a significant difference among the treatments. Also the program was used to check the variation of Yields, within and between the blocks for each treatment if there is a significant difference. The excel spread sheet was used to plot different graphical representation and input some equation governing several situations.

Weather data, crop characteristics data and soil properties data were used to run the CROPWAT model to simulate yield reductions, calculate crop water requirements and irrigation scheduling.

The percentage experimental yield reductions (Θ) were calculated as a ratio of the difference between the yields from reference treatment that received 100% of calculated ETC T4 (YT4) and other treatments T3 (YT3), T2 (YT2) and T1 (YT1) to the yield reference treatment YT4 (Equations 4,5 and 6).

$$\Theta 1 = \frac{YT4 - YT1}{YT4} \times 100 \ldots\ldots\ldots\ldots (4)$$

$$\Theta 2 = \frac{YT4 - YT2}{YT4} \ldots\ldots\ldots\ldots (5)$$

$$\Theta 3 = \frac{YT4 - YT1}{YT4} \ldots\ldots\ldots\ldots (6)$$

Where $\Theta 1, \Theta 2$ *and* $\Theta 3$ are percentage yield reductions for T1, T2 and T3 respectively.

YT1, YT2, YT3 and YT4 are yields at T1, T2, T3 and T4 respectively

A comparative analysis between the experimental and simulated results to determine whether they are different or not was done using Genstat statistical package. The decision to whether the model adequately simulated the experiment was done based on statistical results stating clearly the percent level of significance.

CHAPTER FOUR

4.0 RESULTS AND DISCUSION

4.1 Experimental Results

4.1.1 Rainfall

The rainfall which was recorded indicated an increase in amount during the growth period (2009-2010) with October (2009) experiencing lowest monthly rainfall value, while January (2010) experienced the highest monthly rainfall amount compared to the rest of the months (Fig. 4). There were some differences between the recorded rainfalls during the experiment to the values from CLIMWAT database (Table 1). This is because the CLIMWAT database uses the average values of rainfall of more than 30 years while in the experiment the exact rainfall values were recorded using an automatic rain gage in each rainfall event. However the pattern was the same as the values were increasing from October to December. Furthermore the values from CLIMWAT and from the experiment were not significantly different at $p<0.05$ (Appendix 7).

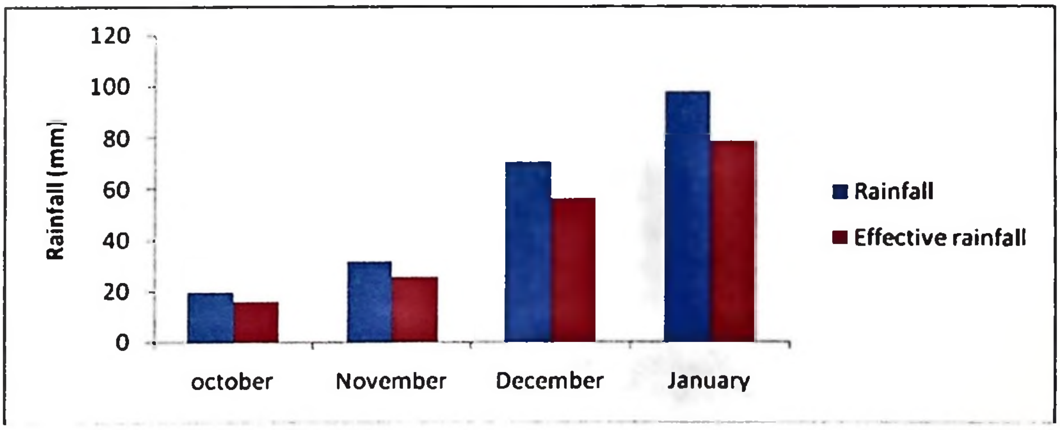

Figure 4: Rainfall recorded during growth period

4.1.2 Soil moisture characteristics

The average soil moisture characteristics as measured by the diviner unit in different treatments during experimental period have shown a non uniform distribution pattern in different profiles (Fig. 5). Irrigation was performed in equal intervals but with different amount of water applied in accordance to treatment recommendations. The values plotted represent the average of the readings from 10cm to 120cm depth for three different profiles with the same treatment. A 120cm depth was assumed to be the optimum rooting depth for maize (Doorenbos and Pruitt, 1977). The highest average volumetric moisture value was observed in T4 which received optimum amount of water required by the crop and the lowest average value was observed in T1 which received 40% of the required amount of water. The variations in the graphs show the effective drying and wetting events due to irrigation. For all the treatments, the moisture values were high in the period ranging from 17 December 2009 to 7 January 2010. This was due to increase in rainfalls during this period.

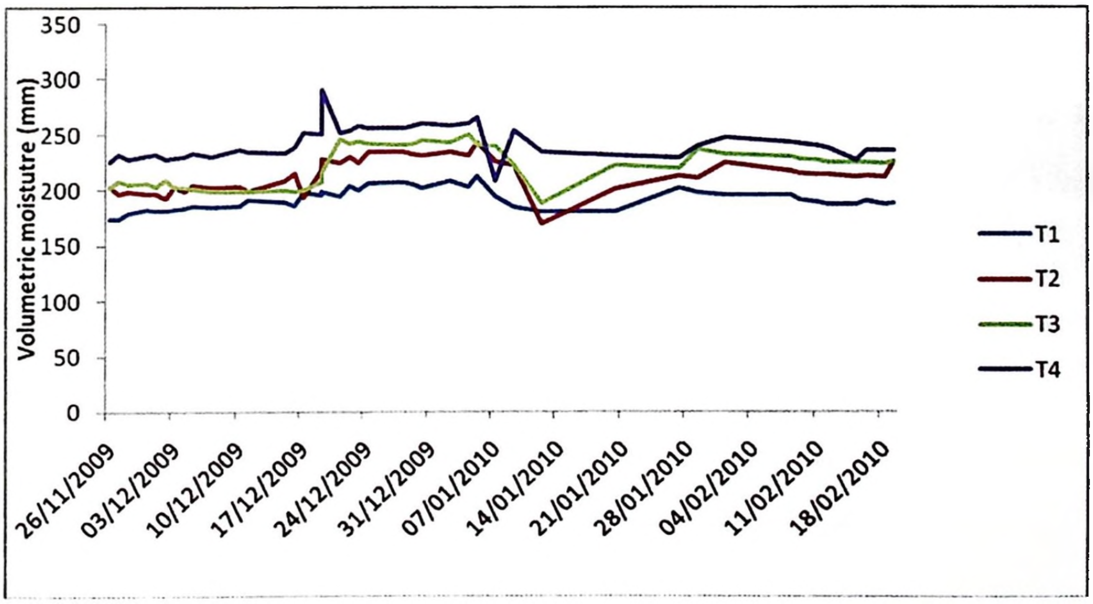

Figure 5: Soil moisture characteristics during the growth period

4.1.3 Biomass accumulation at 45 DAP

The accumulation of biomass during the first 45 days of growth (Fig. 6) indicate that there was more dry matter accumulation in optimum irrigation sub-plot (T4) as compared to other deficit irrigated sub-plots. The values of biomass in all blocks (replications) increased with increasing irrigation water to optimum irrigation.

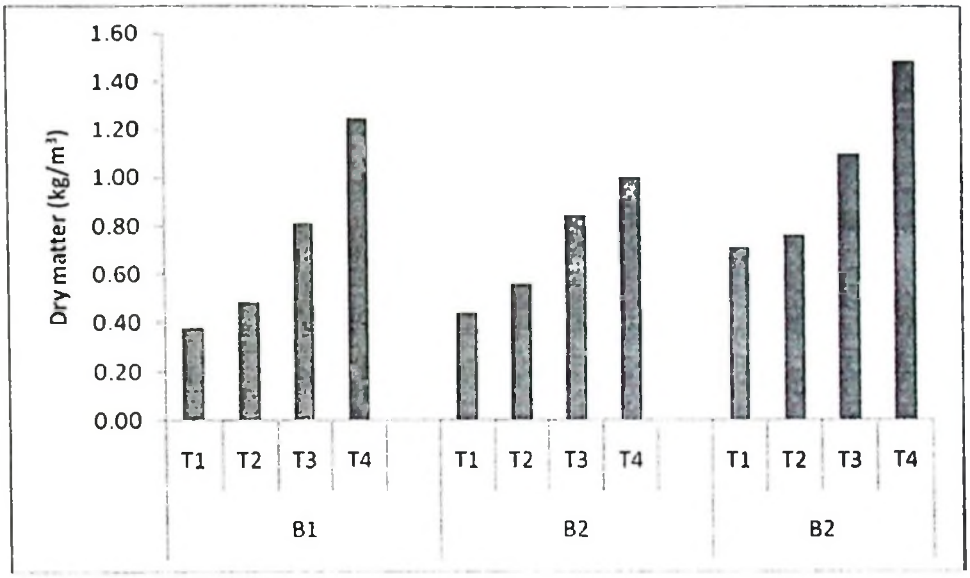

Figure 6: Accumulation of biomass at 45 DAP

The average maximum value of biomass accumulation observed at 45 DAP was 1.25 kg/m^2 observed in T4 (Fig. 7) while the lowest value was 0.512 kg/m^2 in T1. The average percentage reduction in biomass accumulation at 45 DAP was 58.94% in T1, 51.57% in T2 and 26.31% in T3; On the other hand the trend was similar at 75 DAP as shown in Figure 8. The actual reduction in dry matter accumulation at 75 DAP in T1 was 32.88%, in T2 was 33.97%, and in T3 was 24.66%. The mean biomass production between treatments were significant different ($p<0.05$) at 45 DAP and at 75 DAP. At 45 DAP mean biomass production for T1, T2, T3 and T4 were 0.512, 0.604, 0.92 and 1.248 kg/m^2 respectively and at 75 DAP mean biomass production for T1, T2, T3 and T4 were 0.684, 0.728, 1.049, 1.378 kg/m^2 respectively.

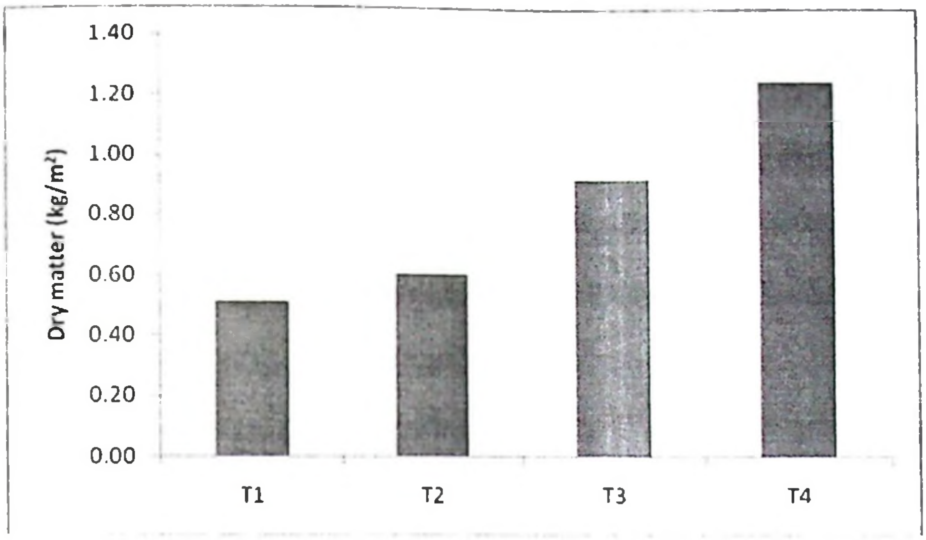

Figure 7: Average biomass accumulation in different treatments 45 DAP

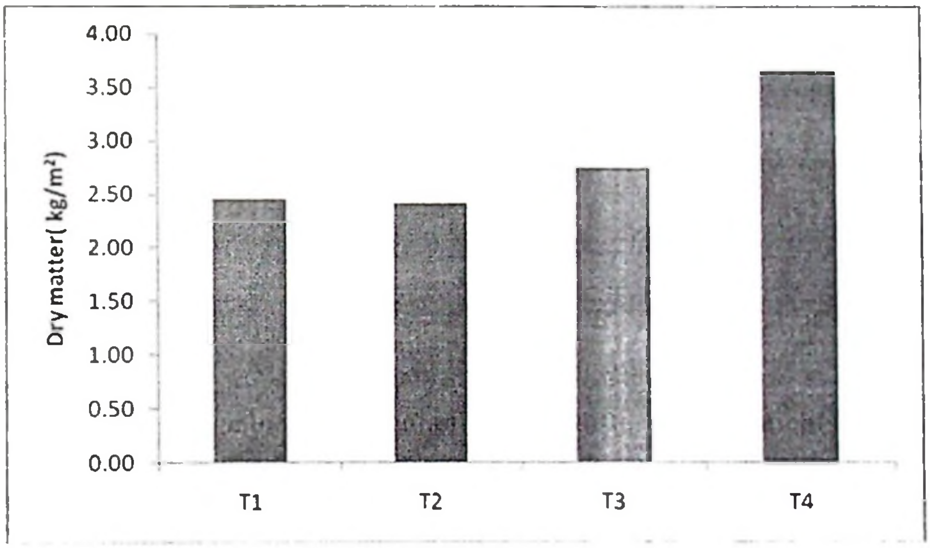

Figure 8: Biomass at 75 DAP

4.1.4 Grain yield

The maximum grain yield was observed in the optimum irrigation plots (Fig. 9). T4 in block 2 had the highest yield of 4.9 tons/ha while the smallest yield (2.5 tons/ha) was observed in T1 in block 1.

