OPTIMIZATION OF TOMATO WATER PRODUCTIVITY UNDER DEFICIT SUB-SURFACE DRIP IRRIGATION AND MULCHING SYSTEMS

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EGERTON UNIVERSITY

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DECLARATION AND RECOMMENDATION

Declaration

I do declare that this is my original work and that it has not been presented before in any other institution for any award.

Signature……………………………………… Date 01/07/2020

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Recommendation

This thesis has been submitted with our recommendation as University supervisors.

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DEDICATION

To the Almighty God and to my loving parents Mr. and Mrs. Lagat for encouraging me to pursue education to the high levels. I also dedicate this work to my caring husband Paul Tarus and daughters Shirleen and Lyne.

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ABSTRACT

The greatest challenge in the agriculture is to produce more food with low quantity of water. The challenge facing tomato farmers in Njoro Sub - County is the unfavourable conditions for tomato growth which includes very low rainfall during the seasonal dry periods. However, there is limited information on optimum water management practices, or deficit irrigation that would increase tomato crop yield and additionally improve the tomato quality when drip irrigation is used. The objective of this study was to evaluate the effect of deficit sub – surface drip irrigation and mulching systems on water productivity of tomato (*Lycopersicon esculentum* mill) crop in Njoro Sub - County. The study was carried out on experimental plots measuring 4 m^2 in a shade at Egerton University. Factorial experimental design was used in this study where the treatments were

three water levels (100 % ET_C, 80% ET_C and 60 % ET_C) and four grass mulch densities (0, 0.5, 1.0 and 1.5 kg/m^2) replicated three times. Drip laterals for the drip irrigation system were laid at a depth of 5.0 cm below the ground surface. An estimated water depth was applied to the respective experimental plots based on the various irrigation levels as guided by the four tomato crop growth stages. The agronomic parameters and yield were monitored on weekly basis over a period of 135 days. The results of tomato crop water productivity under the interactive effect of deficit sub – surface drip irrigation and grass mulch densities was highest at 60 % ET_C and 1.0 kg/m^2 of grass mulch and lowest at 100 % ET_C and 1.5 kg/m^2. Aquacrop model was used to estimate the tomato water requirements, water productivity, yield and biomass under deficit irrigation and mulching. The findings for the Aquacrop model showed a fair correlation between the actual and simulated yield, biomass and water productivity as determined by the Nash and Sutcliffe efficiency (NSE), Root Mean Square Error (RMSE) and Coefficient of determination (R^2). The findings show application rates for farmers that will enable them to produce more tomato yields with little water. This has the potential to enhance farmer's income from tomatoes thus leading to increased income by improving the agri-business of the small scale farmers in Njoro Sub - County.

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LIST OF ABBREVIATIONS AND ACRONYMS

CB	Cost Benefit
CO_2	Carbon Dioxide
CWR	Crop Water Requirement
DI	Deficit Irrigation
ET_a	Actual Evapotranspiration
ET_c	Crop Evapotranspiration
ET_o	Reference Evapotranspiration
Gm	Grams
IWR	Irrigation Water Requirement
K_c	Crop Coefficient
Kg	Kilogram
K_{sat}	Saturated hydraulic conductivity
MC	Moisture Content
PWP	Permanent Wilting Point
TAW	Total Available water
WP	Water Productivity
WUE	Water Use Efficiency
Θ	Volumetric Water Content

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LIST OF SYMBOLS

Θ	Volumetric Water Content
$\boldsymbol{\omega}_s$	Sunset hour angle
Φ	Latitude
∂	Solar declination
U	Wind speed
e_s	The saturation vapour pressure
e_a	The actual vapour pressure
Γ	The psychometric constant
Λ	Latent heat of vaporization
C_p	Specific heat at constant pressure
ε	Ratio molecular weight of water vapour/dry air
Z	Elevation above sea level
N	Porosity
ρ_b	Bulk density
ρ_p	Particle density

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CHAPTER ONE

INTRODUCTION

1.1 Background Information

Worldwide, tomato crop (*Lycopersicon esculentum* mill) is among the most commonly grown vegetables crops under irrigation. However, due to unfavourable weather conditions which include high/low rainfall and high/low temperatures, there is necessity to optimize tomato crop yields with low quantity of water use. Varying tillage and mulching practices are some of the agronomic measures that could increase water productivity. Deficit irrigation refers to the process of subjecting a crop to a particular reduced quantity of water during a certain growing period, or along the entire growing season, without serious decline in yield and it increases the water productivity (Birhanu & Tilahun, 2010). To improve the crop water productivity drip irrigation with mulching is an appropriate system. Surface mulch can been used to increase soil water retention and to decrease wind velocity and temperature at the soil surface. The utilization of mulch is becoming an important management practice for economic growth of valuable crops in majority of the places of the world, thus optimizing the water utilization fraction by the plant and therefore improving on the growth of crops. Mulch when applied over the soil surface, creates a favourable condition between the soil water and the plant (Singh, 2016).

Agriculture has the capability to meet the food needs of approximately 6 billion people thus substantially decreasing the proportion of the population facing starvation in the world, although there is little information on how this can be successfully reached by sustainable means (Tilman *et al.*, 2002). It is exceptionally basic to utilize water by changing more area to irrigation through the accessible restricted water sources. This could be accomplished by presenting advanced techniques for irrigation with improved water management practices. The potentiality of drip irrigation system applying water at exceptionally moderate rates (1.2 l/h) offers the means to convey water to the soil in little and regular amounts at a generally minimal effort when compared with other pressurized systems, for example, sprinkler irrigation (Amare *et al.*, 2017). Right irrigation planning could give ideal developing conditions to the harvest and limit unreasonable utilization of water. Utilization of mulch (organic or inorganic) improves crop yield by saving soil water (Mukherjee *et al.*, 2018).

The accessible water assets are deficient to meet Kenya's water needs. Kenya is generally positioned as a water-stressed nation. Alternative based approaches for assessment and

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management of water scarcity is required. This is also a gateway to meet Kenya's Vision 2030 (Mekonnen & Hoekstra, 2014). Efficient utilization of water and land resources increases crop production and increases the sustainability of irrigated agriculture (Muema *et al.*, 2018). In Kenya, studies on drip irrigation and mulching have been carried out under open field conditions suggesting the need to conduct further studies under controlled conditions (Polyhouse) (Kere *et al.*, 2003).

In Njoro Sub - County, tomato is one of the most developed vegetable crop. The crop is to a great extent grown in the open-field under rainfed conditions. The sensitivity of tomatoes to climatic conditions has a few outcomes including, low crop yield and high food demand and costs. Further, unfavourable climatic conditions leads to diminished farm output. With varying climatic conditions, tomato production in a greenhouse is becoming more famous as crops grown under controlled environment like in a greenhouse, provides protection against unfavorable weather conditions (Wachira, 2012). Weather conditions have been changing in Njoro area leading to decline in water resources. This has adversely affected tomato crop production and calls for increased tomato crop production but with less quantity of water. Thus there was need to conduct studies on water productivity of tomato under a shade using both deficit drip irrigation and mulching systems as was the case in this study.

1.2 Statement of the Problem

The study sought to evaluate the interactive effect of deficit sub-surface drip irrigation and mulching systems on the productivity of tomato crop under a polyhouse in order to increase the tomato water productivity. There is water scarcity in most parts of the tropical zones and Nakuru County being one of them has a low production of tomatoes accounting to 2.7% of the Kenya's total tomato production (Geoffrey *et al.*, 2014). In Njoro Sub County, tomato crop is majorly grown in the open-field under rain-fed conditions hence the vulnerability of tomatoes to weather conditions. The main consequence being reduction in yield as a result of disease built up due to low rainfall amounts during the growing periods. Additionally, the farmers who grow crops under greenhouses practice total irrigation thus leading to wastage of irrigation water hence leading to low crop water productivity. Limited research has been conducted on the effect of deficit sub – surface drip – irrigation regimes and their interaction with different mulching densities on tomato water productivity under controlled environmental conditions in most parts of Kenya (Kere *et al*., 2003).

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1.3 Objectives

1.3.1 Main Objective

The main objective of this research was to evaluate the effects of deficit sub – surface drip irrigation and mulching systems on tomato water productivity.

1.3.2 Specific Objectives

The specific objectives were to:

i. Estimate the tomato crop water requirement for Njoro Sub - County at different growth stages using FAO Penman Monteith method using data for Njoro sub - county.
ii. Determine the interactive effect of deficit sub – surface drip irrigation and grass mulch densities on water use efficiency at different growth stages of tomato.
iii. Model tomato water productivity under deficit sub – surface drip irrigation and grass mulch densities using Aquacrop model.

1.4 Research Questions

i. How is the distribution of tomato crop water requirement in the different growth stages when determined by FAO Penman - Monteith method?
ii. How does the interactive effect of deficit sub – surface drip irrigation and grass mulch densities affect water use efficiency for the growth stages of tomato?
iii. How does the tomato water productivity vary under deficit sub – surface drip irrigation and grass mulch densities when modeled using Aquacrop model?

1.5 Justification

The farmer's objective under limited water supplies ought to be to optimize net gain per unit of water use instead of per unit of land. Emphasis has been put on the idea of water productivity (WP) increasing under deficit irrigation (DI), comparative with its value under full irrigation, as observed for some crops (Fereres & Soriano, 2006). Deficit irrigation planning is one method for maximizing water use effectiveness. The crop is subjected to a specific degree of water stress either during a specific period or all through the entire developing period. Any yield decrease coming about because of the water stress is viewed as acceptable compared to the advantages increased through using the saved water to irrigate more area. Crop varieties that are appropriate for deficit irrigation include those with a short developing season and are resistant to dry spell. In actualizing deficit irrigation, thought must be driven to soil retention capacity, adjustment of agronomic practices like plant density, planting date and nutrient

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application. Tomato plants are delicate to water deficiency and prove high connection between evapotranspiration and crop yield (Ramalan *et al.*, 2010). Drip irrigation in combination with mulch has an important use in increasing the yield and water productivity of various crops, for instance, tomatoes hence improving the agro – business of the farmers (Amare *et al*., 2017). The yield at 60% ET_C with 1.0 kg/m^2 of grass mulch was higher than the control (100% ET_C with no mulch) by 11.4 %, hence this study leads to increased production with less water. The saved quantity of irrigation water could be used to irrigate more area minimizing the cost of irrigation water and thus saving on the pumping and storage costs.

1.6 Scope and Limitations of the Study

The study was carried out at Egerton University, Njoro through experimental plots in a controlled environment and therefore the effect of possible rainfall variation was not taken into consideration during the study. Climatic parameters (temperature, reference evapotranspiration, wind speed and the relative humidity) for Njoro Sub County were considered for simulations and calibration of the Aquacrop model. There are numerous management practices that generally increase water productivity. This study concentrated on the utilization of grass mulch of various densities and use of various drip irrigation levels. The secondary data that were required for crop water requirement modeling using Aquacrop model were rainfall, minimum and maximum air temperature, and ET_O. The study only assessed the effect of deficit sub – surface drip irrigation and different grass mulch densities. Grass mulch was used because it is readily available.

1.7 Conceptual Framework

This research study involved planting of tomato crop in a polyhouse shade at Egerton University, Nakuru County. The experimental site was prepared, drip irrigation system laid and mulch applied to the respective plots. The experiment composed of thirty six plots each measuring 2×2 m^2 and the total treatments were twelve. Three water levels which were 100, 80 and 60% ET_C and four grass mulch densities which were 0.0, 0.5, 1.0 and 1.5 kg/m^2 were used. The tomato water requirement was estimated at 100% ET_C and then calculated for the 80 and 60% ET_C respectively. Tomato crop was planted, soil and crop parameters determined during the study period including the total yield. Aquacrop model was used to simulate the tomato biomass, yield and water productivity.

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CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Water Saving and Irrigation

Water saving systems in agriculture incorporate; irrigation strategy, growing dry spell tolerant crops, dry cultivation, fertilizer, cover crops and protection cultivation (Molden *et al.*, 2010). Drip irrigation is known to be more efficient and thus leads to water saving and has been adopted for water application method in crop production (Cetin *et al.*, 2004).