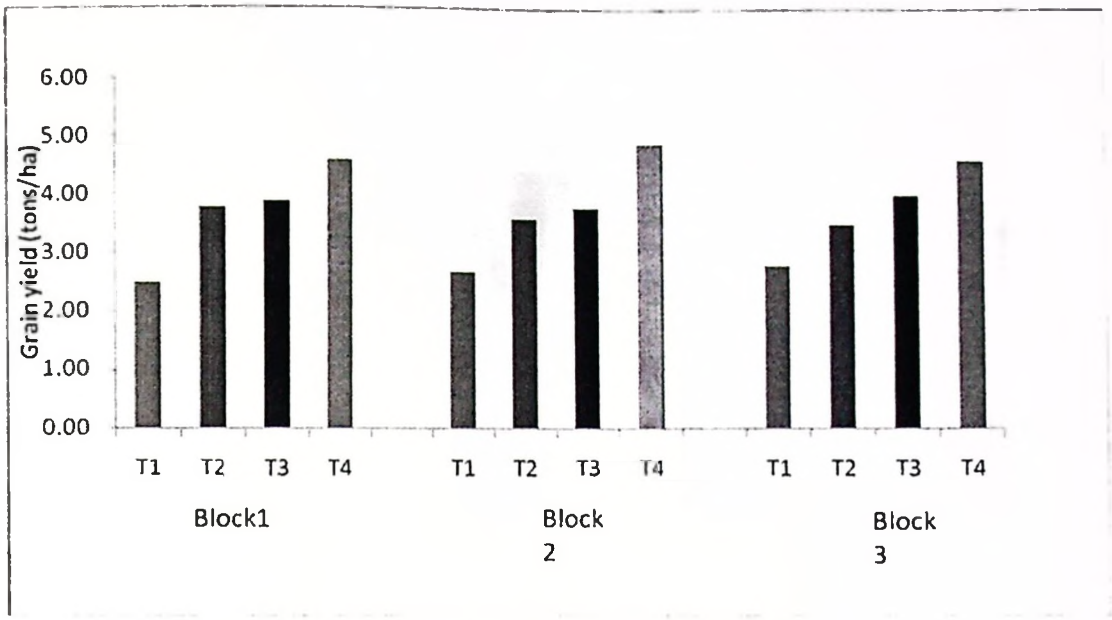

Figure 9: Grain yield (Tons/ha) for different treatments

The mean yields (Fig. 10) for each treatment were 2.67 tons/ha for T1, 3.62 tons/ha for T2, 3.89 tons/ha for T3 and 4.7 tons/ha for T4. The average percentage yield reduction in T1 was 43.19 %, in T2 was 22.98% and in T3 was 17.23% as compared to optimum treatment T4 which was given 100% of the calculated crop water requirement. The mean grain yield between treatments were statistically different ($p<0.05$). From the LSD test the mean yield from T2 was not different from T3 but the rest had mean grain yields which were significantly different ($p<0.05$).

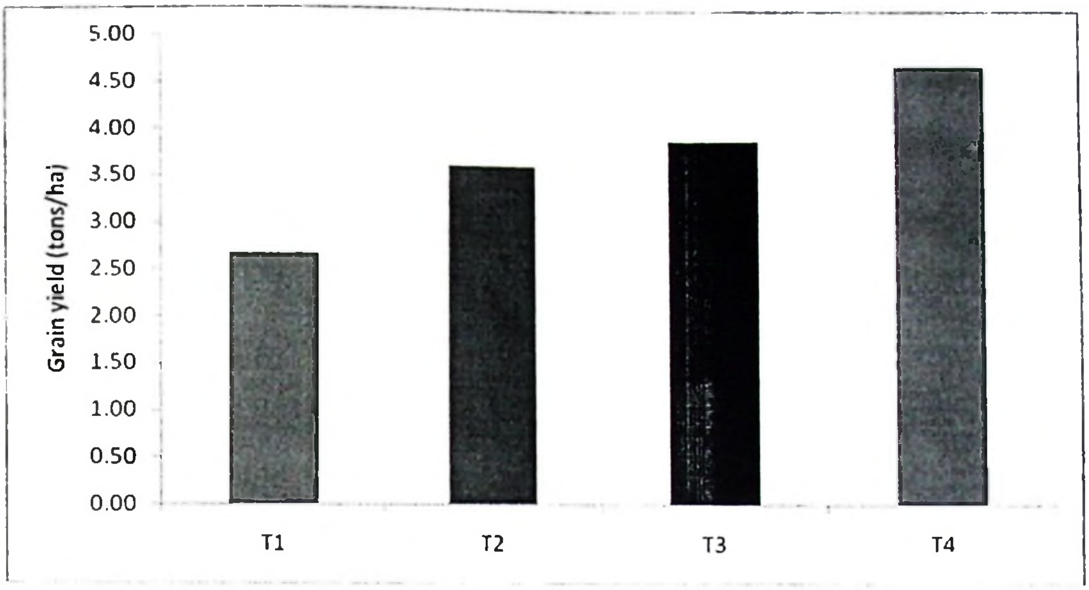

Figure 10: Average grain yields under different water levels

4.1.5 Harvest index

The mean harvest index was high in T4 with the highest value of 0.45 kg/kg. This indicated that there was a better ratio of grain yield to biomass in T4 compared to the other treatments T1, T2 and T3, with the values 0.33, 0.43, 0.44, kg/kg respectively. Harvest index increased with reduced water stress. Poor harvest index in T1 was due to poor grain production which was caused by water stress. Njovu, (2000) reported harvest index values ranging between 0.41 and 0.51 kg/kg for the Staha composite maize variety under rainfed and irrigation at Hombolo irrigation project. He pointed out that the higher harvest index values were due to the crops being stunted at the initial development stages. The little build up of biomass in the initial stages due to water stress and provision of enough water in flouring stage helps the plant to store some food which later can be used in the cobs and grain formation. Figure 11 shows variation in plant growth due to different water deficit levels. Water stress is a strong reason for poor harvest index however there are some other factors such as soil fertility, permeability, texture and structure (which were assumed to be uniform) that could also influence harvest index values. Further investigation is needed to determine the levels of which these other factors could reduce or increase the harvest index values.

Figure 11: Growth stage of TMV-1 maize variety under deficit drip irrigation

4.1.6 Water productivity

The highest value of water productivity (2.3 kg/m^3) was observed in T2 in block 1 and the lowest value (1.59 kg/m$^{3)}$ of water productivity was observed in T1 within block1 (Fig. 12).

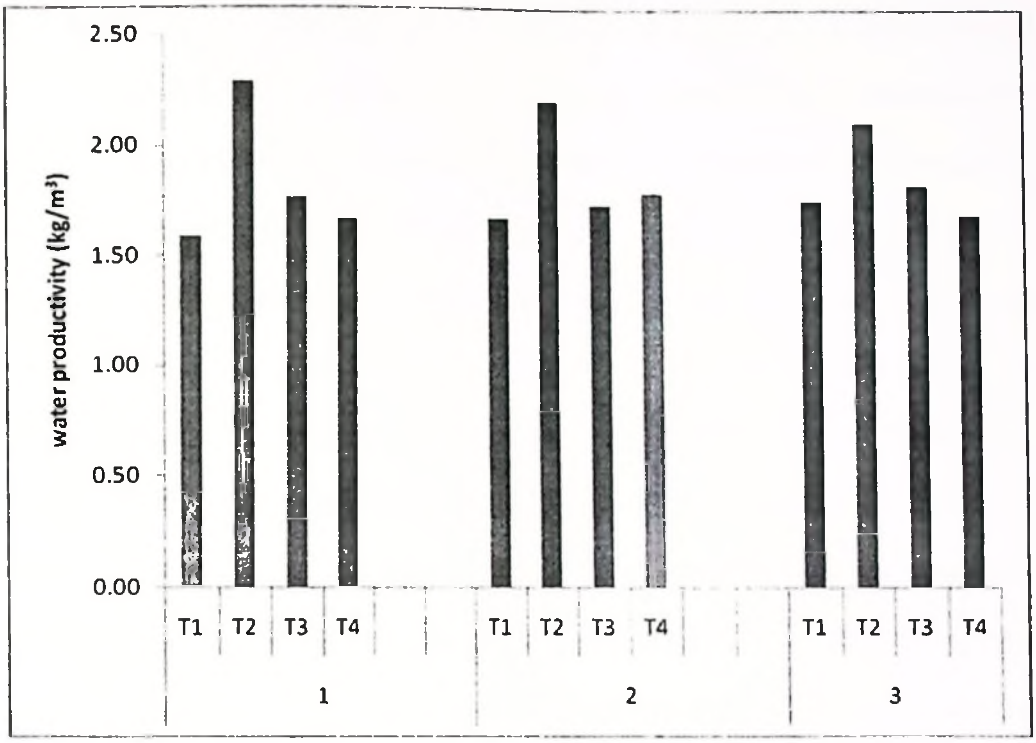

Figure 12: Water productivity under different water deficits.

The average values of water productivity per treatment for the whole trials (Fig. 13) indicates that there was high average water productivity (2.2 kg/m^3) in T2 which received 60% of the required amount of water. In T3 which received 80% of the required water had second highest value of WP (1.78 kg/m^3) followed by T4 (1.72 kg/m^3) which received 100% of the required amount of water. T1which received 40% of the required amount of water had the lowest value of WP (1.67kg/m^3) compared to the rest of the treatments. This was due to low grain yields. The average grain WP were significantly different ($p<0.05$). However from the Least significant difference of means (l.s.d) test with l.s.d value of 0.1675, indicated that WP in T2 was different from all other treatments, while T1,T3 and T4 were not significantly different at $p<0.05$. The highest value of 2.2 kg/m^3 was observed in T2 which received 40% deficit of crop water requirement. Other values were 1.67, 1.78, 1.72 kg/m^3 for T1,T3 and T4 respectively.

Cai and Rosegrant, (2003) also reported that water productivity for cereals other than rice ranged from 0.2 kg/m^3 to 2.4 kg/m^3 which is in agreement with the results reported in this study. However the results from this study differed to the values of the average WP of the developed country of 0.47kg/m^3 and developing countries 0.39 kg/m^3 which were also reported (Cai and Rosegrant, 2003). The reason should be because the average values comprises of different types of irrigation systems including surface irrigations which uses more water than drip irrigation. Furthermore these reported values are for all cereals while in this study maize was used specifically. On the other hand the WP of 1.0-1.7 kg/m^3 was observed in China, 1.7-2.4 kg/m^3 was observed in the USA, Brazil and in western European countries while lower than 0.4 kg/m^3 was observed in south Asia, central Asia, northern and central sub-Saharan Africa. Hamphreys *et al.*, (2005) reported the values of maize WP of 1.4, 1.7 1 and 1.3 kg/m^3 for sprinkler, drip and furrow irrigation respectively. The value of 1.71 kg/m^3 WP for a drip system (Hamphreys *et al.*, 2005) was very close to the results obtained in this study in the optimum irrigation schedule (1.72 kg/m^3).