2.2 Description of Irrigation

Irrigation implies to a process of applying regulated amount of water to horticultural crops, plantations and landscapes at regulated intervals. An irrigation system is a system off applying water to lands by methods for artificial canal, ditches, and pipes, particularly to advance the growth of crops. The irrigation water is passed on and conveyed to the crop through different water distribution methods. The basic water application methods incorporate; sprinkler irrigation, surface irrigation (basin, flooding, and furrow), sub-surface irrigation and drip irrigation (Orang *et al.*, 2008). The systems are discussed as follows;

2.3 Sprinkler Irrigation

Sprinkler irrigation method is a technique for applying irrigation water such that it imitates normal precipitation. Pressurized water is conveyed through an arrangement of pipe networks normally by pumping, at that point splashed into the air through sprinklers to such an extent that it separates into little water droplet which fall to the ground (Ahaneku, 2010). Sprinkler irrigation method is composed of a layout of the mainline, sub mainline, laterals and nozzles which are held above the ground using a riser pipe as shown in Appendix A.1. Sprinkler irrigation method have high initial investment cost, are affected by wind drift, experiences water loss due to evaporation from the soil during irrigation and an average field application efficiency of about 70% and therefore was not considered in this study.

2.4 Surface Irrigation

In surface irrigation systems, field water application can be through basins, furrows or flooding.

2.4.1 Basin Irrigation

Basin irrigation method is mostly used for irrigating rice, orchard trees and other crops and is the most commonly used irrigation method worldwide. In basin irrigation system water surface is levelled into basins and perimeter walls that allow for infiltration after the water flow and to

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prevent developed runoff (Hakala & Pekonen, 2008). In basin irrigation method there is risk to soil erosion, loss of water due to evaporation and percolation and a lower application efficiency of about 60% meaning that a lot of water is lost and therefore, the water productivity values is likely to be very low. For basins the terrace width varies from 1.5 m for 4% land slopes to 150 m for 0.1% land slopes (Savva & Frenken, 2002b).

2.4.2 Furrow Irrigation

Furrow irrigation method is among the surface irrigation methods whereby channels of small and regular shapes allow water flow across the field. Furrow irrigation method is applicable to deep and moderately permeable soils with uniformly flat or gentle slope of 0.1-0.5% for crops planted in rows including vegetables, maize, cotton, tomato and potato (Teklu, 2016). Furrow irrigation method is composed of an inlet, furrows (holding water), bunds and an outlet as shown in Appendix A.2 (Akay, 2015). Though farmer friendly and ideal for areas where there is plenty of water there is water wastage, dependency on soil slope and has a lower field application efficiency of about 60%. Furrow widths varies from 250-400 mm, depth from 150-300 mm and the spacing between furrows from 0.75-1.0 m. furrow lengths vary from about 60 m to 500 m. Furrows slopes should be between 0.05% and 2% (Savva & Frenken, 2002b).

2.4.3 Flooding Irrigation

Flood irrigation is the method of applying water by gravity flow directly onto the soil. In flooding irrigation there is wastage of water and hence lower application efficiency of 60% (Hakala & Pekonen, 2008).

2.5 Drip Irrigation System

In drip irrigation, water is directed to the field through an arrangement of pipes. In the field, by the column of crops or trees a tube is introduced. At normal intervals close to the plants or trees an opening is made in the pipe and fitted with an emitter. Through the emitters water is applied drop by drop to the plants (Bamohuni, 2011). A drip irrigation method layout is composed of a source, water filter, mainline, sub mainline, laterals and emitters (Keshtgar, 2012). An example of a typical layout of a drip irrigation system is presented in Appendix A.3.

Sub-surface drip irrigation method has little water loss because of evaporation and overflow and is along these lines useful for mulched regions since it can directly wet the soil without carrying away the mulch. Drip irrigation applies water directly to the point of interest therefore

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leading to high application efficiency of approximately 90% with minimal labour cost, hence this water distribution method was ideal for this water productivity study.

2.6 Climate Change and the Impacts

Climate change is referred to as the occasional changes over a significant period as for the developing aggregation of ozone harming substances in the atmosphere. Climate change can impact on; ecological resources, population development, water use productivity, hydrology, farming and water resources.

2.6.1 Climate Change Impact on Environmental Resources

The effects of climate change incorporate environmental fluctuation and is now realized in many parts of the world. This leads to increased temperatures and flood or dry spell conditions that change agricultural exercises and livelihoods. Progressively irregular precipitation designs and unpredictable high temperature spells reduces crop productivity (Mngumi, 2016). The water resources in the future will be progressively affected by climate change leading to the gap between water supply and demand to ascend. With hotter climate, water need is expected to increase while water availability is expected to diminish. Agricultural utilization, which is the significant user for water resources, will be reduced because of both diminishing precipitation and expanding evapotranspiration (Azadani, 2012).

2.6.2 Climate Change Impacts on Population Growth

Because of climate change the expense of living and production is probably to be increased and the general crop yield to decrease, raising the risk of poverty and hunger hence a reduction in the population growth (Abbaspour *et al.*, 2009).

2.6.3 Climate Change Impact on Water Use efficiency

The anthropogenic activities are leading to changes in climate due to activities that lead to increase in greenhouse gas concentrations. Irrigation water requirements change with the equalization between precipitation and evapotranspiration hence deviation in soil moisture status. Temperature and rainfall patterns are influenced by global warming leading to steady impacts on soil moisture (Silva *et al.*, 2007). Climate change impacts on the balance between soil and water prompts variation of soil evapotranspiration and the crop development period later on may shorten affecting water productivity. Crop yields influenced by climate change are anticipated to be distinctive in different territories, in certain regions crop production may increase and for other region, it might decline depending upon the latitude and irrigation water

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application. Modeling results shows that an expansion in rainfall increases the crop production which is more sensitive to precipitation than temperature (Kang *et al.*, 2009). With decreased water accessibility expected in the future, soils with high water holding limit could be desirable to diminish the effect of draught while maintaining crop yield. With the projected temperature increase and precipitation variances in the future, water accessibility and crop production are probably going to diminish. Whenever irrigated areas are developed, the crop production goes up, in any case, food and ecological quality may diminish (Roudier *et al.*, 2011).

This study focused on drip irrigation as a water saving technique as a means of maintaining food production in the future in order to cope with climate changes. The future climate change include declining rainfall amounts and increase in temperatures thus increasing evapotranspiration and hence reduction in crop yields.

2.7 Protected Cultivation Techniques

Protected cultivation is an alternative technique for seasonal and off-season vegetable cultivation and can be successfully practiced for niche areas of agriculture. The protected cultivation techniques include; shade net house, greenhouses and polyhouse (Negi *et al.*, 2013).

2.7.1 Shade Net House

A field experiment was conducted to investigate the effect of irrigation regimes on drip irrigated tomatoes grown under shade net house at the plasticulture farm, Rajasthan. Four different levels of drip irrigation which were 100, 80, 60 and 40 per cent of crop evapotranspiration (ETc) with five replications that based on gravimetric method were tested for determining the crop water requirement inside a shade net house. The results from the authors revealed that the optimum water requirement for the tomato under the shade net house was around 80 per cent of ETc outside the shade net house (Sharma *et al.*, 2015). The nets provided a physical barrier for protecting vegetables against pests and the associated viral diseases. Agro nets improve the microclimate of vegetables with notable improvements in temperature, relative humidity light and soil moisture thus contributing towards improved production of vegetables (Singh & Vishwavidyalaya, 2017). Shade net house technology though a good technology, it was not used in this study because of its high market prices.

2.7.2 Greenhouses

Greenhouse is an advanced technology for protected horticulture and addresses the major environmental factors of light, temperature, water, nutrition, and carbon dioxide, and features

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extensive discussions of greenhouse types, construction, and climate control. Greenhouse is a means of overcoming climatic adversity by use of a free energy source which is the sun. Greenhouse production acts as a means to maximize utilization of scarce resources like water (Hanan, 2017). The adoption of affordable and context-appropriate greenhouses can lead to improved lifestyles for farmers and entrepreneurs while improving food security. Although greenhouses can significantly increase smallholder productivity and improve livelihoods, current designs are too expensive making them unfavourable in this study (Pack & Mehta, 2012).

2.7.3 Polyhouse

Polyhouse cultivation of crops is developing as a specialized production technology to overcome organic and inorganic stresses and to avoid the seasonal barrier to production. It ensures production of high value crops, like capsicum and tomato throughout the year, including during the off-season (Murthy *et al.*, 2016). Polyhouse provides optimum environmental medium for better crop growth in order to gain maximum yield and high quality products and thus the technology was used in this study. These require comparatively less land area for agricultural production system resulting in increased land productivity and facilitate year round production of crops (Santosh *et al.*, 2017).

2.8 Crop Water Requirement

The Crop Water Requirement (ETc) is the measure of water required to meet the water loss through evapotranspiration or the measure of water required by the different crops to develop ideally. If irrigation is the only source of water supply for the plant, the irrigation water requirement must always be greater than the crop water requirement to allow for inefficiencies in the irrigation system (Savva & Frenken, 2002a). A number of techniques and models have been developed and applied in simulating crop water requirements such as Aquacrop, CROPWAT and CERES models as discussed in section 2.13.

2.9 Water Saving Irrigation Strategies

There are several water saving irrigation techniques which include deficit irrigation, mulching systems, managed full season drought management and partial season drought management (Evans & Sadler, 2008). Details of each of the methods is presented in the following sub sections:

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2.9.1 Deficit Irrigation

Deficit irrigation is the process of supplying limited irrigation water than the full requirement of the crop. This means the crop is to face certain amount of stress. Haidula (2016) Characterized deficit irrigation as a controlled water system strategy that reduces water use, with little effect on crop yield and quality to guarantee manageable agricultural efficiency. Salokhe *et al.* (2005) did a test utilizing four different levels of drip irrigation system which were 100, 75, 50 and 25% of the crop evapotranspiration (ETc), in view of Penman–Monteith (PM) technique, to decide their impact on crop development, crop yield, and water productivity. The authors developed Tomato (*Lycopersicon esculentum*) in a poly-net greenhouse and compared the outcomes with the open cultivation system as a control. Their outcomes uncovered that drip irrigation system at 75% of crop evapotranspiration gave the greatest yields and irrigation system efficiency.

In an alternative irrigation level varying technique, Kuscu *et al.* (2014) carried out a study in Bursa region, Turkey to study the reaction of tomato (*Lycopersicon esculentum* Mill) to deficit irrigation so as to direct projects for the advancement of improved water management practices. The authors subjected industrial tomato plants to various degrees of irrigation levels utilizing a drip system in the field for two years where well - watered plants were irrigated at 100% crop evapotranspiration (ETc) at three day intervals. In different treatment irrigation was not applied during the vegetative, flowering, yield development or maturing stages or either during combination of these stages. The outcomes from the authors indicated that full irrigation during the entire developing season was advisable for better return and overall gain. Proposals were that the use of full irrigation until the start of the fruit ripening stage and stopping of full irrigation after that time was the best. The study did not consider the impact of mulching in the water productivity of tomatoes.

Another study by Sibomana *et al.* (2013) to quantify the effects of water stress on the growth and yield of tomatoes was carried out at Egerton University, Horticultural Research and Teaching Field between 2009 and 2010. Tomato “Money Maker variety” was subjected to four soil moisture threshold levels of 100% ETc, 80% ETc, 60% ETc and 40% ETc under randomized complete block design (RCBD) with four replications. Five weeks old tomato seedlings were transplanted into 10-litre pots put under polyethylene covered tunnels. The results from the authors revealed that the highest yield reduction of 69% was observed in the most stressed plants. The decrease in plant growth and yield as a result of water stress can be

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attributed to the effects water has on the physiology of the crop. The effect of mulch was not considered in the study as was the case, in this study.

2.9.2 Mulching

Mulching includes placing a cover material on the ground surface around plants for protection of soil moisture, improving fertility and strength of the soil, diminishing weed development and upgrading the visual appearance of the area. Mulching materials incorporate paddy straw, sugarcane bark, dry grass, tree leaves, paper, wool, animal manure, saw dust, wood chips and peat moss (Jordan *et al.*, 2011). There are additionally two kinds of plastic mulches which are transparent and black, that have been evaluated to determine the efficiency of various crops (Yaghi *et al.*, 2013). Saeed and Ahmad (2009) carried out a study to observe the effects of organic mulch on vegetative growth and productive yield of tomato plant (*Lycopersicon esculentum* Mill.). The results from the authors revealed a significant decrease in vegetative growth and productive yield proportionate to increasing salinity levels. The use of mulch treatments uncovered critical increment under both saline and non - saline conditions. The utilization of organic mulches with or without gypsum to soil being irrigated with saline water increases the yield by lessening salinity dangers which could be measured on development of tomato plant.