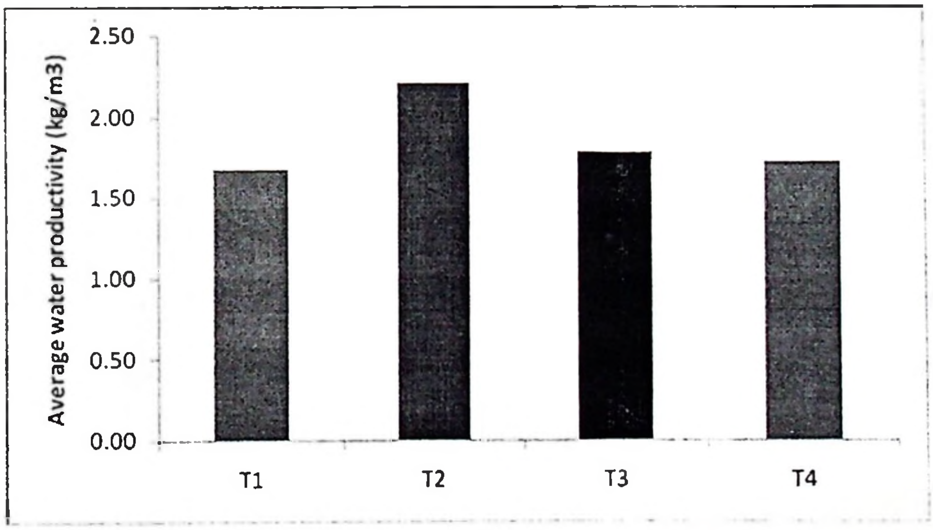

Figure 13: Average water productivity of maize under different water deficits

4.1.7 Synthesis of the experimental results and discussion

The T2 treatment which received 0.6 of the crop water requirement used $1 m^3$ of water to produce 2.2 kg of maize, meaning that it will require 1000 m^3 of water to produce 2.2 tons of maize. On the other hand T4 which received optimum irrigation used $1 m^3$ of water to produce 1.72 kg of maize meaning that it will require $1000 m^3$ of water to produce 1.72 tons of maize. This is 22% percent less as compared to T2. It means that approximately 225.23 m^3 in every 1000 m^3 of water was saved that could be used for other production or other use in T2 as compared to T4. If this can be done with only 1000 farmers in Morogoro then a total of 225 230 m^3 of water will be made available for other production or use.

Furthermore, if it is decided that this saved water is to be used for other production activities then 495 506 tons of maize can be produced using the 225 230 m^3 of the saved water. Also comparing T2 with the lowest productive practice in T1 which received only 40% of the crop water requirement had 247.75 m^3 of water lost in every 1000 m^3 used. This loss is equivalent to 24.75% loss compared to T2.

4.2 Results from CROPWAT Simulation Model

4.2.1 Crop water requirement

The ET_C was high in December (>54 mm) and lowest values were observed in January (Fig. 14 and Appendix 16). December had peak values of ET_C because the crops were at the mid development stage which required more water. High values of ETo (4.43mm/day) and increased kc values (from 0.75 and 1.15) due to crop growth caused an increase in the total ET_C value in December. The irrigation requirement was less than ET_C because effective rainfall compensated some of the crop water requirement. In October, and

November the values of ET_C were close to irrigation requirement due to less amount of rainfall in these months.

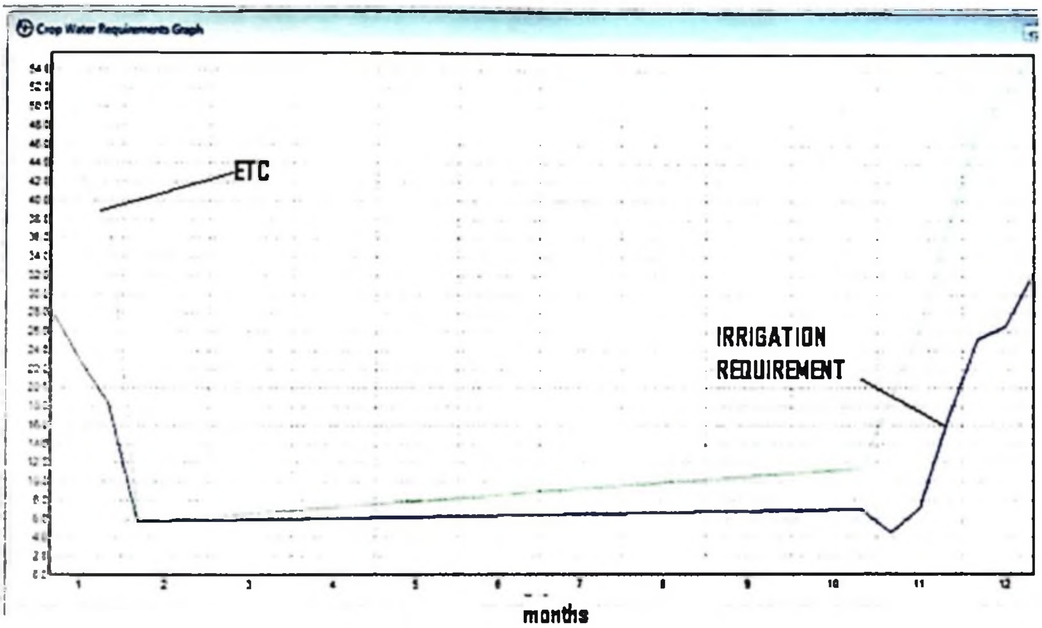

Figure 14: CROPWAT simulation of ET_C and irrigation requirement in mm

4.2.3 Daily soil moisture balance

There was enough readily available moisture in the soil when the optimum irrigation was practiced. The plant did not experience water stress as the water was available throughout the growing period (Fig. 15). The total gross irrigation requirement for the season was 177.2 mm with the net irrigation being 150.6 mm. The potential water use by the crop was 381.7 mm while the actual water use by crop was 377.1 mm; rainfall was 331.7mm (Appendix 16). Between 25 DAP and 30 DAP there was an indication of water stress to the crop. This shows that the crop water requirement adjustment was supposed to be made at 25 DAP. Furthermore from 75 DAP the graph of depletion touches the line of RAM, this is the period when the crop has matured and it requires less water to help it reach full maturity and dry.

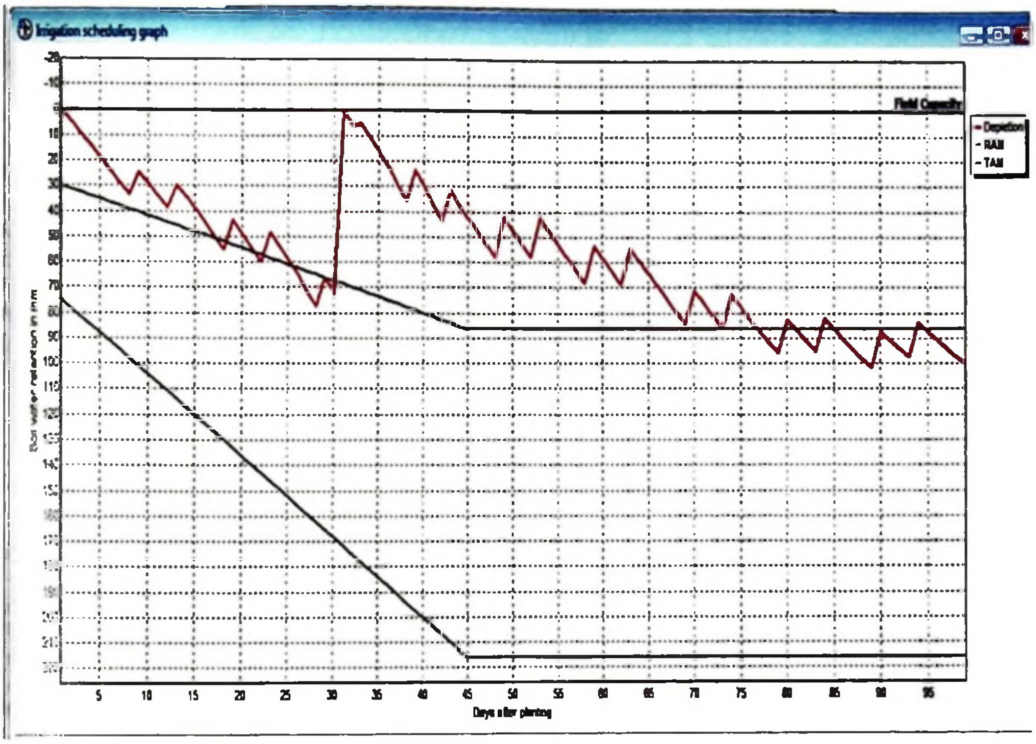

Figure 15: Daily soil moisture balance at optimum irrigation schedule

There was less soil moisture readily available for the plants when the 60% depletion was allowed (Fig.16). In the first 15 DAP the plant did not suffer from water stress. This is because in the first 15 DAP the plant needed less water for germination and growth meaning that the moisture in the soil was enough to support the plants. Just after 15 DAP the plant most of the time was under water stress. The soil moisture retained was most of the time between TAM and RAM zone indicating continuous water stress to the crops. The total gross irrigation requirement for the season was 63.1 mm with the net irrigation being 53.6 mm. The potential water use by the crop was 381.7 mm while the actual water use by crop was 301 mm; rainfall was 331.7mm (Appendix 19).

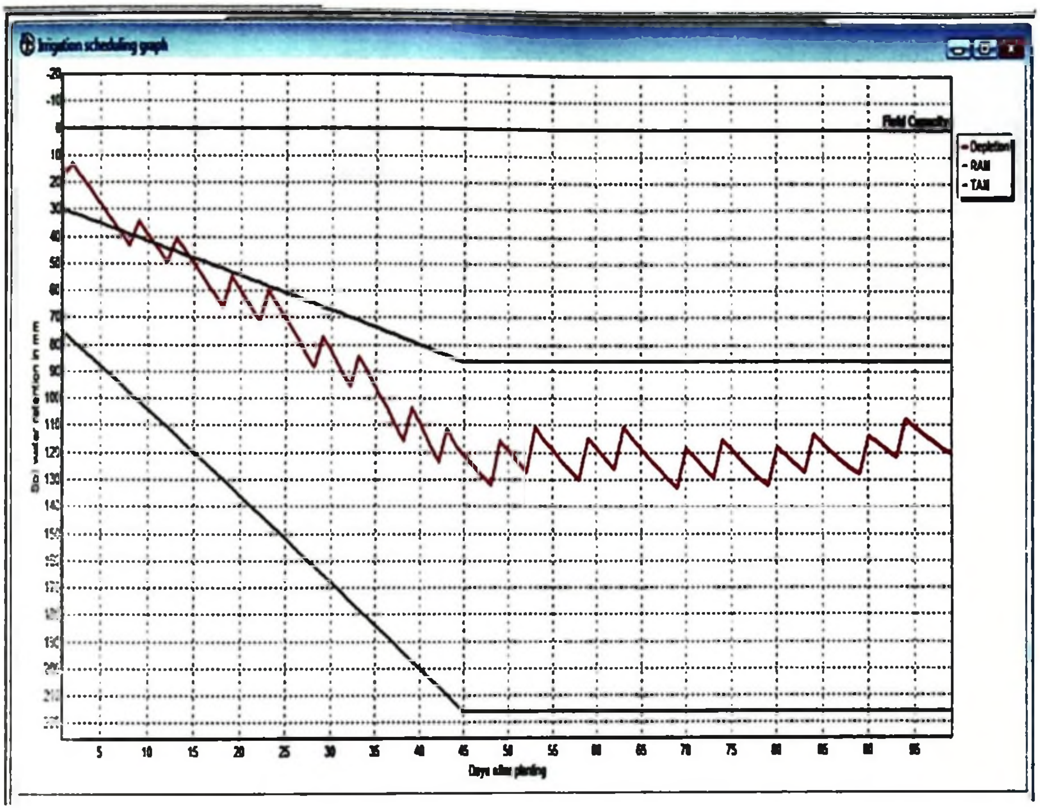

Figure 16: Daily soil moisture balance at 60% deficit irrigation schedule

At 40% deficit the soil moisture was depleted to between RAM and TAM zone at just 22 DAP. However the Figure 17 shows that the first 22 days the stress induced didn't have much effect on the availability of water in the soil for crop growth. The soil had enough moisture to support plants germination and growth since the plant roots were still on the shallow depth which had enough water to support the plant growth. The amount of water available in the soil here was slightly higher than in 60% deficit. The crop started to experience water stress continuously from 22 DAP to the end of the growth period. The total gross irrigation requirement for the season was 70.2 mm with the net irrigation being 59.6 mm. The potential water use by the crop was 381.7 mm while the actual water use by crop was 306.7 mm; rainfall was 331.7mm (Appendix 18).

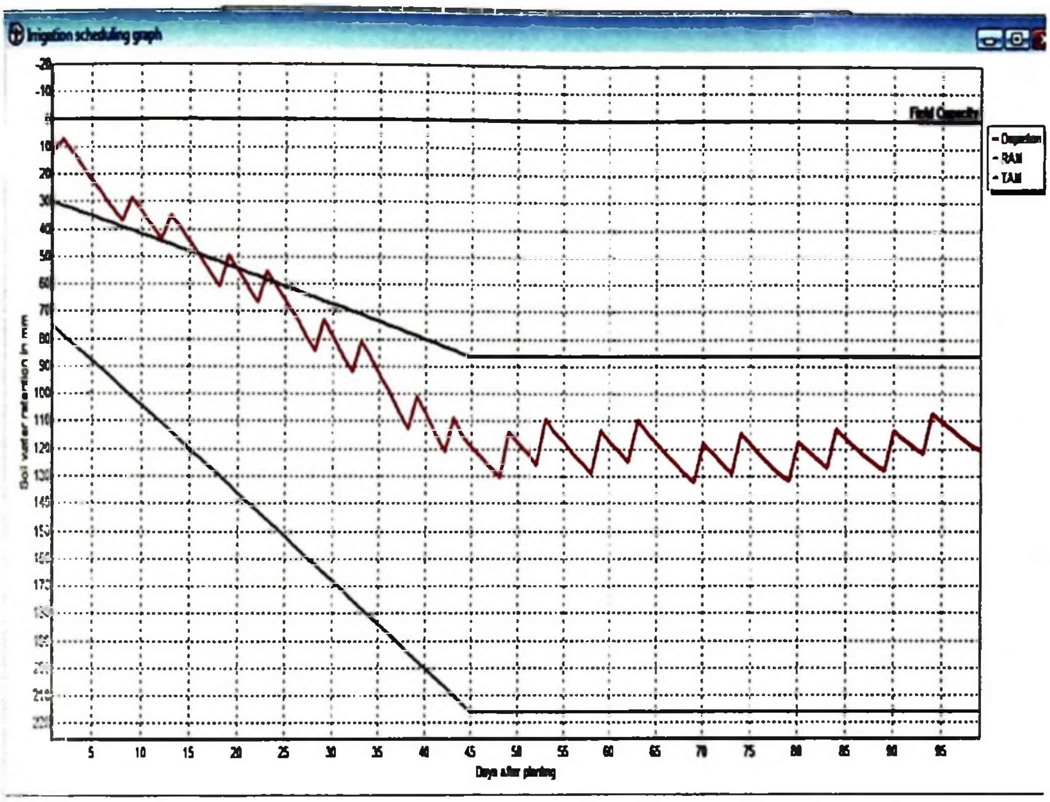

Figure 17: Daily soil moisture balance at 40% deficit irrigation schedule.

At 20% depletion level T3, most of the time the soil moisture was maintained between readily available moisture (RAM) and Total available moisture (TAM) (Fig. 18). Not much stress was experience during the first 25 DAP as the more water was readily available to the plant to support the germination and growth. The amount of water available in the soil here was slightly higher than in 60% and 40% deficits. The total gross irrigation requirement for the season was 77.2 mm with the net irrigation being 65.6 mm. The potential water use by the crop was 381.7 mm while the actual water use by crop was 312.3 mm; rainfall was 331.7mm (Appendix 17).

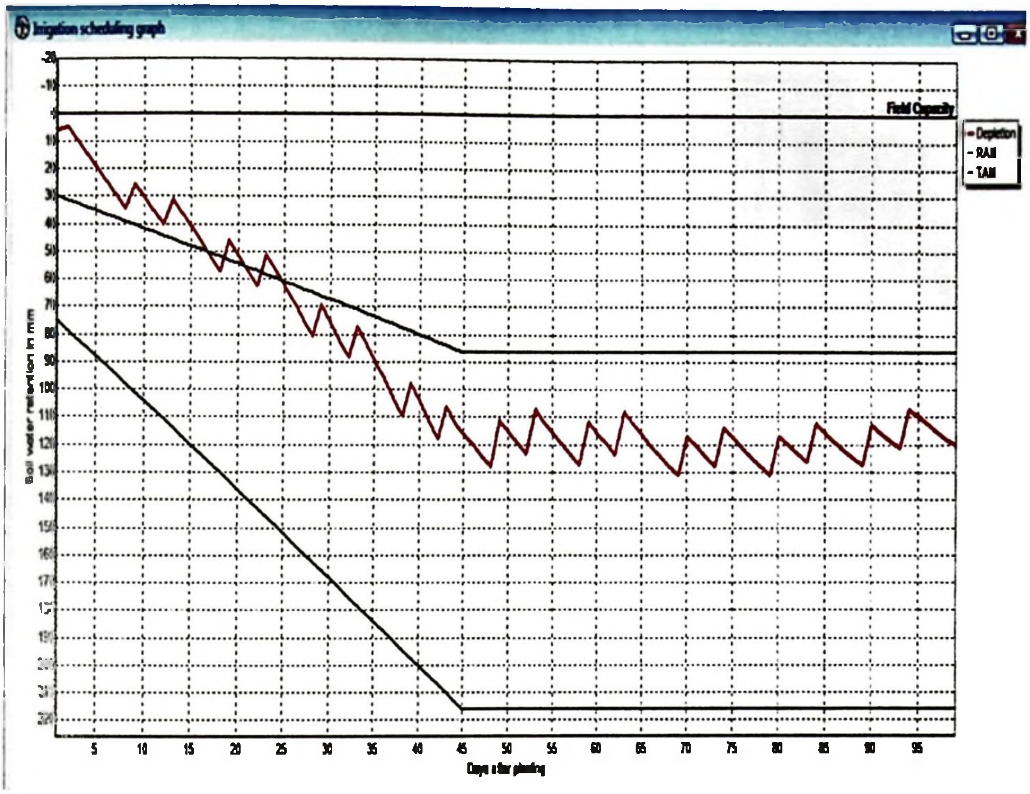

Figure 18: Daily soil moisture balance at 20% deficit irrigation schedule

4.2.4 Yield response to water from CROPWAT model

Despite provision of optimum amount of water, still CROPWAT simulation model indicated little percentage yield reduction. Little stress caused during the initial growth stages managed to reduce the biomass build up by 2.4% and 1.2% in the development stage. The overall expected yield reduction was 1.5 % (Appendix 20).

The results (Table 2 and Appendix 21) shows that a 22.7% cumulative season yield reduction at 20% water deficit (T3) simulated by CROPWAT model was expected. High yield reductions of 16.6 % was obtained in development stage (stage B). This indicates that at this level effects of water deficit were more sensitive. The initial stage (A) was the least affected stage by water stress with 2.4% yield reductions.

Table 2: Reductions at 20% deficit irrigation schedule

Yield reductions (%)					
Stage	**A**	**B**	**C**	**D**	**SEASON**
Reduction in ETC	6.1	11.1	22.4	23.3	18.2
yield response factor	0.4	1.5	0.5	0.2	1.25
yield reductions	2.4	16.6	11.2	4.7	
cumulative yield reductions	2.4	18.7	27.8	31.1	22.7

Results from Table 3 (40% water deficits) shows that a cumulative season yield reduction of 24.6% was expected. Crop development stage (Stage B) with 20.9% expected yield reduction was the most affected by water stress while stage A with 2.4% expected yield reductions was the least affected (Appendix 22).

Table 3: Reductions at 40% deficit irrigation schedule

Yield reductions (%)					
Stage	**A**	**B**	**C**	**D**	**SEASON**
Reduction in ETC	6.1	13.9	23.7	23.8	19.6
yield response factor	0.4	1.5	0.5	0.2	1.25
yield reductions	2.4	20.9	11.9	4.8	
cumulative yield reductions	2.4	22.8	32	35.2	24.6

At 60% water deficits (Table 4 and Appendix 23), a cumulative season yield reduction of 26.4% was expected. Crop development stage (Stage B) with 25.9% expected yield reduction was the most affected, followed by mid season stage (stage C) with 12.4% yield reduction. Initial stage (Stage A) with 2.7% expected yield reductions were the least affected.

Table 4: Reductions at 60% deficit irrigation schedule

Yield reductions (%)					
Stage	**A**	**B**	**C**	**D**	**SEASON**
Reduction in ETC	6.8	17.3	24.7	24.2	21.1
yield response factor	0.4	1.5	0.5	0.2	1.25
yield reductions	2.7	25.9	12.4	4.8	
cumulative yield reductions	2.7	27.9	36.8	39.9	26.4

4.2.5 Relationship between measured and simulated yield reductions

The relationships of the percentage yield reductions between the experimental and simulated results are shown in Figures 19 and 20, Figures 21 and 22, and Figures 23 and 24. The CROPWAT model slightly under predicted the values of yield reductions in T1 and T3 when compared to the experimental results in the first 45 DAP (Fig. 19 and 20 and Appendix 24). In general the model simulated the biomass build up of the maize crop linearly ($y = 3.462x - 34.49$) with $R^2=0.869$ (Fig. 19). The best representation ($R^2=1$) was found to be quadric related ($y = -0.512x^2 + 27.43x - 307.4$) as shown in Figure 20. Despite these facts, to a large extent the experimental and simulated results were different during 45 DAP (α= 10, 5, 2.5, and 1%). Only at the levels of significant (α=0.5 and 0.1 %) the simulated values were not different from experimental results (Appendix 27). The reason could be because of the fertilization factor. The model works under optimal fertility conditions, while the experiment was conducted under minimum fertilizations (done at development stage) which caused a slow crop growth in the initial stage. A good calibration equation of the model simulated to the experimental results at this point of growth is through a quadratic equation (Fig. 20).

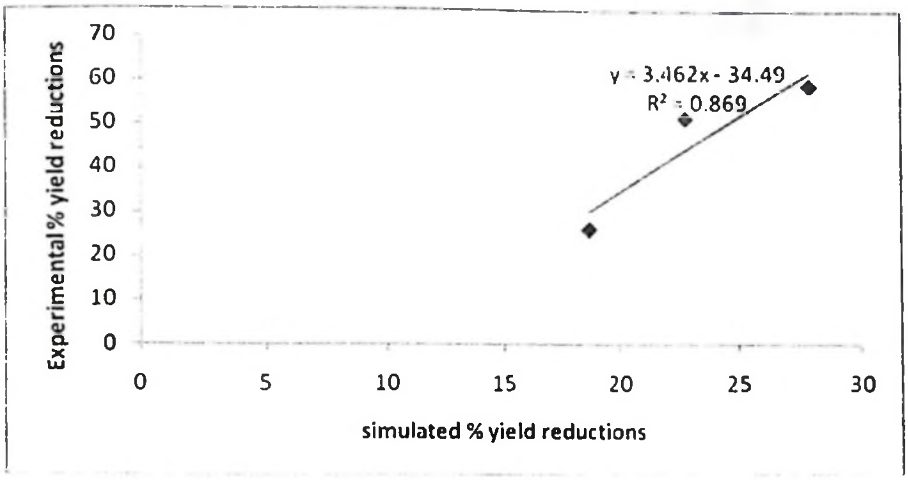

Figure 19: Linear relation of the measured and simulated yield reductions (%) at 45 DAP

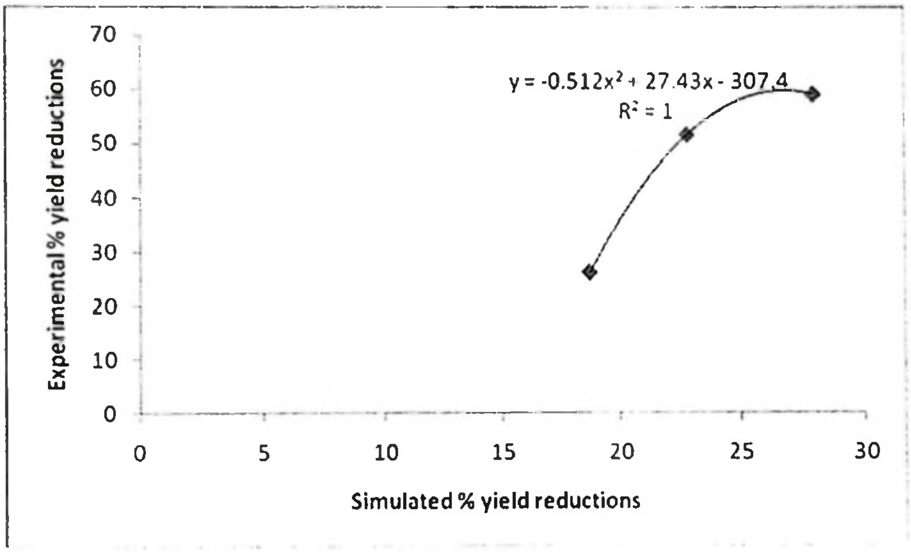

Figure 20: Measured and simulated yield reductions (%) at 45 DAP.