Ortiz (2015) carried out a study aimed at evaluating different management practices in order to increase the status of the soil water, increase water use efficiency, plant performance, crop yield and fruit quality with the treatments being different compost rates in combination with different mulching techniques (garlic straw, oat straw, plastic and no mulch). Plant performance (plant height, canopy density and canopy volume) and crop yield were evaluated on a weekly basis. The study revealed that the use of straw mulch has the ability of increasing soil water retention, yields and improving on soil quality. It was realized that additional research was needed to look at long-term benefits in terms of fruit yield, soil quality, potential water savings and profitability. The effect of deficit irrigation on the productivity of tomatoes was not considered as was the case in this study. This study assessed the effect of different grass mulch densities on the water productivity of tomatoes.

2.10 Vegetables

Vegetables are important constituents of human diet since they are a source of nutrients, vitamins and minerals. It gives good returns to the farmer, when well cultivated as it fetches

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higher prices in the market. However, like other crops, it is also being affected by the impact of climate change. Variations in climate lead to crop failures, shortage of yields, and reduction in quality and increase in pest and disease problems thus resulting in unprofitable vegetable cultivation (Ayyogari *et al.*, 2014). In this study tomato, which is a vegetable was assessed because of its shorter maturity period and high prices in the market hence more profitable to the farmer or rather, a high value crop. It's a crop that can be grown throughout the season under a controlled environment, meaning that crop intensification is very high. Further, it is one of the main crops in Njoro area grown under limiting rain-fed conditions.

2.10.1 Strategies for Improving Vegetable Farming Productivity

There are several strategies that increases yield by improving vegetable farming techniques. They include; crop rotation, irrigation, mulching and cultural practices (Pena & Hughes, 2007). Crop rotation is the practice of growing a series of different types of crops in the same area in a regular sequence. It helps in reducing soil erosion, increasing soil fertility and crop yield and minimizing pests and disease build up (Muthoni & Kabira, 2010). With improving new technologies, farmers need to better address production strategies through irrigation. For maximum return on investment, production has to be market – driven. Farmers need to target their production to off – season periods when prices are highest. There is need for continued development and adaptation of the new technologies and programs (Ngigi, 2002). Several crop management practices help to conserve soil moisture, reduce soil degradation, and protect vegetables from heavy rains, high temperatures and flooding. Organic and inorganic mulches are used in vegetable production systems. These layers help reduce evaporation, enhance soil fertility and structure, regulate soil temperature, minimize soil runoff and erosion, prevent fruits from direct contact with soil and reduce weed growth (Zribi *et al.*, 2015). This study employed irrigation and mulching systems as strategies for improving tomato water productivity.

2.10.2 Tomato crop

Tomato crop is commercially important all over the world for the fresh fruit market and the processed food industries. It is grown in a wide range of weather conditions in the open field and in the controlled environment (Atherton & Rudich, 2012). It is the world's largest vegetable crop after potato and sweet potato and leads in the list of canned vegetables. Tomato is an important ingredient in most diets and a very cheap source of vitamins. It also contains a large quantity of water (%) and calcium (%) all of which are of significant importance in the metabolic activities of a man. Tomato is a significant source of vitamins A, C and E and

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minerals that are very important for the body and they protect the body against diseases (Marjanović *et al.*, 2012). In the present study tomato crop was used because of its short growing period and high prices in the market.

2.11 Interactive Effects of Deficit Irrigation and Mulching

Deficit irrigation and mulching are both techniques of achieving optimal crop water productivity. A study was conducted between September 2001 and August 2002 to investigate the influence of irrigation schedule and mulching materials on yield and quality of greenhouse grown fresh market tomato in Kenya Highlands. The experimental design was split plot embedded in randomized complete block design replicated three times with irrigation schedules as main plot consisting of irrigation on daily basis, after every two and three days, respectively. Mulching material which included clear plastic, dry grass mulch and no mulch formed the sub plot. Their results revealed that grass mulch and irrigation after three days should be adopted for greenhouse tomato in warm tropics. The effect of different irrigation rates was not considered (Kere *et al*., 2003).

Fereres and Soriano (2006) conducted a field experiment at Water Technology Centre, to study the effect of drip irrigation levels and mulching on tomato productivity laid out in strip plot design. The experiment consisted of three drip irrigation levels as main treatments (100% ET_c, 80% ET_c, 60% ET_c) and four mulches (bio-degradable mulch, polythene mulch, paddy straw and no mulch) as the sub treatments with three replications. From the study the authors concluded that drip irrigation scheduling at 100% ET_c with application of polythene mulch would be the best combination for getting higher tomato productivity under the agricultural climatic conditions of the semi - arid regions. The study did not consider the impact of grass mulch of different densities. In another study the combined effects of drip irrigation and mulching on yield, water-use efficiency and economic return of tomato were evaluated. The treatments consisted of different combinations of three drip irrigation levels (100, 75 and 50% of crop water requirement, ETc) and two mulching materials (black polyethylene sheet and paddy straw). From the study the highest water use efficiency of 592 kg/ha/mm was obtained with 50% water application under polyethylene mulch and thus revealed that drip irrigation with mulch has a significant role in increasing the land and water productivity of tomato (Biswas *et al.*, 2015). The study did not consider the interactive impact of deficit sub – surface drip irrigation and grass mulch of different densities.

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The interactive effect of deficit irrigation under drip irrigation system and mulching on yield and water-use efficiency on tomato production at Miawa Farmer Training center, South Wollo, and Kallu Worda during 2016 irrigation season was studied. A factorial combination of three levels of water (70%, 80% and 90% ETc) and three mulching materials (without mulch (WM), sugarcane mulch (SM) and bulrush mulch (BM) with three replications was used. The highest water use efficiency of 142.96 kg/ha/mm was obtained with 80% water application under sugarcane mulch. The study thus reveals that drip irrigation with mulch has an important role in increasing the yield and water productivity of tomato (Amare *et al.*, 2017). However the effect of full water supply and inadequate supply was not studied to determine the impact of all the possible water levels on tomato water requirement. The study did not consider the impact of grass mulch of different densities.

2.12 Reference Evapotranspiration Estimation Methods

Reference evapotranspiration (ETO) is the rate of evapotranspiration from a hypothetical grass with an expected yield tallness of 0.12 m, a fixed surface resistance of 70 sec m-1 and an albedo of 0.23. ET_O can be estimated using different methods depending on the availability and reliability of climatic data. The different methods of ETo estimation include; FAO-24 Penman –Monteith, FAO-24 Blaney-Criddle, Hargreaves and Christiansen Pan methods (George & Raghuwanshi, 2012).

2.12.1 Blaney-Criddle Method

The Blaney Criddle method is utilized to estimate the reference evapotranspiration and is basic with low parameter prerequisite (Xu & Singh, 2002). It is expressed by Equation 2.1.

$$ET_o = p(0.46T_a + 8.13) \tag{2.1}$$

where:

ET_O = Reference evapotranspiration (mm day^{-1}),

T_a = Mean temperature (◦C)

$$T_a = \frac{T_{max} + T_{min}}{2} \tag{2.2}$$

Where,

T_{max} = Maximum temperature (◦C)

T_{min} = Minimum temperature (◦C)

p = Percent of daytime hours for the utilized period (every day or every month) out of

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all out daytime hours of the year (365 × 12). The estimation of p can be assessed from Appendix B.1 (dimensionless).

This method though easy to use, has an error value of +2% (Trajkovic *et al.*, 2000). Blaney Criddle method therefore underestimates the reference evapotranspiration and was therefore not used in this study (Subedi & Chávez, 2015).

2.12.2 Hargreaves Method

The Hargreaves equation is a basic method for evaluating reference evapotranspiration and requires few parameters (Talaee, 2014). It has not been used by most researchers and has an error value of +14% (Córdova *et al.*, 2015). It is expressed by Equation 2.3.

$$ET_o = 0.0023 \times (T_a + 17.8) \times (T_{max} - T_{min})^{0.424} \times R_a \quad (2.3)$$

where:

ET_O = grass reference evapotranspiration (mm day^{-1}),

T_{max}, T_{min} and T_a = are the maximum, minimum and mean air temperatures (°C), respectively.

Ra = the water equivalent of the extraterrestrial radiation (mm day^{-1})

The water equivalent of the extraterrestrial radiation, Ra According to Allen *et al.* (1998b), is expressed by Equation 2.4.

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\partial) + \cos(\varphi)\cos(\partial)\sin(\omega_s)] \quad (2.4)$$

where:

G_{sc} = Solar constant = 1.362 kW/m^2

d_r = Inverse relative distance Earth – Sun

$$d_r = 1 + 0.033\cos\left[\frac{2\pi}{365} J\right] \quad (2.5)$$

J = No. of the day in the year between 1 (1^{st}January) and 365 or 366 (31^{st} December)

$\boldsymbol{\omega}_s$ = sunset hour angle (rad)

$$\omega_s = \arccos[-\tan(\varphi)\tan(\partial)] \quad (2.6)$$

φ = latitude (rad)

∂ = Solar declination

$$\partial = 0.409\sin\left[\frac{2\pi}{365} J - 1.39\right] \quad (2.7)$$

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In this study the Hargreaves technique was not used to assess reference evapotranspiration, however it is basic and requires low parameters, it was viewed as inaccurate (Trajkovic, 2007).

2.12.3 FAO Penman–Monteith method

The Penman - Monteith strategy was considered as the most precise and a standard technique to estimate reference evapotranspiration however its limitation is a few parameter prerequisite (Sentelhas *et al.*, 2010). The function is expressed by Equation 2.8.

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma(900/T + 273)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{2.8}$$

where:

ET_0 = grass reference evapotranspiration (mm day^{-1}),

Δ = the slope of the saturated vapor pressure curve (kPa $^oC^{-1}$),

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T + 237.3}\right)\right]}{(T + 237.3)^2} \tag{2.9}$$

R_n = the net radiation (MJ m^{-2} day^{-1}),

G = the soil heat flux density (MJ m^{-2}). It is null for daily estimates,

T = daily mean air temperature (^oC) at 2 m based on the average of maximum and minimum temperature

$$T = \frac{T_{max} + T_{min}}{2} \tag{2.10}$$

U_2 = average wind speed at 2 m height (ms^{-1})

$$U_2 = U_Z \frac{4.87}{\ln(67.8z - 5.42)} \tag{2.11}$$

where:

U_2 = wind speed at 2 m above ground surface (m/s)

U_Z = measured wind speed at z m above ground surface (m/s)

z = height of measurement above ground surface (m)

e_s = the saturation vapour pressure (kPa),

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \tag{2.12}$$

$$e^oT_{max} = 0.6108\exp\left[\frac{17.27T_{max}}{T_{max} + 237.3}\right] \tag{2.13}$$

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$$e^{o}T_{\min} = 0.6108\exp\left[\frac{17.27T_{\min}}{T_{\min}+237.3}\right] \quad (2.14)$$

e_a = the actual vapour pressure (kPa)

The actual vapour pressure was determined using the actual vapour pressure calculator from the relative humidity and the saturated vapour pressure.

(e_s - e_a) = the saturation vapour pressure deficit (Δe, kPa) and

γ = the psychometric constant (0.0677 kPa $^{o}C^{-1}$)

$$\gamma = \frac{C_P P}{\varepsilon\lambda} = 0.665\times10^{-3}P \quad (2.15)$$

γ = Psychrometric constant (kPa/^{o}C)

P = Atmospheric pressure (kPa)

λ = Latent heat of vaporization 2.45 (MJ/kg)

C_p = Specific heat at constant pressure 1.013×10^{-3} (MJ/kg/^{o}C)

ε = Ratio molecular weight of water vapour/dry air = 0.622

$$P = 101.3\left[\frac{293-0.0065z}{293}\right]^{5.26} \quad (2.16)$$

P = Atmospheric pressure (kPa)

z = elevation above sea level (m)

The Penman - Monteith method was considered as a standard and the most accurate method to estimate reference evapotranspiration and was therefore the most ideal for use in this study (Dinkar, 2017).