On the other hand the CROPWAT model was able to simulate the actual experimental results at 75 DAP by more than 95%. The straight line calibration equation ($y = 1.382x - 12.91$) with $R^2=0.952$ indicated good association between the experimental and simulated results (Fig. 21 and Appendix 25). To a very high accuracy ($p<0.001$) the model adequately simulated the experimental yield responses due to water stress during 75 DAP (Appendix 28). The reason was because of similarity of the conditions that the model operates to the actual field conditions (fertilization was done at this stage). Despite this fact still the best calibration equation was found to be a quadratic ($y = -0.119x^2 + 9.127x - 136.5$) with $R^2=1$ (Fig. 22).

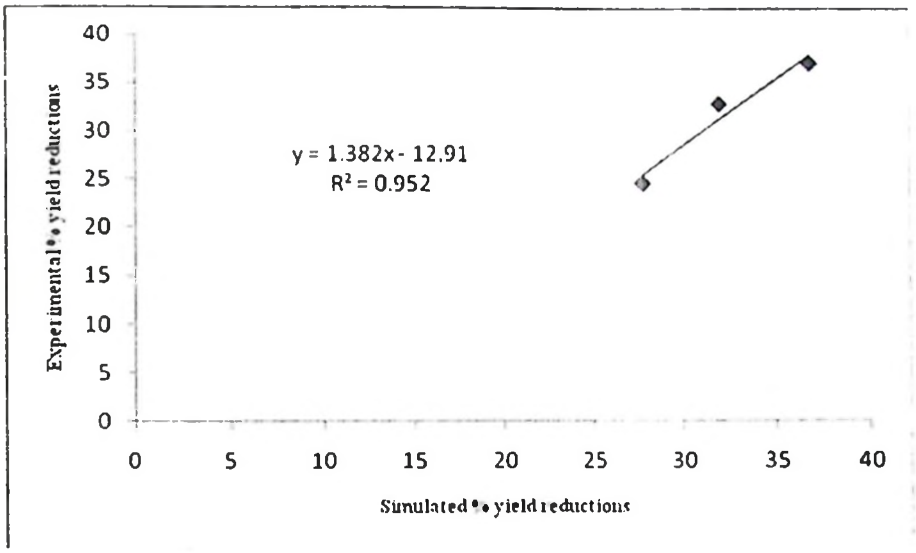

Figure 21: Dry matter accumulation relationship 75 DAP

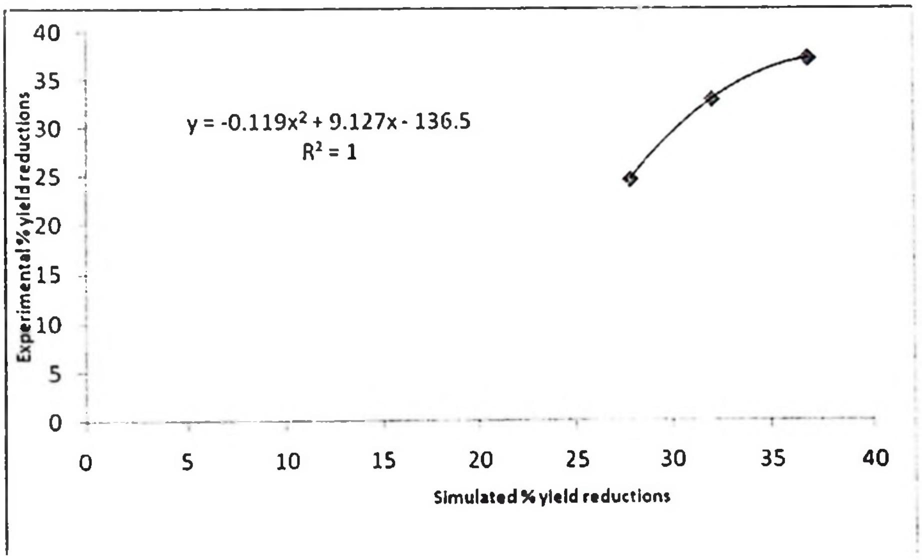

Figure 22: Measured and simulated yield reductions (%) at 75 DAP.

Furthermore the CROPWAT model managed to simulate adequately the overall season yield reduction (Appendix 32). The experimental and simulated results were not different statistically ($p<0.05$)). The line of the best fit ($y = 6.686x - 136.9$) indicated strong relationship ($R^2 = 0.914$) between the experimental and simulated results (Fig. 23 and appendix 29). In order to estimate an experimental result for each simulated result again the quadratic equation ($y = 1.815x^2 - 82.82x + 962.0$) proved to be the best ($R^2 = 1$) as shown in Figure 24.

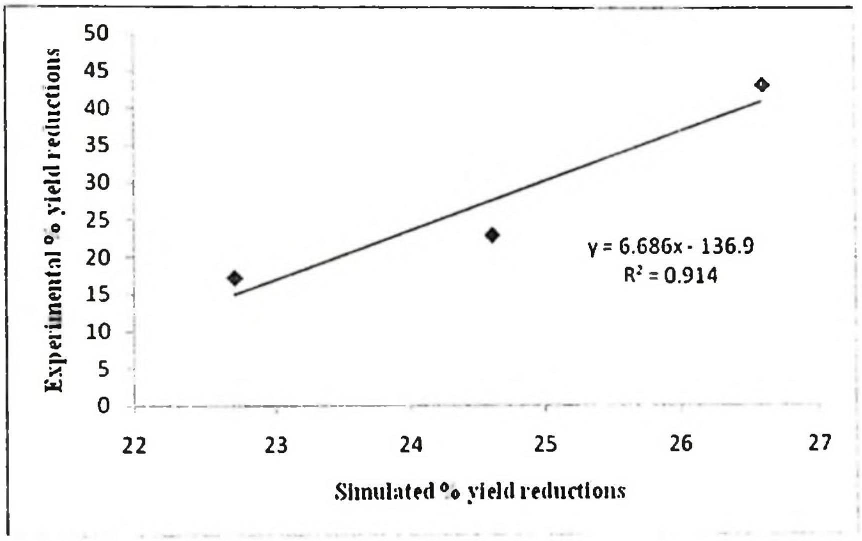

Figure 23: Seasonal grain yield reduction relationship

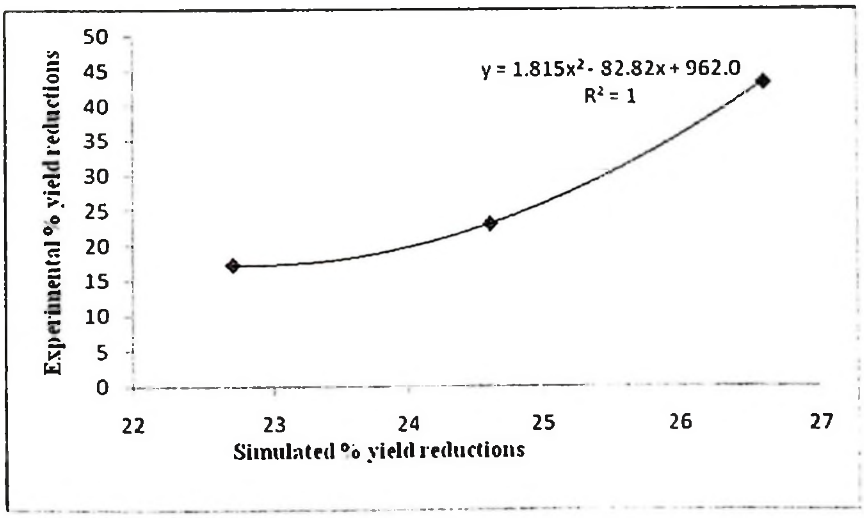

Figure 24: Seasonal grain yield reduction relationship

Generally, the model adequately simulated the experimental results (Appendix 30) the whole growth trend of biomass build up to grain production for the measured and the simulated were not statistically significantly different($p<0.05$) as seen in Appendix 31. Several researches have also reported good performance by the CROPWAT model. Cavero, (2000) did a comparison between the EPIC phase and the CROPWAT model performance and concluded that the model CROPWAT adequately calculated yield reduction caused by water stress, which makes this model a valuable tool for irrigation planning for maize. Similar results have been reported by many scientists (Nazeer, 2009; Giorgis *et al*., 2010; Kambikambi 2010; Karanja 2010). This can be a good indication that the model can also be adopted in Tanzania. Since the model has been able to produce positive results in different areas, it will be of interest to try to use the model not only in Morogoro Region but also in other areas of Tanzania. The combination of the model with deficit irrigation can help in increasing the crop water productivity.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the study the following conclusions can be made

1. Dry matter accumulation and grain yield increase with increase in water application to the optimum value of water and decrease with decrease in water application from optimum to the lowest water application
2. High increase in dry matter accumulation is observed between crop development stage and mid season stage.
3. Applying water to 40% deficit is the best option when water productivity is a concern in maize production. If that is applied then 247.74 m^3 of water in every 1000 m^3 water used in maize production can be saved and be made available for other uses.
4. Good water management will assure sustainable water productivity in maize and hence food security to water scarce areas.
5. To a large extent CROPWAT model adequately simulated yield reductions of maize under different water stress levels

5.2 Recommendations

From the study the following recommendations can be made

1. Allowing little water stress (40 % water deficit) to the crops to save water is very a plausible idea when water productivity is a concern especially in dry areas. However care must be taken here, especially in knowing exactly at what point of crop growth the stress will have much effect on the yield. Therefore people having enough water in

their area need to be sensitized on how to perform the proper irrigation in their areas so that they conserve water which will be available to others who are in need of water.

2. Also there is a need to find out exactly at what stages of growth the 60% water deficit has an influence on yield. This will help to make a decision of whether to supply full irrigation (when water is available) or not at the most effective stage.
3. The application of seasonal weather forecasts together with CROPWAT model allows the estimation of soil water supply and the irrigation need. However the training should be provided to extension officers and irrigation/Agricultural engineers on how to use it so that they can be in good position to advise farmers and decision makers to minimize negative consequences of unfavourable weather conditions or take advantages of favourable conditions and use water efficiently.
4. The use of simulation models, as an essential component of agricultural applications of seasonal climate prediction, calculations of crop water requirement, and effects of water stress to the crops should be sensitized to researchers, irrigation structures designers (engineers) and extension officers since it provides useful information to the benefit of agriculture.
5. Although CROPWAT performance has shown very positive results, there is still a room for some improvements. For example if the model could be able to directly predict the yield instead of yield reduction it could be very easy for different groups like (researchers, engineers, extension officers and farmers) to understand directly what they are expecting to get after harvest. Other than the way it is now, when you know the percentage yield reductions for different water stress hence more mathematics required to understand exactly what is to be the expected yield. Furthermore the CROPWAT model doesn't incorporate a fertilization option in its operation which I think it would have made it produce a very reliable prediction results.

6. Despite the few shortfalls, there is evidence in this study that the model has done well and can be adopted. I still recommend further research using different type of maize variety and or different crops is important to be conducted in Morogoro and other areas in the country so that enough evidence can be obtained to make a conclusive decision on the utilization of the CROPWAT model in Tanzania.