2.13 Modeling

A model is anything that represents something else, usually on a smaller scale. Modeling is a method of simulating real life situations with mathematical equations to predict their future character (Moore *et al.*, 2013). Simulation is the process of imitating the character of a situation or a process by means of similar things. Simulation is the application of a model with the objective to derive strategies that help solve a problem or answer a question pertaining to a system. A mathematical model is a tool used by one to describe a physical system to obtain information from the model in order to make decisions that will influence the physical system (Velten, 2009). Model validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use

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of the model (Ling & Mahadevan, 2013). Some of the common CWR models include; CROPWAT and Aquacrop as discussed in the subsequent sub sections.

2.13.1 CROPWAT Model

Understanding crop water requirements is important for desirable irrigation practices, scheduling and water use efficient since the water availability through rainfall is not sufficient. Bouraima *et al.* (2015) estimated the irrigation water requirement of rice in Benin's sub-basin of Niger River (BSBNR), using CROPWAT model. The Crop coefficients (Kc) from the phenological stages of rice were applied to adjust and estimate the actual evapotranspiration (ETc) through a water balance of the irrigation water requirements. From the results the BSBNR crop evapotranspiration (ETc) and the crop irrigation requirements were estimated at 651 mm and 383 mm, respectively in rainy season and 920 mm and 1, 148 mm, respectively within a dry season.

Karanja (2006) used CROPWAT method to evaluate the crop water requirements of six selected agricultural sub - counties namely, Kiambu, Makueni, Kwale, Laikipia, Vihiga and Migori, distributed across six provinces of Kenya that is Central, Eastern, Coast, Rift Valley, Western and Nyanza provinces respectively. Their results showed that increase in temperature increased the percentage change in crop water use and that the changes in crop water use from the output of the CCCM scenario were lower than those from the GFDL3 for all the sub - counties studied.

2.13.2 Aquacrop Model

The FAO Aquacrop model estimates crop productivity, water requirement, and water use efficiency (WUE) under water-limiting conditions. The ease of use of the Aquacrop model, low input parameter requirement and its sufficient degree of simulation accuracy makes it a valuable tool for estimating crop productivity. It has been used under rainfed conditions, supplementary, deficit irrigation, and on-farm water management strategies for improving the water use efficiency in agriculture (Heng *et al.*, 2009). The potential of Aquacrop model in deficit irrigation practice was studied for wheat in Gavkhuni river basin. From the results of the authors it was observed that the model provided better simulations of the water productivity and found that water productivity for the studied crop was in the range of 0.91 to 1.49 kg m^{-3} and its maximum value was in 40% deficit irrigation treatment (Salemi *et al.*, 2011).

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Darko *et al.* (2016) carried out field experiments in Mfantseman District of the Central Region of Ghana to calibrate and test Aquacrop model for tomato (*Lycopersicon esculentum*) grown under both deficit and full irrigation. The model was calibrated using data from the first experiment and validated using data obtained from the second experiment. The calibrated Aquacrop model focused on its performance to simulate crop yield and crop water requirement where four treatments were investigated: no irrigation after plant establishment, 50% ETc restoration, 100% ETc restoration up to beginning of flowering, then 50% ETc restoration and 100% ETc restoration. From the results it was revealed that the model was able to predict well the seasonal water requirements in both experiments. In this study Aquacrop model was used because of its ability to simulate yields in response to water (water productivity), simplicity and the fewer number of parameter requirements.

There are several equations governing the Aquacrop model. Yield response to water is expressed by Equation 2.17.

$$1-\frac{Y}{Y_x}=K_y\left[1-\frac{ET}{ET_x}\right] \tag{2.17}$$

where:

Y_x = Maximum yield (kg)

Y = Actual yield (kg)

$1-\frac{Y}{Y_x}$ = The relative yield decline (dimensionless)

ET_x = Maximum evapotranspiration (mm/day)

ET = Actual evapotranspiration (mm/day)

$\left[1-\frac{ET}{ET_x}\right]$ = Relative water stress (dimensionless)

K_y = Proportionality factor (dimensionless) (K_y lies between relative yield decline and relative reduction in evapotranspiration)

Aquacrop model uses the FAO Penman Monteith Equation 2.8 to estimate the reference evapotranspiration.

The FAO Penman Monteith equation is further discussed in detail under sub section 2.8.3.

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2.14 Green Canopy Cover

Green Canopy Cover (GCC) is the fraction of the soil surface that is occupied by the canopy (Vanuytrecht *et al.*, 2014). It is expressed by Equation 2.18.

$$GCC = 1.005 \times \left[1 - \exp(-0.6LAI)\right]^{1.2} \quad (2.18)$$

where:

GCC = Green canopy cover (dimensionless)

LAI = Leaf area index (dimensionless)

Leaf area index

$$LAI = A \times N \quad (2.19)$$

where:

A = Area per plant (m^2)

N = Number of plants/m^2

$$A = 0.75\sum_{i=1}^{n}\left(L_i \times W_i\right) \quad (2.20)$$

where:

A = Leaf area per plant (cm^2)

n = Number of leaves per plant

L = Leaf length (cm)

W = Leaf width (cm)

2.15 Water Extraction Pattern

Plants normally have a higher concentration of roots in the upper part of the root zone and near to their base. The extraction pattern is shown in Figure 2.1 (Raes *et al.*, 2011).

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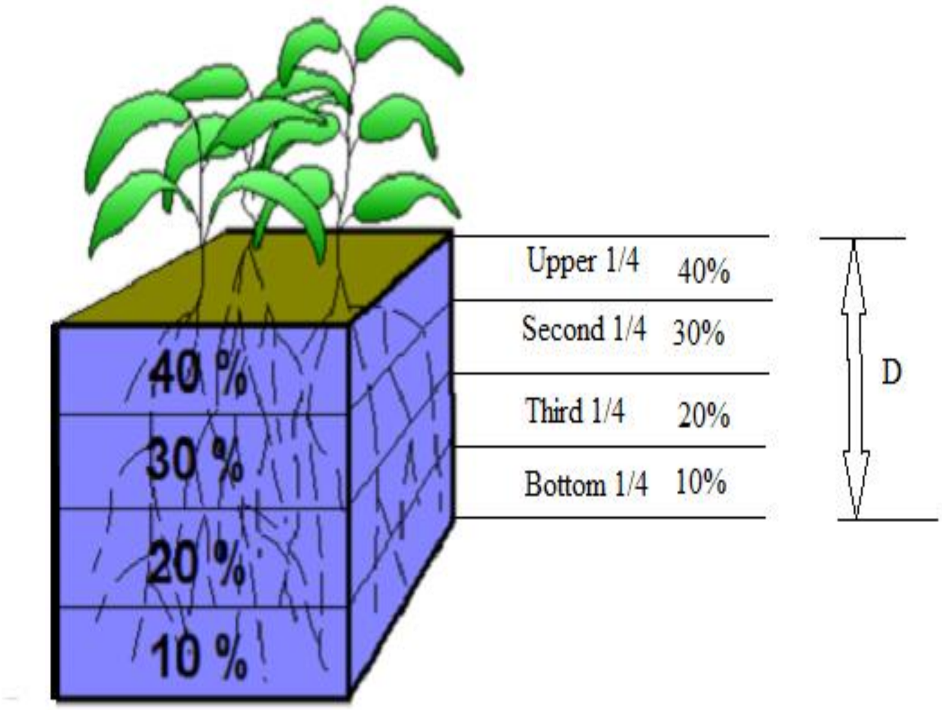

Figure 2.1: The water extraction pattern

The total root volume determines the total amount of water that can be extracted out of the root zone. In the upper quarter of the maximum rooting depth 40% of the water extraction occurs, the second quarter 30%, the third quarter 20% and the bottom quarter 10%.

2.16 Experimental Design

An experimental design is a plan for assigning experimental units to treatment levels and the statistical analysis associated with the plan. The experimental designs include randomized block design (RBD), completely randomized design, least significance difference and factorial design (Kirk, 2012). The designs are discussed in sub – sections 2.16.1, 2.16.2, 2.16.3 and 2.16.4.

2.16.1 Randomized Block Design

The randomized block design is a family of experimental designs in which the experimental material is split up into a number of mini-experiments that are combined in the final statistical analysis. In each block there is a single experimental unit to which each treatment is assigned. There can be any number of replications (blocks) (Festing, 2014). In randomized block experimental design, the treatments are allocated to the experimental units or plots in a random manner within homogeneous blocks or replications. It is appropriate only when the experimental material is heterogeneous. Also, there is a limited number of treatments one

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research project can study, and naturally the number of blocks is directly affected by the number of variables on which the data can be blocked (Ariel & Farrington, 2010). Randomized Block Design was not considered in the present study.

2.16.2 Completely Randomized Design

A completely randomized design (CRD) is the simplest design for comparative experiments, as it uses only two basic principles of experimental designs which are randomization and replication. In CRD, the treatments are allocated to the experimental units or plots in a completely random manner. In a properly randomized experiment, every treatment is equally likely to be applied to every experimental unit (Casler, 2015). Completely Randomized Design was not used in the current study.

2.16.3 Latin Square Design

The Latin square design generally requires fewer subjects to detect statistical differences than other experimental designs. In a Latin square design, each treatment is assigned once to each row and each column. Although the sequences of rows and columns may be randomized one treatment immediately precedes a certain treatment never or more than once (Kim & Stein, 2009). The design is limited to the experiments in which the number of levels of each blocking variable is equal with the number of levels of the treatment factor. Moreover, it could be applied under the assumption that there are no interactions between the blocking variables or between the treatment variable and the blocking variables (Sorana *et al.*, 2009). Latin Square Design was not used in this study.

2.16.4 Factorial Experimental Design

A factorial design considers possible interactions between the factors, and the conclusions are highly reproducible. Therefore it is economical for characterizing a complicated process. The split-plot factorial design is appropriate for experiments with two or more treatments where the number of treatment combinations exceeds the desired block size (Meshkini *et al.*, 2010). The factorial experimental design was used in this study.

CHAPTER THREE

MATERIALS AND METHODS

3.1 The Study Area

The experiment was done at Egerton University, Nakuru County, Kenya. Njoro Sub - County covers a territory of around 780 km^2. Njoro Town is the headquarters of Njoro Sub - County and is situated around 200 km North West of City of Nairobi and 18 km south west of Nakuru Town. With an average altitude of 2400 meters above sea level, Njoro lies between Latitude 0º 15’0” and 0º 42’ 30” South and Longitude 35º 45’0” and 36º 10’ 0” East (Figure 3.1).