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APPENDICES

Appendix 1: Measured seasonal rainfall

Months	Rainfall
October	19.5
November	31.3
December	70
January	97.8

Appendix 2: Average soil moisture data measured by diviner2000 unit (10-120 cm depth)

Date	T1	T2	T3	T4
26/11/2009	174.0517	203.9311	202.1753	226.0632
27/11/2009	173.5122	196.5696	208.7648	232.6564
28/11/2009	178.5581	198.7282	205.3935	227.569
30/11/2009	181.8863	196.6611	206.6625	230.9443
01/12/2009	181.4921	196.9874	203.3748	232.3179
02/12/2009	181.4469	192.9796	209.2288	227.7166
03/12/2009	182.4218	203.3229	202.4264	229.3775
04/12/2009	183.8786	198.7704	202.1309	230.2879
05/12/2009	185.2702	204.3655	201.0701	233.7995
07/12/2009	184.4683	202.0428	199.1994	230.4111
10/12/2009	185.9339	203.1156	198.9165	236.498
11/12/2009	191.4403	199.4521	198.2962	234.7637
15/12/2009	188.6002	208.8451	200.1309	232.9543
16/12/2009	185.8215	214.9697	199.3029	239.0497
17/12/2009	197.9813	193.3337	200.2632	252.1252
19/12/2009	195.6151	218.8177	207.4723	250.8424
19/12/2009	199.4049	227.6616	216.3636	290.5016
21/12/2009	194.6458	225.3309	247.019	251.953
22/12/2009	204.4389	230.0336	241.9221	253.6297
23/12/2009	200.5015	224.5223	244.1757	257.6889

24/12/2009	206.1388	235.1287	242.0298	256.208
28/12/2009	207.5732	235.0946	241.2629	256.3013
29/12/2009	205.7391	232.6095	242.6882	258.2906
30/12/2009	202.4456	231.5126	246.1582	259.8245
02/01/2010	208.7355	234.5857	243.4069	258.1226
04/01/2010	203.6112	231.4316	251.1798	259.9458
05/01/2010	213.2588	243.2175	241.3812	266.1956
07/01/2010	194.6252	225.4913	240.161	208.5839
09/01/2010	184.3225	222.9233	222.3656	253.4974
12/01/2010	180.677	170.1023	187.8704	234.601
20/01/2010	180.5546	201.1775	223.2946	230.7409
27/01/2010	202.6851	213.1882	219.9127	229.357
29/01/2010	198.0922	210.7119	236.7688	239.7458
01/02/2010	195.258	224.749	232.7782	247.1855
08/02/2010	195.1041	217.412	230.564	243.4241
09/02/2010	191.0738	215.5669	228.7119	241.9947
11/02/2010	189.0845	214.6433	227.1205	240.0696
12/02/2010	186.3202	214.4395	224.961	238.1614
15/02/2010	187.1731	212.4015	225.4054	227.3064
16/02/2010	189.8502	212.5757	224.5187	235.8546
18/02/2010	187.083	211.84	223.6094	235.2412
19/02/2010	187.6583	225.7298	225.8127	235.9566

Appendix 3: Biomass accumulation at 45 DAP

Block	Treatment	Average Biomass matter
B1	T1	380.02
	T2	485.42
	T3	814.50
	T4	1249.27
B2	T1	440.44
	T2	560.23
	T3	846.18
	T4	1006.94
B3	T1	715.59
	T2	765.10
	T3	1097.87
	T4	1487.26

Appendix 4: Average biomass accumulation at 45 DAP

Treatment	Average dry matter accumulation g/m^{2}
T1	512.01
T2	603.58
T3	919.52
T4	1247.82

Appendix 5: Biomass accumulation at 75 DAP

Block	Treatments	Total dry matter
1	T1	608.5337
	T2	742.6632
	T3	954.3304
	T4	871.3411
2	T1	751.0525
	T2	709.1433
	T3	1246.804
	T4	1213.935
3	T1	687.4911
	T2	733.2471
	T3	946.1503
	T4	1174.951

Appendix 6: Average biomass accumulation at 75 DAP

Treatments	Average Biomass accumulation kg/m^3 after 75days
T1	682.36
T2	728.35
T3	1049.09
T4	1086.74

Appendix 7: Analysis of variance for rainfall

Variate:Rainfall

Source of	d.f	s.s	m.s	v.r	F pr
Block stratum	1	471.25	471.25	6.6	
Treatment	3	10078.25	3359.42	47.08	0.005
Residual	3	214.04	71.35		
Total	7	10763.53			

Appendix 8: Water productivity kg/m^3

Block	Treatment	Water productivity
1	T1	1.59
	T2	2.29
	T3	1.77
	T4	1.67
2	T1	1.67
	T2	2.21
	T3	1.74
	T4	1.79
3	T1	1.76
	T2	2.11
	T3	1.83
	T4	1.69

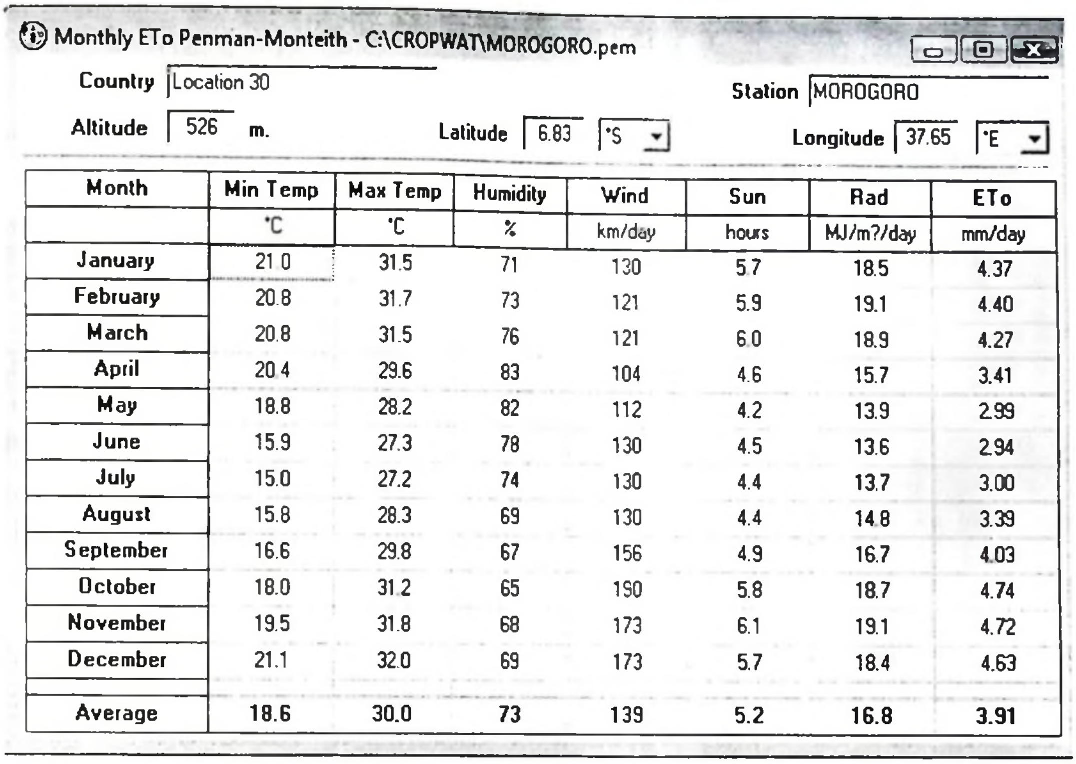
Appendix 9: Average water productivity in kg m $^{-3}$

Treatment	average water productivity
T1	1.67
T2	2.20
T3	1.78
T4	1.72

Appendix 10: Average grain yield in tons per hectare for each treatment

Treatment	Grain yield
T1	2.67
T2	3.62
T3	3.89
T4	4.70

Appendix 11: CROPWAT Model Simulation (weather parameters)

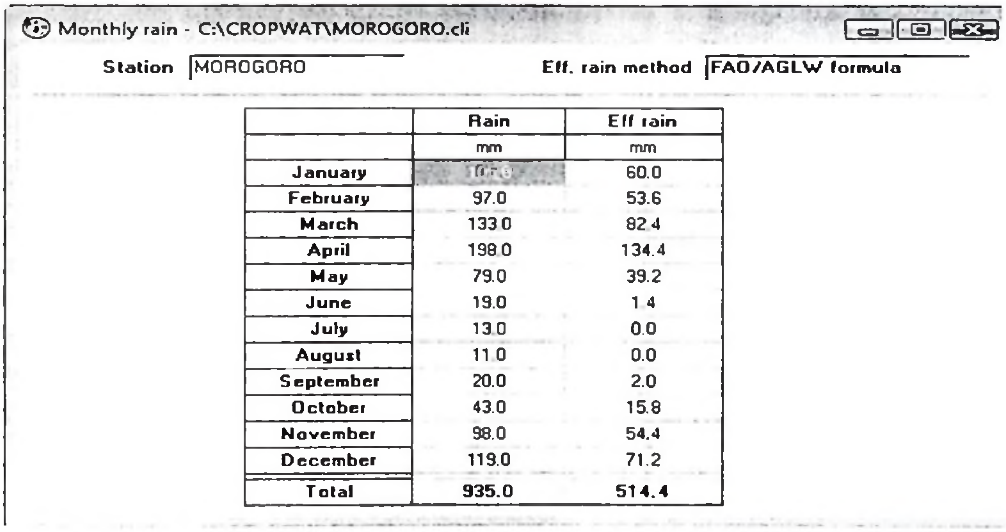


Monthly ETo Penman-Monteith - C:\CROPWAT\MOROGORO.pem

Country Location 30
Station MOROGORO
Altitude 526 m.
Latitude 6.83 °S
Longitude 37.65 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m?/day	mm/day
January	21.0	31.5	71	130	5.7	18.5	4.37
February	20.8	31.7	73	121	5.9	19.1	4.40
March	20.8	31.5	76	121	6.0	18.9	4.27
April	20.4	29.6	83	104	4.6	15.7	3.41
May	18.8	28.2	82	112	4.2	13.9	2.99
June	15.9	27.3	78	130	4.5	13.6	2.94
July	15.0	27.2	74	130	4.4	13.7	3.00
August	15.8	28.3	69	130	4.4	14.8	3.39
September	16.6	29.8	67	156	4.9	16.7	4.03
October	18.0	31.2	65	190	5.8	18.7	4.74
November	19.5	31.8	68	173	6.1	19.1	4.72
December	21.1	32.0	69	173	5.7	18.4	4.63
Average	18.6	30.0	73	139	5.2	16.8	3.91

Appendix 12: CROPWAT Model Simulation (rainfall)

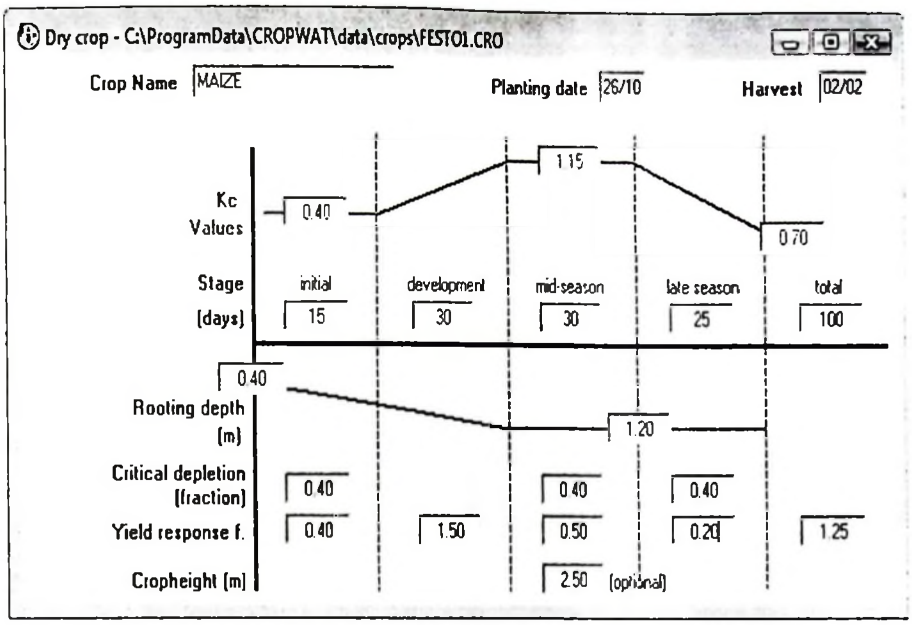


Monthly rain - C:\CROPWAT\MOROGORO.cli

Station MOROGORO
Eff. rain method FAO/AGLW formula

	Rain	Eff rain
	mm	mm
January	[illegible]	60.0
February	97.0	53.6
March	133.0	82.4
April	198.0	134.4
May	79.0	39.2
June	19.0	1.4
July	13.0	0.0
August	11.0	0.0
September	20.0	2.0
October	43.0	15.8
November	98.0	54.4
December	119.0	71.2
Total	935.0	514.4