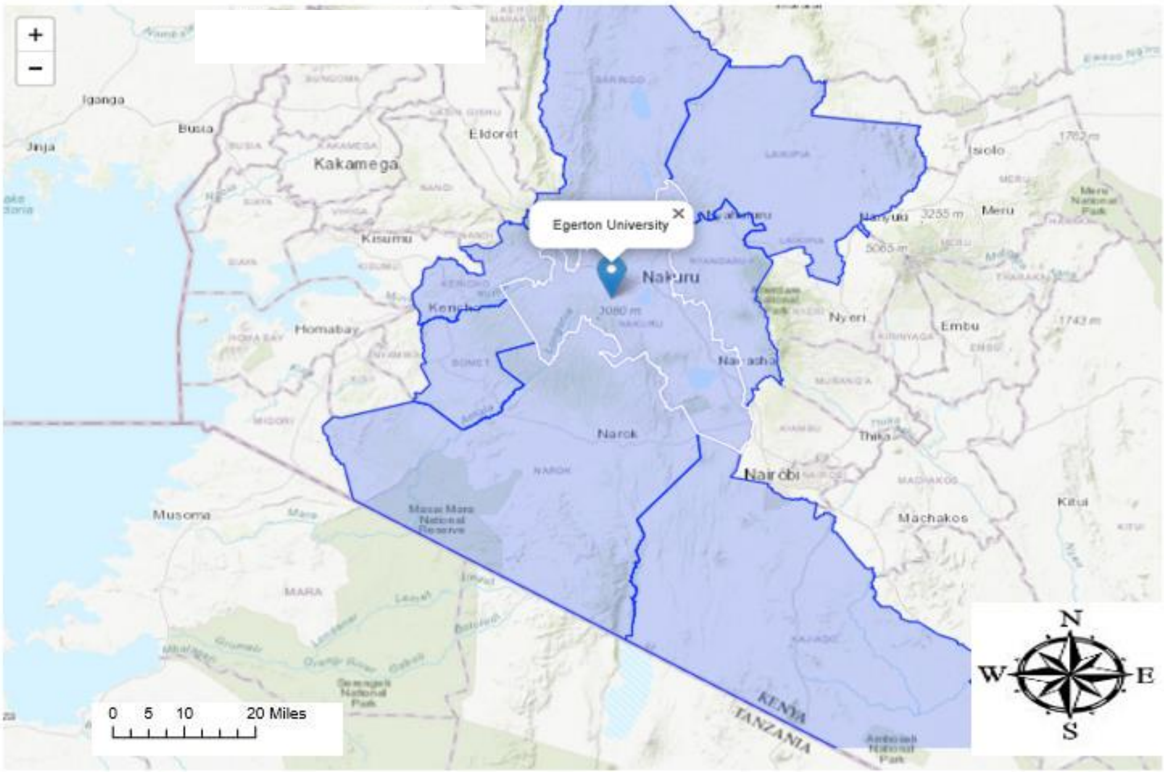

Figure 3.1: Location of Egerton University, Nakuru

The climate in Njoro Sub - county is classified as warm and temperate. Mean yearly rainfall estimated at Egerton University from 1987-2016 is 1073 mm. Minimum measure of rainfall occurs in January with the average being 20 mm. The maximum rain falls in April, averaging 140 mm. Njoro area has a trimodal rainfall pattern with the peaks in April, August and November as shown in Figure 3.2 for average rainfall from 1987 to 2016 (30 years) (Egerton University weather station).

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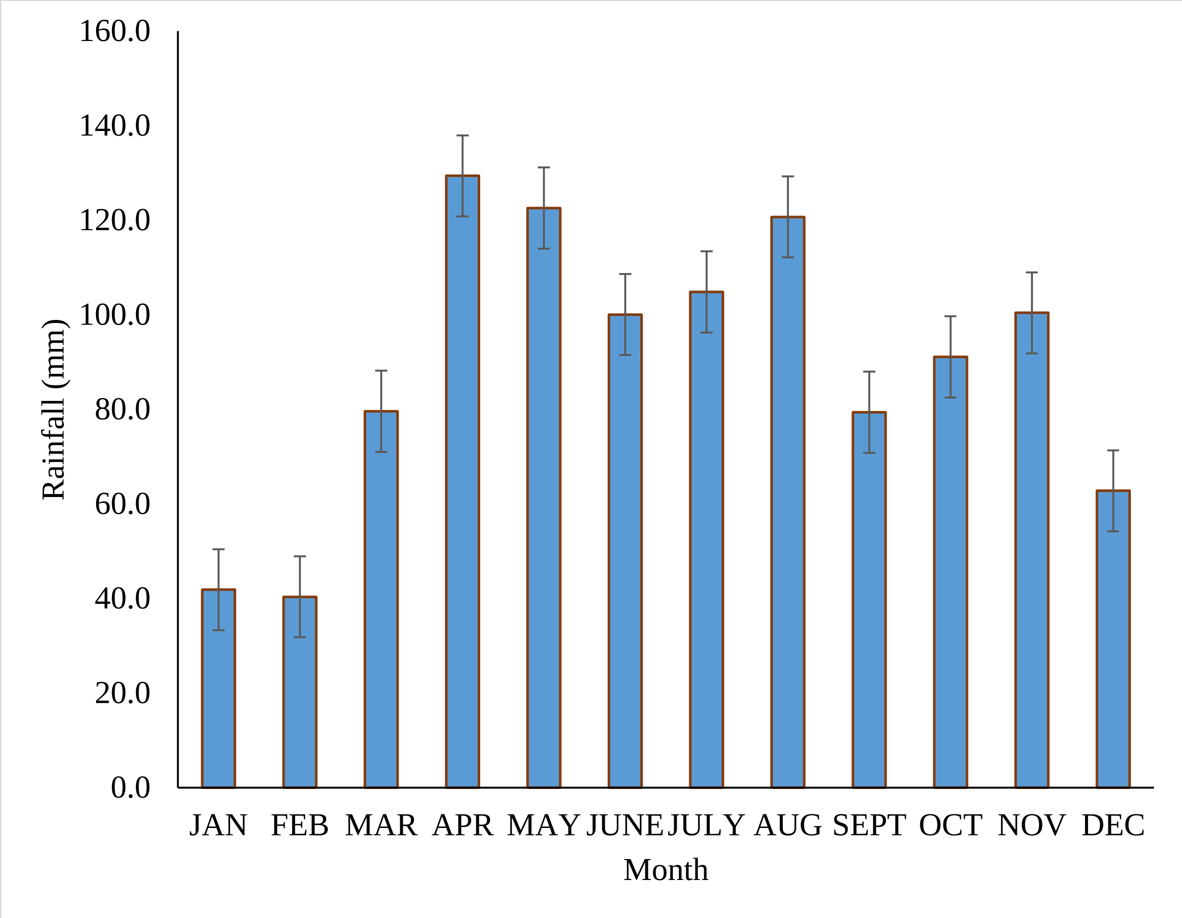

Figure 3.2: Average Rainfall pattern for Njoro Sub-county (1987-2016)

The average maximum yearly temperature for the area is 26.4 °C while the average minimum temperature is 7.8 °C (Sibomana *et al*., 2013). The drainage classes of the soil in Njoro sub county range from poorly drained, moderately well drained, well drained to excessively drained, with surface roughness of sandy clay loam and structures ranging from moderately strong to strong (Mainuri & Owino, 2013).

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3.1.1 Experimental Set Up and Data Acquisition

The study was carried out on 36 experimental plots each with an area measuring 4.0 m^2. The layout consisted of the supply, mainline, sub-mainline and the drip-lines. The layout of the experiments and set up is presented in Figure 3.3.

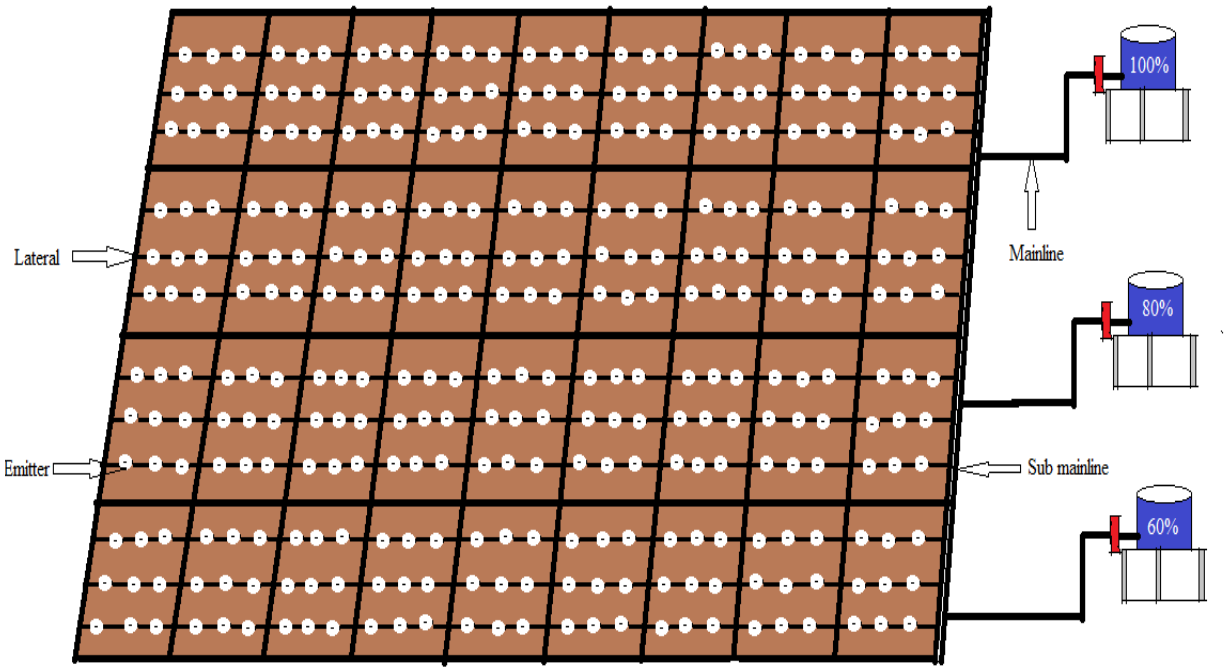

Figure 3.3: Experimental plots layout

A total area of 144 m^2 was used for the sub - surface drip irrigation system layout. The dimensions of the experimental plots was measuring 2.0 m by 2.0 m were used. Twelve treatments were administered in the plots using factorial experimental design with three replications, giving the total number of plots as thirty six.

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Table 3.1: Treatments and water levels

Treatment number	Irrigation level (%ET_c)	Mulching system
T_1	100	No mulch
T_2	80	No mulch
T_3	60	No mulch
T_4	100	Mulch (0.5 kg/m^2)
T_5	80	Mulch (0.5 kg/m^2)
T_6	60	Mulch (0.5 kg/m^2)
T_7	100	Mulch (1.0 kg/m^2)
T_8	80	Mulch (1.0 kg/m^2)
T_9	60	Mulch (1.0 kg/m^2)
T_{10}	100	Mulch (1.5 kg/m^2)
T_{11}	80	Mulch (1.5 kg/m^2)
T_{12}	60	Mulch (1.5 kg/m^2)

The experimental site was demarcated and ploughed between 18th and 30th December, 2018 after which the 36 plots were laid out as shown in Figure 3.3. Grass mulch of densities 0.5, 1.0 and 1.5 kg/m^2 were applied to the appropriate plots as shown in the Table 3.1.

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Table 3.2: Treatment allocation to the plots

Plot 1	Plot 2	Plot 3	Plot 4
100% ET_C	60% ET_C	80% ET_C	100% ET_C
0.5 kg/m^2	No mulch	1 kg/m^2	0.5 kg/m^2
Plot 5	Plot 6	Plot 7	Plot 8
80% ET_C	100% ET_C	60% ET_C	80% ET_C
0.5 kg/m^2	No mulch	1 kg/m^2	0.5 kg/m^2
Plot 9	Plot 10	Plot 11	Plot 12
60% ET_C	80% ET_C	100% ET_C	60% ET_C
0.5 kg/m^2	No mulch	1 kg/m^2	0.5 kg/m^2
Plot 13	Plot 14	Plot 15	Plot 16
100% ET_C	60% ET_C	80% ET_C	100% ET_C
1 kg/m^2	1.5 kg/m^2	No mulch	1 kg/m^2 kg
Plot 17	Plot 18	Plot 19	Plot 20
80% ET_C	100% ET_C	60% ET_C	80% ET_C
1 kg/m^2	1.5 kg/m^2	No mulch	1 kg/m^2
Plot 21	Plot 22	Plot 23	Plot 24
60% ET_C	80% ET_C	100% ET_C	60% ET_C
1 kg/m^2	1.5 kg/m^2	No mulch	1 kg/m^2
Plot 25	Plot 26	Plot 27	Plot 28
100% ET_C	60% ET_C	80% ET_C	100% ET_C
1.5 kg/m^2	0.5 kg/m^2	1.5 kg/m^2	No mulch
Plot 29	Plot 30	Plot 31	Plot 32
80% ET_C	100% ET_C	60% ET_C	80% ET_C
1.5 kg/m^2	0.5 kg/m^2	1.5 kg/m^2	No mulch
Plot 33	Plot 34	Plot 35	Plot 36
60% ET_C	80% ET_C	100% ET_C	60% ET_C
1.5 kg/m^2	0.5 kg/m^2	1.5 kg/m^2	No mulch

Drip lines were mounted at a depth of 5.0 cm below the ground surface because within the first quarter of the root zone depth corresponding to 20.0 cm, 40% of the crop water requirement is abstracted. This also corresponds to the zone with high root concentration. The drip lines were placed at the shallow depth to accommodate the water conservation by grass mulch on the soil

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surface. Tomato was planted at a spacing of 50 cm between rows and 60 cm between plants (Kirimi *et al.*, 2011). One type of mulch (dry guinea grass) of three densities (0.5, 1 and 1.5 kg/m^2) and three levels of deficit irrigation were used which are 100% ET_c, 80% ET_c, and 60% ET_c to account for water saving through deficit irrigation that is 20 to 40% irrigation water at yield reductions below 10%.

From the past studies grass mulch of densities 0.75 kg/m^2 by Hudu *et al.* (2002), 1.2 kg/m^2 by Agele *et al.* (1999) and 3.0 kg/m^2 by Awodoyin *et al.* (2010) have been used. In this study grass mulch densities within the recommended range that was 0.5, 1.0 and 1.5 kg/m^2 were used to determine their effect on tomato growth.

3.1.2 Land preparation, Seedbed Preparation and Transplanting

A seedbed was prepared and tomato seeds planted. After 30-40 days the seedlings were transplanted to the test plots. The experimental site was furrowed using a hoe and harrowed using a scraper and a rake. After the experimental plot preparation grass mulch of the different densities were applied to the appropriate plots. Transplanting of the tomatoes was done on 12th January, 2019 and the entire growing period ended in 26th May, 2019.

3.1.3 Drip Irrigation System Layout

The mainline was made of PE pipe of internal diameter 25 mm. The sub mainline was made of PE pipe of internal diameter 25 mm. The lateral line was made of PE of internal diameter 10 mm and spacing of laterals was 0.50 m. A 1000 litre tank was raised at a height of 2 m above the ground for supplying water to the 100 litre tanks which were raised at a height of 1.5 m above the ground that supplied water to the experimental plots through the mainline, sub mainlines and the laterals. The 100 litre tank was used to measure the exact volume of water to be supplied to the field.

3.1.4 Fertilizer Application, Pest and Disease Control

Di - ammonium phosphate (DAP) fertilizer was applied at 200 kg/ ha and urea at 100 kg/ha. 25g of Karate pesticide was applied two days after transplanting to control cutworms. Early and late blight diseases were controlled using 50g Ridomil in 20 litres of water at weekly intervals. Aphids, white flies and mites were controlled using Actara at 10g in 20 liters of water.

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3.1.5 Bio Data for Tomato Crop

The information about tomato crop that included base period, duty, delta and net radiation were as shown in Table 3.3.

Table 3.3: Bio data of tomato crop

Parameter	Approximate value	Units
Base period	75	Days
Duty	0.000125	Ha
Delta	0.8	M
R_n	591.726	W/m^2
Rooting depth	75	Cm

Where,

Base period = the time period between planting and harvesting

Duty = Area of land that can be irrigated with a unit volume of water supplied across the base period

Delta = depth of water required to raise a crop over a unit area

R_n = Net radiation

Rooting depth = Depth within the soil profile that a crop can effectively extract water and nutrients for growth

3.2 Estimation of Crop Water Requirement using FAO Penman - Monteith Method

The crop water requirement of tomato for Njoro Sub - County was estimated using Equation 3.1 (Allen, 1998).

$$ET_c = ET_o \times k_c \tag{3.1}$$

where:

ET_C = Crop evapotranspiration (mm day^{-1})

ET_o = Reference evapotranspiration (mm day^{-1})

K_c = Crop coefficient (dimensionless)

The reference evapotranspiration was estimated using the FAO Penman - Monteith method while the crop coefficient was obtained from the FAO Kc tables presented in Appendix B.2 as discussed in sub-sections 3.2.1 and 3.2.2.

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3.2.1 Estimation of Reference Evapotranspiration (ETo)

The reference evapotranspiration (ET_O) was estimated using the FAO Penman - Monteith method defined by Equation 2.8 and the results compared with those obtained directly from the Egerton weather station. The input to the method were relevant climatic parameters such as maximum and minimum air temperature, wind speed, net radiation and the relative humidity. These climatic parameters were obtained from the Egerton University weather station (Number: 9035092). Data collected was for a period of ten years. The average value of the reference evapotranspiration was used as input into Equation 3.1.

3.2.2 Estimation of Crop Coefficient

The crop coefficients for the different growth stages of tomato were obtained from the FAO Kc table Appendix B.2. The available crop coefficients and their stages are for initial, development, mid and late growth stages and denoted as $K_{c\ ini}$, $K_{c\ dev}$, $K_{c\ mid}$ and $K_{c\ late}$ respectively. The crop evapotranspiration was then determined by obtaining the product of the estimated reference evapotranspiration and the crop coefficient values as shown in Equation 3.1. The crop water requirement was equated to the crop evapotranspiration estimated at the different growth stages of tomato and was therefore used to apply the required amount of water to the crop on the agricultural field or research field 3 in Tatton Agricultural Farm located within Egerton University.

3.3 Effect of Deficit sub-surface drip irrigation and mulching on water productivity

Tomato water productivity was determined based on the yield per unit of water used. The water productivity based on the yield was evaluated by the water productivity function (Payero *et al.*, 2008). The water productivity based on the tomato yield was determined using Equation 3.2.

$$WP = \frac{Y_T}{I_W} \tag{3.2}$$

where:

WP = Water productivity (kg/m^3)

Y_T = Total yield (kg/m^2)

I_W = Irrigation water used (m^3/m^2)

To determine the total yield, tomato fruits were harvested at an interval of one week from the maturity period to the end of harvest period. The mass of tomatoes was measured using a digital

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Electronic Balance after every harvest and the readings recorded to determine the yields. The total mass was then determined at the end of the harvesting period and the total yield expressed in units of mass per unit area of crop field. The yield from each treatment was determined for estimation of the water productivity at every water level and analyzed at the differences in production levels.

The total irrigation water used was determined considering the water application levels in the different plots. The total irrigation water used in the different water levels was evaluated by Equation 3.3.

$$I_w = ETo \times K_c \times I_l = ET_c \times I_l \tag{3.3}$$

where:

I_w = Total irrigation water used (mm/day)

ETo = Reference evapotranspiration (mm/day)

K_c = crop coefficient (dimensionless)

I_l = Irrigation level (dimensionless)

ET_c = Crop evapotranspiration (mm/day)

The interactive impacts of both deficit sub – surface drip – irrigation and three mulching levels were used to evaluate the tomato water productivity because of their ability to save and optimize irrigation water. Grass mulch was used in this study because it was readily available and had no disposal problems. Deficit irrigation allows saving up to 20 – 40% irrigation water at yield reductions below 10%. The suggested deficit irrigation levels (I_l) are thus 100% ET_c, 90% ET_c, 80% ET_C, 70% ET_C and 60% ET_c (Kogler & Soffker, 2017). In this study three water levels within the range were used as recommended.

The water productivity at every water level was then determined and conclusions made on the treatment with the highest water productivity.

3.4 Modeling Tomato Water Productivity under Deficit Sub – Surface Drip Irrigation and Mulching using Aquacrop Model

The reference evapotranspiration and crop water requirement was estimated by the Aquacrop model with the input to the model being climatic, soil and crop parameters. The climatic parameters were obtained from Egerton weather station (Number: 9035092) during the period of the data collection. The soil parameters were determined during the study in the field and in

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the laboratory using different methods as described in the subsequent sub – sections 3.4.1 and 3.4.2. Crop parameters were also determined in the field during the study. These climatic, soil and crop parameters were used as input to Aquacrop model to simulate the reference evapotranspiration, crop water requirement and the water productivity of tomato. The Aquacrop input and output parameters are summarized in Table 3.4.

Table 3.4: The Aquacrop model input data and model output

Soil data	Climatic data	Crop data	Management practices	Model output
Ksat	Daily rainfall	Plant density	Mulching	Crop productivity
FC	Max and min air temp.	Effective rooting depth	Irrigation/rainfed	Crop water requirements
PWP	ET_O		Application method (drip)	Yield
Soil texture	Mean annual Co_2 concentration	Flowering and maturity time	DI strategies	Biomass
Θs				Harvest index

The input parameters to the model were determined in the field using different methods as discussed as follows.

3.4.1 Soil Data

Double ring infiltrometer technique was used to determine the soil hydraulic conductivity for the field experimental site (Pettyjohn, 2014). Volumetric water content at saturation of a soil example is equivalent to the porosity of the soil. Porosity was evaluated from Equation 3.4.

$$n = 1 - \frac{\rho_b}{\rho_p} \tag{3.4}$$

where:

n = Porosity (Ratio)

ρ_b = Bulk density (g/cm^3)

ρ_p = Particle density (g/cm^3)

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The bulk density of the soil in the study area was determined using the core method. A soil sample was oven dried at 105 ^{o}C after determining its volume (Grossman & Reinsch, 2002). The bulk density was then calculated using Equation 3.5.

$$\rho_b = \frac{m_s}{v_s} \tag{3.5}$$

where:

ρ_b = Bulk density (g/cm^3)

m_s = Mass of dry soil (g)

v_s = Volume of soil (cm^3)

The average particle density of soil was estimated to be 2.66 g/cm^3

Field capacity was determined in the laboratory using the pressure plate equipment for soil samples obtained from different plots (Cresswell *et al.*, 2008). The permanent wilting point of a soil sample is the point when there is no water available to plants and was determined in the laboratory by the pressure plate equipment at a tension of 15 bars (Romano & Santini, 2002). The soil texture analysis was done using Hydrometer method and soil samples from different plots were analyzed (Gee & Or, 2002).

3.4.2 Climatic and Crop Parameters

The climatic parameters in Table 3.4 were obtained from the Egerton University weather station (9035092) for the growing period of the tomato. The plant density of a specific bed of plants was depicted by the quantity of plants inside a given unit of area. This was completed by counting the quantity of plants per plot and dividing by the area of the plot. The fruit yield per hectare was determined by taking the mass of the fruits gathered weekly from the field using a digital electronic balance and adding to get the total yield. Biomass is the total above ground amount or mass of organisms in a given area or volume. This was accomplished by measuring the mass of the tomato crop per plot and dividing by the area of the plot. Harvest index is the mass of the harvested product as a percentage of the total mass of the tomato plant. This was accomplished by weighing the fruits collected in the field and dividing by the total weight of the yield in the field. Effective rooting depth is the depth of soil utilized by the principle body of the plant roots to get most of the stored moisture and plant nourishment under controlled water system. This was accomplished by uprooting and measuring the length of the crop. Flowering and maturity time was evaluated in terms days from planting date to flowering and maturity dates respectively. Green canopy cover is the over-the-ground part of a plant

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network or harvest, formed by the assortment of individual plant crowns. Crop germination is the time of the tomato germination in days and was estimated from the planting time to germination time.

3.5 Data Analysis

The tomato yields, biomass and the water productivity were subjected to performance evaluation to determine their goodness of fit to the observed values. The data obtained from the study after analysis was subjected to several components since it is recommended that a good model efficiency evaluation should have at least three important components. The components should include: one dimensional statistic, one absolute error index statistic and one graphical technique whereby when applied all together they form a set of model performance evaluation criteria which offsets the limitation of each other (Ouedraogo *et al.*, 2019). In this study the Analysis of Variance (ANOVA), Nash and Sutcliffe efficiency, Root Mean Square Error, Coefficient of Determination and graphical techniques were used to establish significant differences between the treatments. The components are described in the subsequent sub sections.

3.5.1 Nash and Sutcliffe Efficiency

The performance of the Aquacrop model was evaluated using the Nash and Sutcliffe Efficiency statistical parameter (Heng *et al*., 2009).

Nash and Sutcliffe Efficiency is a normalized statistic that determines the relative magnitude of the residual compared to the measured data variance. NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE of 1.0 being the maximal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values less than zero indicates that the mean observed value was a better predictor than the simulated value, which indicates unacceptable performance (Moriasi *et al.*, 2007). The Nash and Sutcliffe efficiency is expressed by Equation 3.6.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \overline{o_i})^2} \tag{3.6}$$

where:

S_i = simulated values

O_i = observed (measured) values

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$\bar{O}_i$ = mean value of O_i

n = number of observations

3.5.2 Root Mean Square Error

The root mean square error (RMSE) is a statistical indicator that measures the differences in average magnitude between simulations and observations. Good model performance is indicated by values that tend to zero while poor model performance by values that tend to positive infinity (Saad *et al.*, 2014).