Appendix 13: CROPWAT Model Simulation (Crop)



Dry crop - C:\ProgramData\CROPWAT\data\crops\FESTO1.CRO

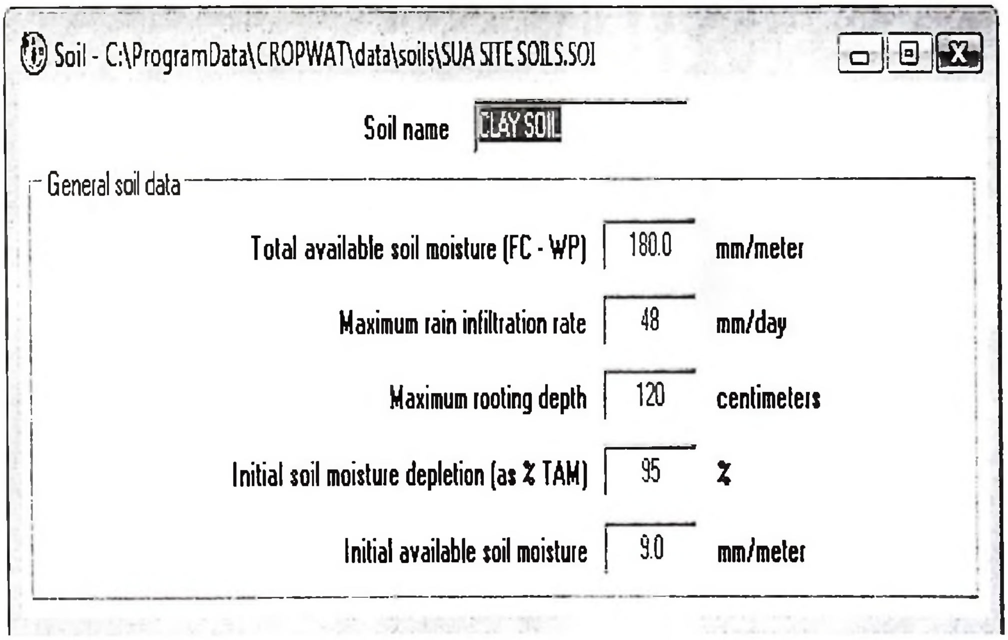
Crop Name MAIZE

Planting date 26/10

Harvest 02/02

Stage	initial	development	mid-season	late season	total
Kc Values	0.40		1.15	0.70	
(days)	15	30	30	25	100
Rooting depth (m)	0.40		1.20		
Critical depletion (fraction)	0.40		0.40	0.40	
Yield response f.	0.40	1.50	0.50	0.20	1.25
Cropheight (m)			2.50 (optional)		

Appendix 14: CROPWAT Model Simulation (Soil)



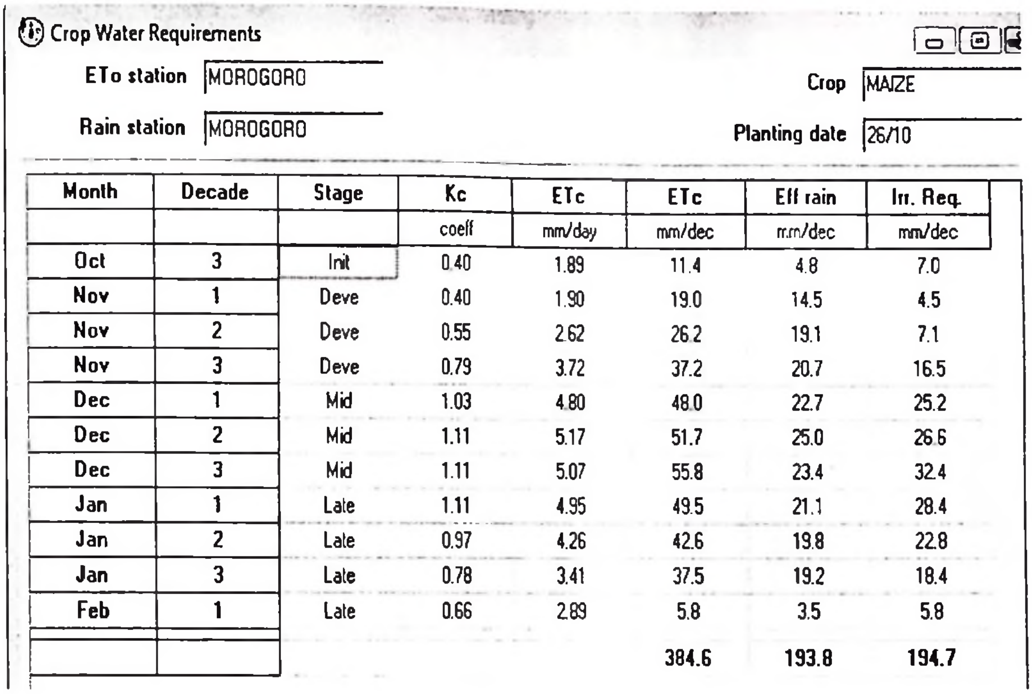
Soil - C:\ProgramData\CROPWAT\data\soils\SUA SITE SOILS.SOI

Soil name CLAY SOIL

General soil data

Total available soil moisture (FC - WP)	180.0	mm/meter
Maximum rain infiltration rate	48	mm/day
Maximum rooting depth	120	centimeters
Initial soil moisture depletion (as % TAM)	95	%
Initial available soil moisture	9.0	mm/meter

Appendix 15: CROPWAT Model Simulation (Crop water requirement)



Crop Water Requirements

ETo station MOROGORO

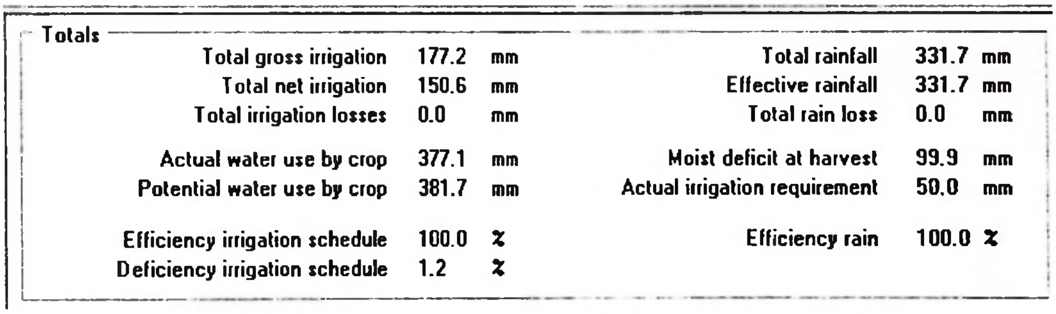
Crop MAIZE

Rain station MOROGORO

Planting date 26/10

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Oct	3	Init	0.40	1.89	11.4	4.8	7.0
Nov	1	Deve	0.40	1.90	19.0	14.5	4.5
Nov	2	Deve	0.55	2.62	26.2	19.1	7.1
Nov	3	Deve	0.79	3.72	37.2	20.7	16.5
Dec	1	Mid	1.03	4.80	48.0	22.7	25.2
Dec	2	Mid	1.11	5.17	51.7	25.0	26.6
Dec	3	Mid	1.11	5.07	55.8	23.4	32.4
Jan	1	Late	1.11	4.95	49.5	21.1	28.4
Jan	2	Late	0.97	4.26	42.6	19.8	22.8
Jan	3	Late	0.78	3.41	37.5	19.2	18.4
Feb	1	Late	0.66	2.89	5.8	3.5	5.8
					384.6	193.8	194.7

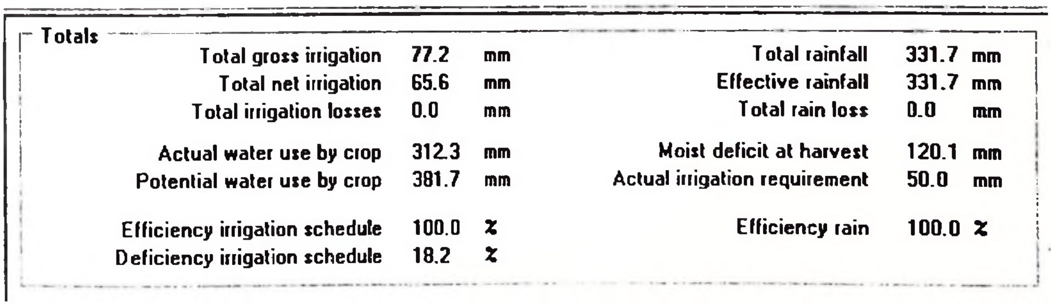
Appendix 16: CROPWAT Model Simulation (Irrigation totals at optimum)



Totals

Total gross irrigation	177.2	mm	Total rainfall	331.7	mm
Total net irrigation	150.6	mm	Effective rainfall	331.7	mm
Total irrigation losses	0.0	mm	Total rain loss	0.0	mm
Actual water use by crop	377.1	mm	Moist deficit at harvest	99.9	mm
Potential water use by crop	381.7	mm	Actual irrigation requirement	50.0	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	100.0	%
Deficiency irrigation schedule	1.2	%			

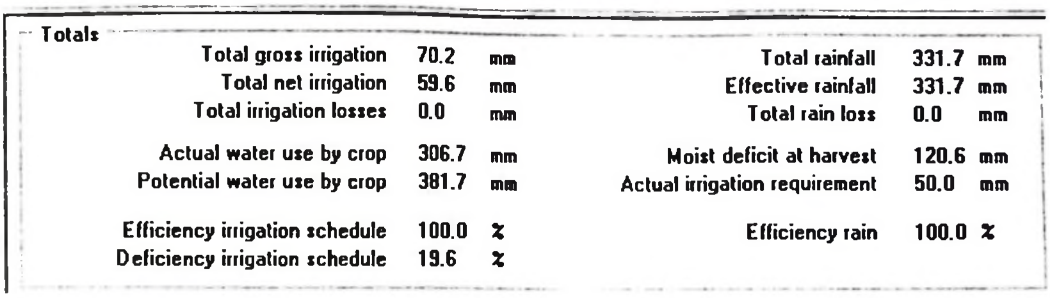
Appendix 17: CROPWAT Model Simulation (Irrigation totals at 20% deficit)



Totals

Total gross irrigation	77.2	mm	Total rainfall	331.7	mm
Total net irrigation	65.6	mm	Effective rainfall	331.7	mm
Total irrigation losses	0.0	mm	Total rain loss	0.0	mm
Actual water use by crop	312.3	mm	Moist deficit at harvest	120.1	mm
Potential water use by crop	381.7	mm	Actual irrigation requirement	50.0	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	100.0	%
Deficiency irrigation schedule	18.2	%			

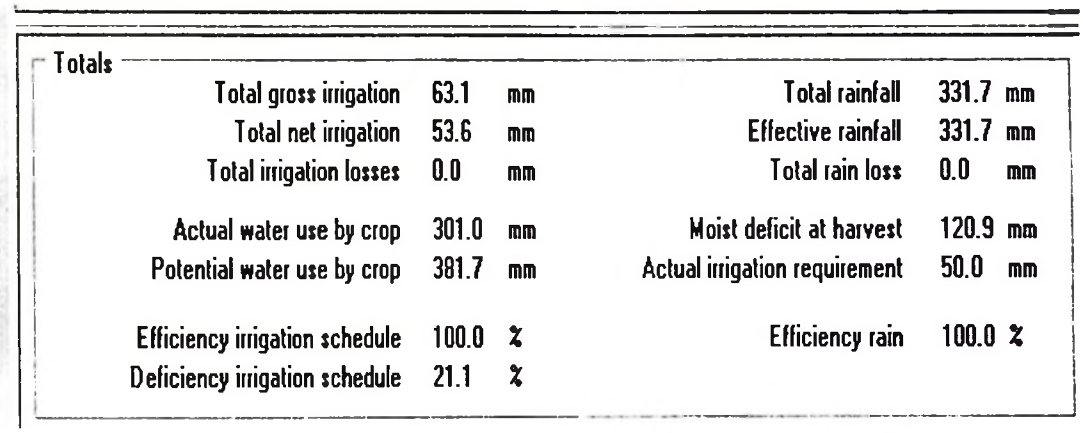
Appendix 18: CROPWAT Model Simulation (Irrigation totals at 40% deficit)



Totals

Total gross irrigation	70.2	mm	Total rainfall	331.7	mm
Total net irrigation	59.6	mm	Effective rainfall	331.7	mm
Total irrigation losses	0.0	mm	Total rain loss	0.0	mm
Actual water use by crop	306.7	mm	Moist deficit at harvest	120.6	mm
Potential water use by crop	381.7	mm	Actual irrigation requirement	50.0	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	100.0	%
Deficiency irrigation schedule	19.6	%			

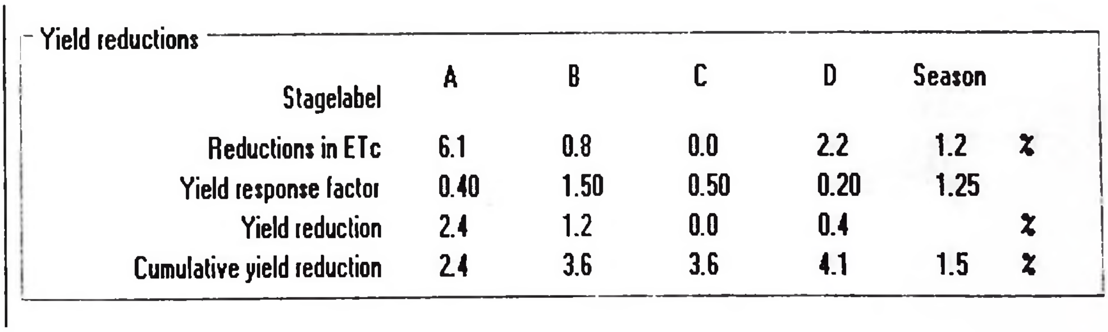
Appendix 19: CROPWAT Model Simulation (Irrigation totals at 60% deficit)



Totals

Total gross irrigation	63.1	mm	Total rainfall	331.7	mm
Total net irrigation	53.6	mm	Effective rainfall	331.7	mm
Total irrigation losses	0.0	mm	Total rain loss	0.0	mm
Actual water use by crop	301.0	mm	Moist deficit at harvest	120.9	mm
Potential water use by crop	381.7	mm	Actual irrigation requirement	50.0	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	100.0	%
Deficiency irrigation schedule	21.1	%			

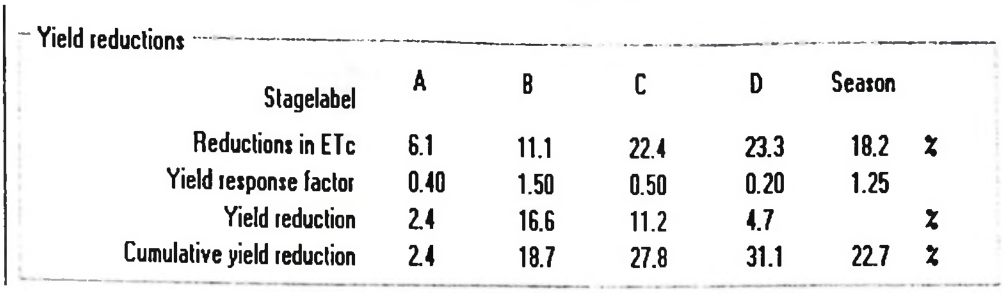
Appendix 20:CROPWAT Model Simulation (Yield reductions at optimum irrigation)



Yield reductions

Stagelabel	A	B	C	D	Season	
Reductions in ETc	6.1	0.8	0.0	2.2	1.2	%
Yield response factor	0.40	1.50	0.50	0.20	1.25	
Yield reduction	2.4	1.2	0.0	0.4		%
Cumulative yield reduction	2.4	3.6	3.6	4.1	1.5	%

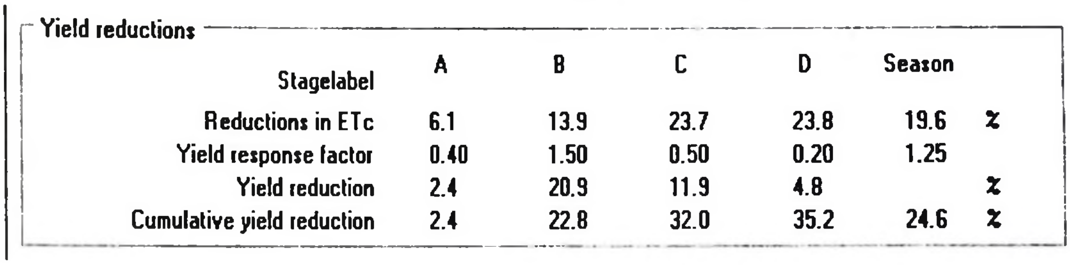
Appendix 21: CROPWAT Model Simulation (Yield reductions at 20% deficit)



Yield reductions

Stagelabel	A	B	C	D	Season	
Reductions in ETc	6.1	11.1	22.4	23.3	18.2	%
Yield response factor	0.40	1.50	0.50	0.20	1.25	
Yield reduction	2.4	16.6	11.2	4.7		%
Cumulative yield reduction	2.4	18.7	27.8	31.1	22.7	%

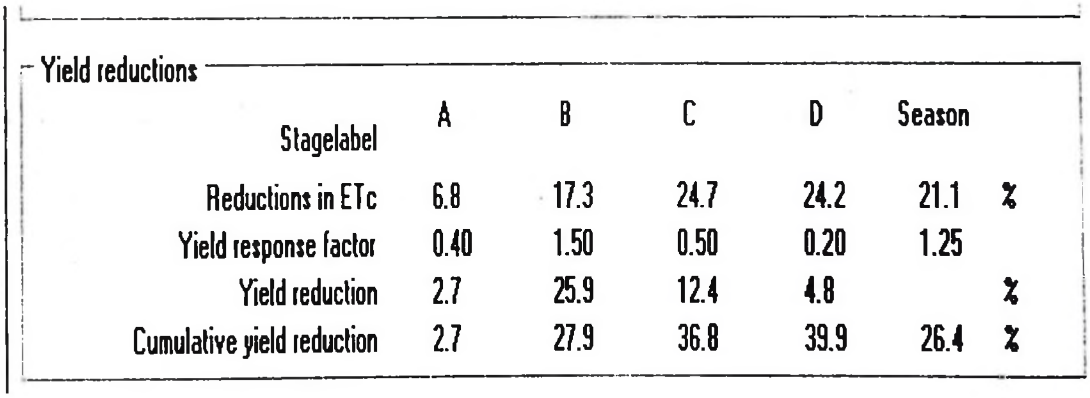
Appendix 22: CROPWAT Model Simulation (Yield reductions at 40% deficit)



Yield reductions

Stagelabel	A	B	C	D	Season	
Reductions in ETc	6.1	13.9	23.7	23.8	19.6	%
Yield response factor	0.40	1.50	0.50	0.20	1.25	
Yield reduction	2.4	20.9	11.9	4.8		%
Cumulative yield reduction	2.4	22.8	32.0	35.2	24.6	%

Appendix 23: CROPWAT Model Simulation (Yield reductions at 60% deficit)



Yield reductions

Stagelabel	A	B	C	D	Season	
Reductions in ETc	6.8	17.3	24.7	24.2	21.1	%
Yield response factor	0.40	1.50	0.50	0.20	1.25	
Yield reduction	2.7	25.9	12.4	4.8		%
Cumulative yield reduction	2.7	27.9	36.8	39.9	26.4	%

Appendix 24: Relationship between experimental and simulated biomass production at 45 DAP

Treatment	Experimental Percentage yield reductions	Simulated percentage yield reduction
T1	58.94	27.9
T2	51.57	22.8
T3	26.31	18.7

Appendix 25: Relationship between experimental and simulated biomass production at 75 DAP

75 days Treatment	Experimental Percentage yield reductions	Simulated percentage yield reduction
T1	37.21	36.8
T2	32.93	32
T3	24.66	27.8

Appendix 26: Relationship between experimental and simulated grain yield reductions

Relationships		
Season reductions Treatment	Experimental Percentage yield reductions	Simulated percentage yield reduction
T1	43.19	26.6
T2	22.98	24.6
T3	17.23	22.7

Appendix 27: Comparative analysis between measured and simulated reductions (at 45 DAP).

Simulated yield reductions	Experimental yield reductions	Ratios of the simulated to measured yield	T-Calculated	Tabulated	Significant level	description
27.9	58.94	0.473363	-5.4	1.638	10%	s
22.8	51.57	0.442118		2.2353	5%	s
18.7	26.31	0.710756		3.183	2.50%	s
		1.626237		4.4541	1%	s
				5.841	0.50%	s
				10.215	0.10%	s

Testing whether the Ratios of the simulated to measured yield reductions is equal or not equal to 1(assumed mean). The percentage yield reductions (simulated and experimental) are significantly different.

Appendix 28: Comparative analysis between measured and simulated reductions (at 75 DAP).

Simulated yield reductions	Experimental yield reductions	Ratios of the simulated	t calculated	Tabulated t	Significant	description
36.8	37.21	0.99	0.609274	1.638	10%	ns
32	32.93	0.97		2.2353	5%	ns
27.8	24.66	1.13		3.183	2.50%	ns
		3.09		4.4541	1%	ns

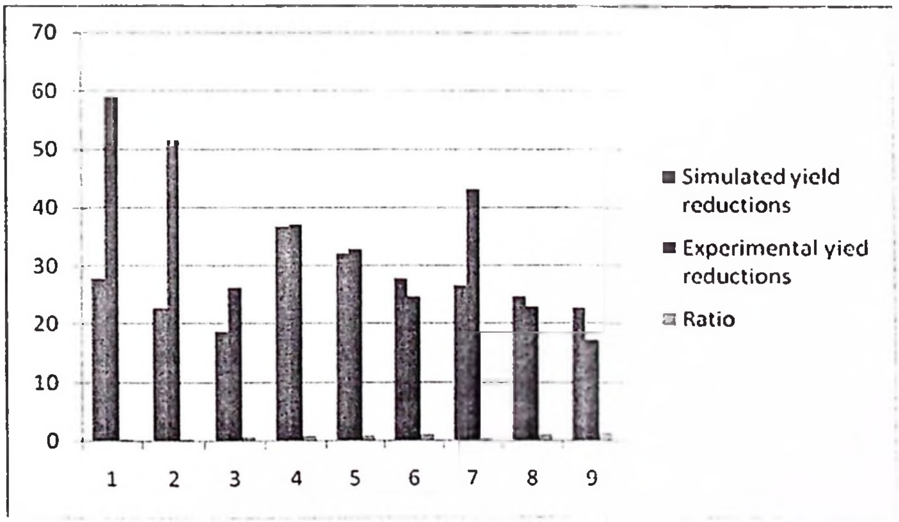
Testing whether the Ratios of the simulated to measured yield reductions is equal or not equal to 1(assumed mean). The percentage yield reductions (simulated and experimental) are not significantly different.

Appendix 29: Comparative analysis between measured and simulated reductions (Seasonal yield reductions).

Simulated yield reductions (%)	Experimental yield reductions (%)	Ratios of the simulated to measured yield reductions	t calculated	Tabulated t	Significant level	description
26.6	43.19	0.615883	0.006244	1.638	10%	ns
24.6	22.98	1.070496		2.2353	5%	ns
22.7	17.23	1.31747		3.183	2.50%	ns
				4.4541		ns

Testing whether the Ratios of the simulated to measured yield reductions is equal or not equal to 1(assumed mean). The percentage yield reductions (simulated and experimental) are not significantly different.

Appendix 30: Trends of yield reduction during the growing period



Appendix 31: Trends of yield reduction during the growing period

Simulated yield reductions	Experimental yield reductions	Ratio	t calculated	tabulated	% significant	Description
27.9	58.94	0.47	- 1.36256394	1.383	10	ns
22.8	51.57	0.44		1.833	5	ns
18.7	26.31	0.71		2.262	2.5	ns
36.8	37.21	0.99		2.822	1	ns
32	32.93	0.97		3.25	0.5	ns
27.8	24.66	1.13		4.297	0.1	ns
26.6	43.19	0.62				
24.6	22.98	1.07				
22.7	17.23	1.32				

Testing whether the Ratios of the simulated to measured yield reductions is equal or not equal to 1(assumed mean). The percentage yield reductions (simulated and experimental) are not significantly different.