The root mean square error (RMSE) is expressed by Equation 3.7

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{3.7}$$

where:

RMSE = Root mean square error

P_i = Predicted values

O_i = Observed values

n = Number of observations

3.5.3 Coefficient of Determination

The coefficient of determination (R^2) is the proportion of the variance in observed data obtained by the model. It ranges from 0 to 1, with values closer to 1 indicating a good model performance with values greater than 0.5 considered acceptable in predictions (Tran, 2018). It is expressed by Equation 3.8.

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)\left(P_i - \bar{P}\right)}{\sqrt{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 \sum_{i=1}^{n}\left(P_i - \bar{P}\right)^2}}\right]^2 \tag{3.8}$$

where:

O_i = Observed values

$\bar{O}$ = Mean value of O_i

P_i = Predicted values

$\bar{P}$ = Mean value of P_i

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3.6 Aquacrop Model Sensitivity Analysis

Sensitivity analysis is a measure used to quantify the effect of parameter uncertainty on general simulation (Crosetto *et al.*, 2000). One at a time sensitivity measure was applied in this study where the parameters were varied then the impact on the model output determined (Hamby, 1994). The parameters tested were the water level and mulch density to determine their impact on yield, biomass and the harvest index output.

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CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Estimation of Crop Water Requirement using FAO Penman-Monteith Equation

The results of crop water requirement of tomato for Njoro Sub - County as estimated using Equation 3.1 and the reference evapotranspiration and tomato crop coefficients based on FAO methods are described in the sections 4.1.1 and 4.1.2.

4.1.1 Estimation of Reference Evapotranspiration (ET_O)

The reference evapotranspiration (ET_O) was estimated using the FAO Penman Monteith method defined by Equation 2.6 and verified with the ET_O calculator estimated values. The ETo, maximum and minimum temperature and the rainfall distribution for the tomato growing period (January to May 2019) was as shown in Figure 4.1.

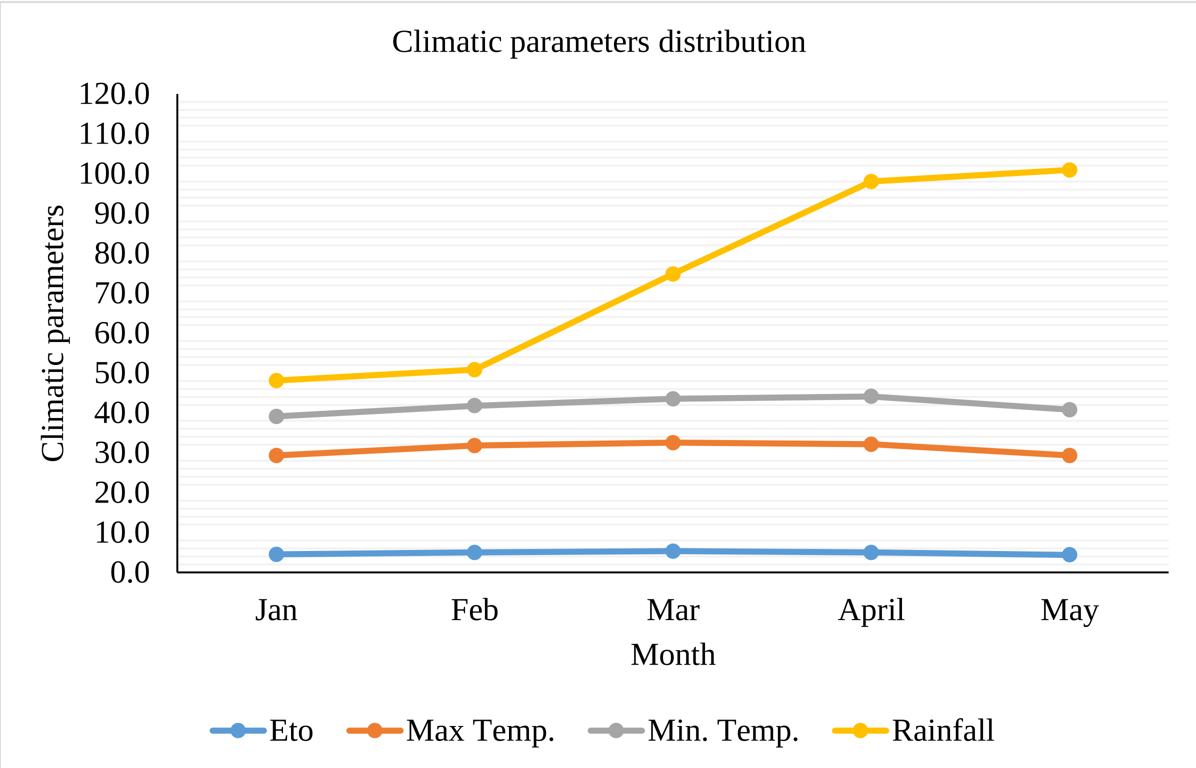

Figure 4.1: ET_O, maximum and minimum temperature and rainfall distribution for the growing period

From Figure 4.1 the highest reference evapotranspiration was observed in February while the lowest in the month of May. This is because of the low rainfall amount and the high temperatures experienced in the month of February than in the month of May where there was significant rainfall amount. The trend concurs with that of Maeda *et al.* (2011) who conducted

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a study in Taita Hills, Kenya, where the reference evapotranspiration was observed to reduce drastically from the month of February to May with the lowest values between the month of April and June. From Figure 4.1 it can be deduced that the irrigation application depth would decreased from February to May due to decreasing evapotranspiration.

The ten year average reference evapotranspiration estimated from the FAO Penman Monteith method was compared with those obtained from the Egerton University Department of Agricultural Engineering weather station data as shown in shown in Figure 4.2.

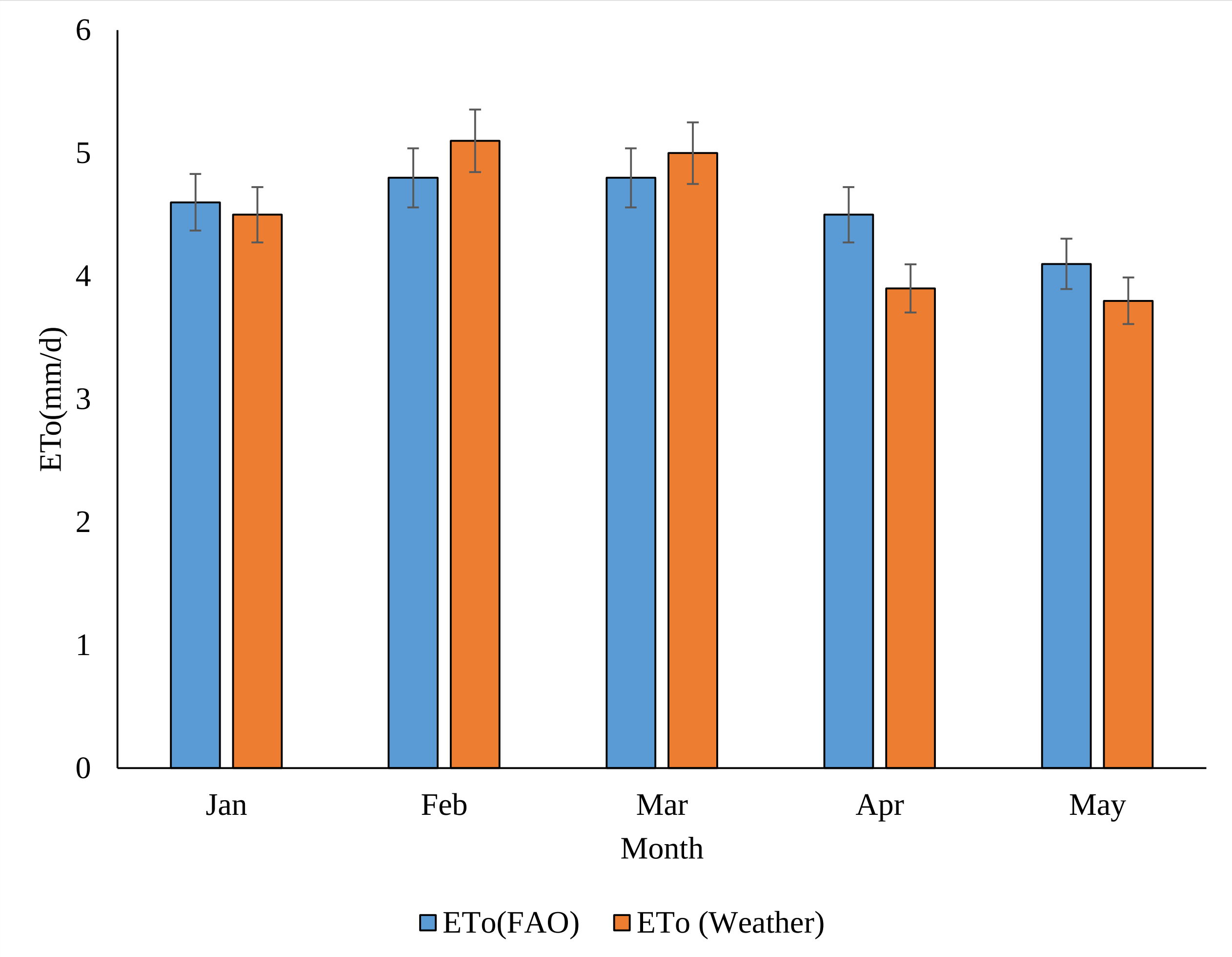

Figure 4. 2: Comparison of the ETo calculated using the FAO Penman Monteith method and the ETo from the weather station

From Figure 4.2 it can be deduced that there is no significant difference between the reference evapotranspiration estimated using the FAO Penman - Monteith method and the one obtained from the weather station except for the month of April where there was a significant difference. The variation may be due to the fault or inaccurate reading of the weather station equipment. This shows that the FAO Penman - Monteith method was able to accurately estimate the

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reference evapotranspiration. The results concur with those of Sentelhas *et al*. (2010) who carried a study in Southern Ontario, Canada and their results revealed that the FAO Penman Monteith estimates the reference evapotranspiration accurately. The reference evapotranspiration was highest in the months of February and March and lowest in the month of May. Similar results are also reported by Cai *et al.* (2007) who conducted a study in China where their ET_O results agreed well with the actual ET_O values and concluded that the FAO Penman - Monteith is an accurate method of estimating reference evapotranspiration. The study relates to those of Carvalho *et al.* (2013) who carried out a research in Minas Gerais State, Brazil where the authors stated that FAO Penman - Monteith method is a good standard method of estimating reference evapotranspiration.

4.1.2 Estimation of the Crop Water Requirement, ETc

Table 4.1 shows the growth stages and crop coefficients for tomato used in determining the crop water requirements according to FAO (Allen *et al.*, 1998a).

Table 4.1: Tomato crop growth periods and crop coefficients after transplanting

Stages	Initial	Development	Middle	Late
Days	30	40	40	25
K_c	0.45	0.75	1.15	0.9

The tomato water requirement for Njoro Sub – county from January to May growing period was calculated from the reference evapotranspiration and crop coefficients using Equation 3.1 and the results are presented in Table 4.2.

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Table 4.2: Tomato crop water requirement for the growing period

Days after transplanting (2019)	**ET_o (mm/d)**	**K_c**	**ET_C (mm/d)**	**Days**	**Total ET_c (mm)**	**Cumulative ET_C**
			Initial stage			
1 - 20	4.6	0.45	2.07	20	41.4	2.07
21 - 30	4.8	0.45	2.16	10	21.6	4.23
			Development stage			
31 - 48	4.8	0.75	3.60	18	64.8	7.83
49 - 70	4.8	0.75	3.60	22	79.2	11.43
			Middle stage			
71 - 79	4.8	1.15	5.52	9	49.7	16.95
80 – 109	4.5	1.15	5.20	30	155.3	22.15
110	4.1	1.15	4.70	1	4.7	26.85
			Late stage			
111 - 135	4.1	0.90	3.70	25	92.3	30.55
Total					**509**	

The crop water requirement ET_C and cumulative ET_C for the different growing periods are presented in Figure 4.3. The values in the graph are by the growing periods below.

Crop stages	1	2	3	4	5	6	7	8
Growing period (days)	0 - 20	21 - 30	31 - 48	49 - 70	71 – 79	80 - 109	110	111 - 135

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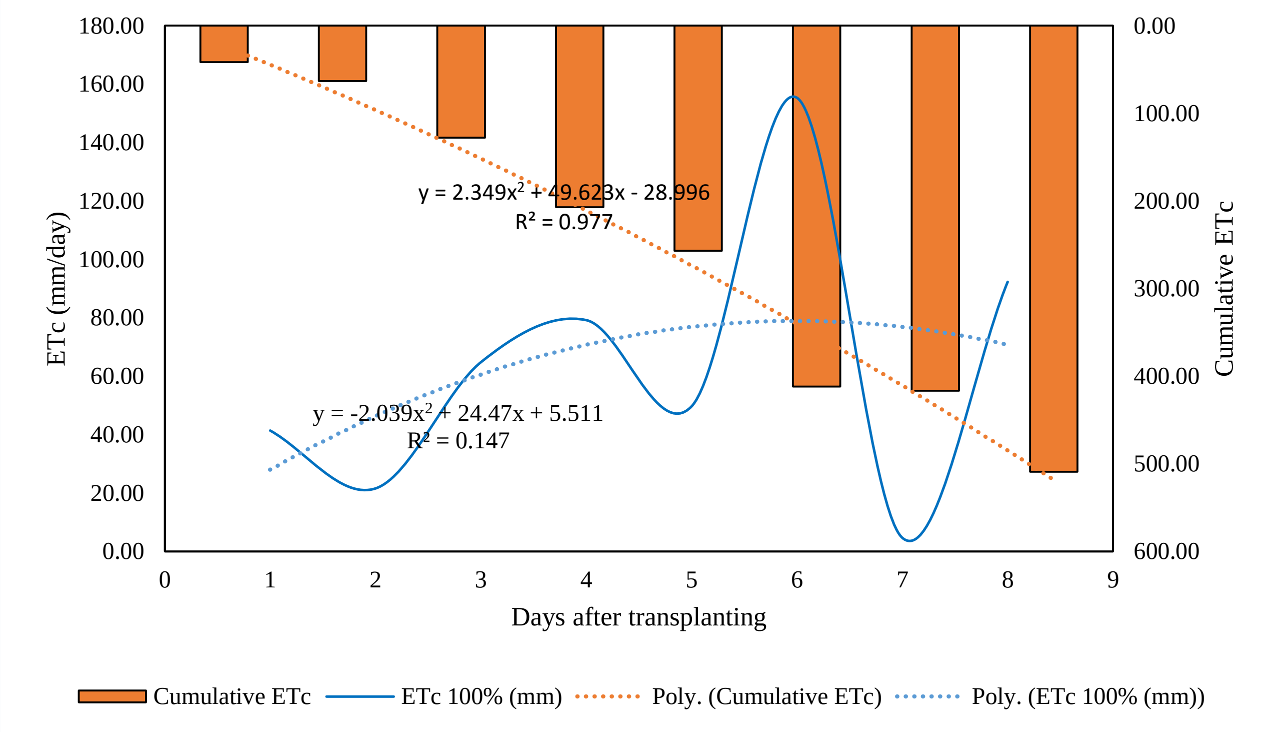

Figure 4.3: Tomato crop evapotranspiration rate

It can be seen from Figure 4.3 that the total water requirement for tomato crop in Njoro Sub - County is approximately 509 mm. The following predictive functions for the daily and total tomato crop evapotranspiration (ET_C) for Njoro Sub County were developed. For the daily crop evapotranspiration the regression Equation 4.1 was formulated.

$$y = -2.039x^2 + 24.47x + 5.511 \quad (4.1)$$

where:

y = Daily crop evapotranspiration (mm/day)

x = Day after transplanting (days)

The function developed for the cumulative evapotranspiration is shown by Equation 4.2.

$$y = 2.349x^2 + 49.623x - 28.996 \quad (4.2)$$

where:

y = Cumulative crop evapotranspiration (mm/day)

x = Day after transplanting (days)

From the estimated crop evapotranspiration, the actual amount of water applied in the field was determined using Equation 4.3.

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$$1mm = 1L/m^2 \tag{4.3}$$

where:

1 mm = Depth of water in millimeters

1 L/m^2 = volume of water in Litres

m = Metres

The total crop water requirement for tomato crop was estimated to be 509 mm at 100% ET_C. Using the relation in Equation 4.3, the actual amount of water applied to the field was 509 L/m^2. The total area under tomato crop was 144 m^2, therefore the total amount of water used during the entire growing season can be predicted as 20,736 litres or 20.74 m^3. An extra 10% of the total amount water can be added to account for the water losses during distribution. The total quantity of water applied could be 22.81 m^3. The functions will therefore enable tomato farmers in Njoro Sub - County to plan for quantity of water required for the entire growing period.

The tomato crop water requirement for the different growth stages are as presented in Figure 4.4.

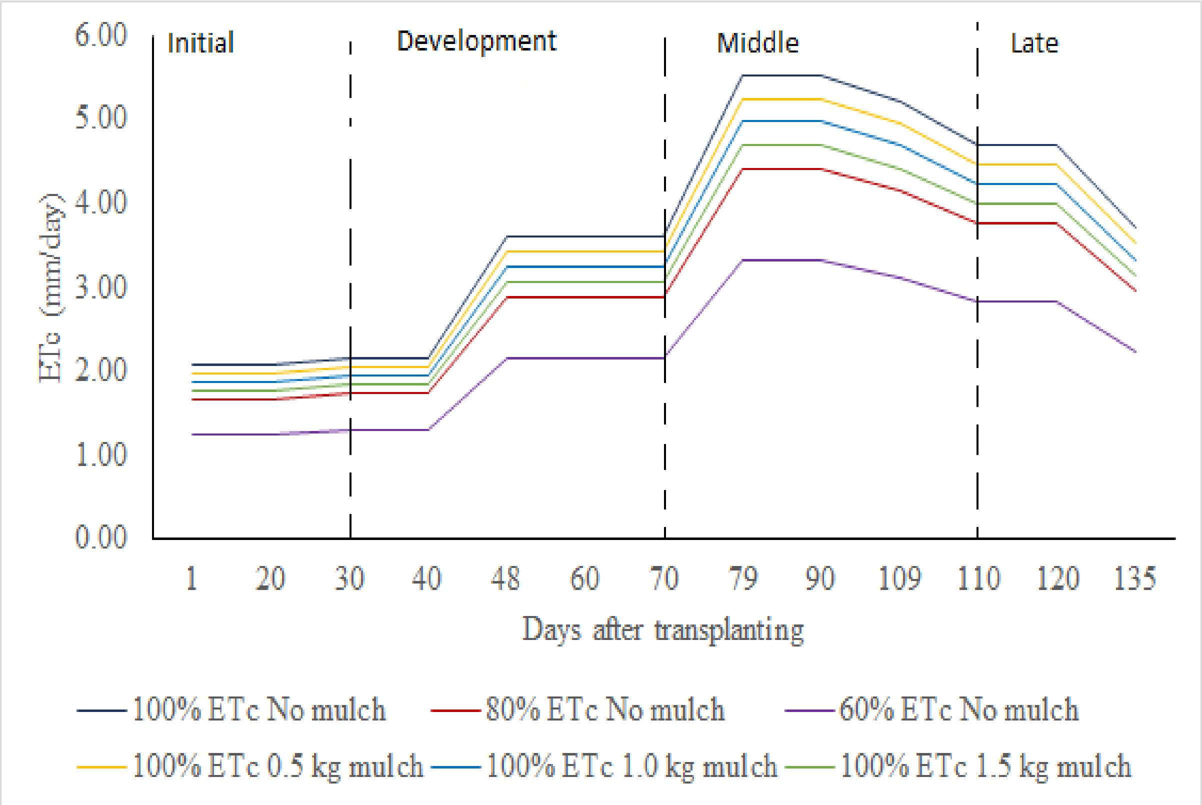

Figure 4.4: Tomato crop water requirements for the different growth stages

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From Figure 4.4 it can be seen that the highest tomato water requirement is at the middle stage. This is because transpiration rate is higher during the flowering and fruit formation periods which occurs at the middle stage. The total tomato water requirement for the entire growing period is shown in Figure 4.5.

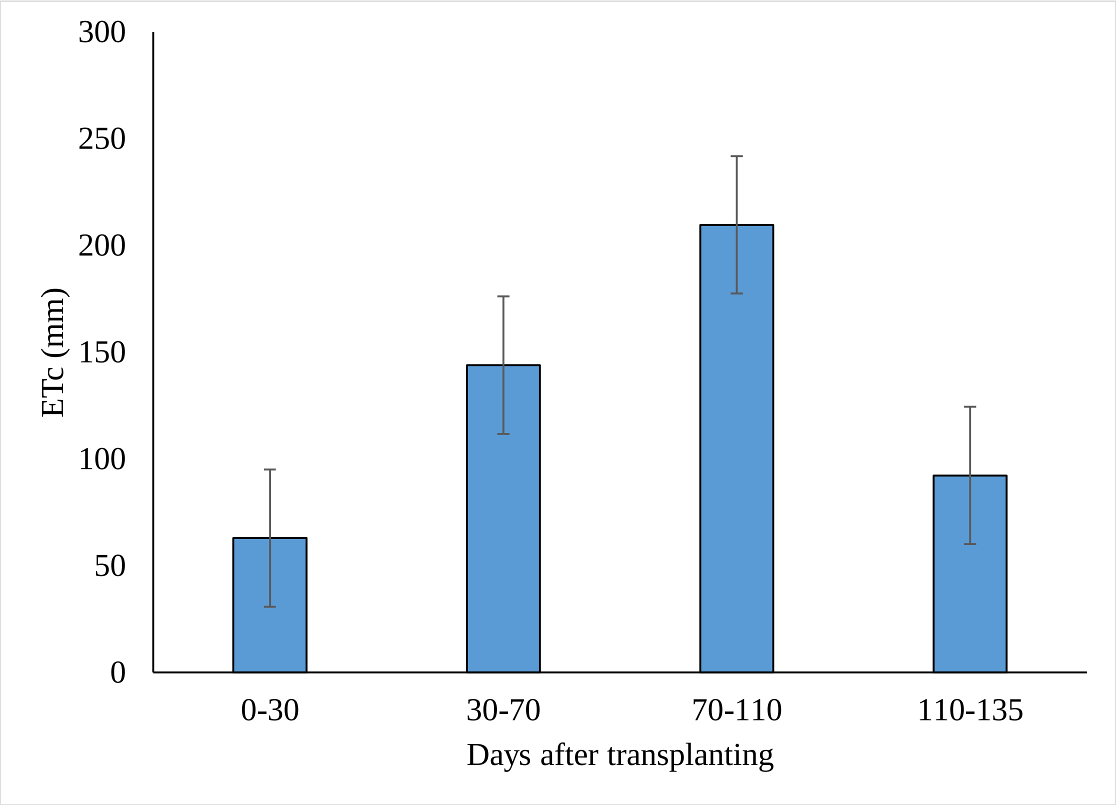

Figure 4.5: Graph of crop evapotranspiration (100 % ET_C) against days after transplanting

The four main stages of tomato described are initial, development, middle and late. From Figures 4.3 and 4.5 the total depth of water applied during the entire tomato growing period was 509 mm for 100% ET_C with the highest crop water requirement period being the middle stage. The results concur with those of Savva and Frenken (2002a) where the total tomato water requirement ranges from 400 mm to 600 mm depending on the climate. Also a study carried out on water productivity of tomato crop in Kibwezi Kenya estimated the total crop water requirement to be 474 mm which is almost similar to the one estimated in this study (Kinyua, 2009). The depth of water applied to the 100% ET_c, 80% ET_c and 60% ET_c treatments were 509 mm, 407 mm and 305mm respectively. The average tomato crop water requirement at 100 % ET_C for Njoro sub – county was thus estimated to be 2.10, 3.60, 5.24 and 3.69 mm/day for the early, development, middle and late stages respectively.

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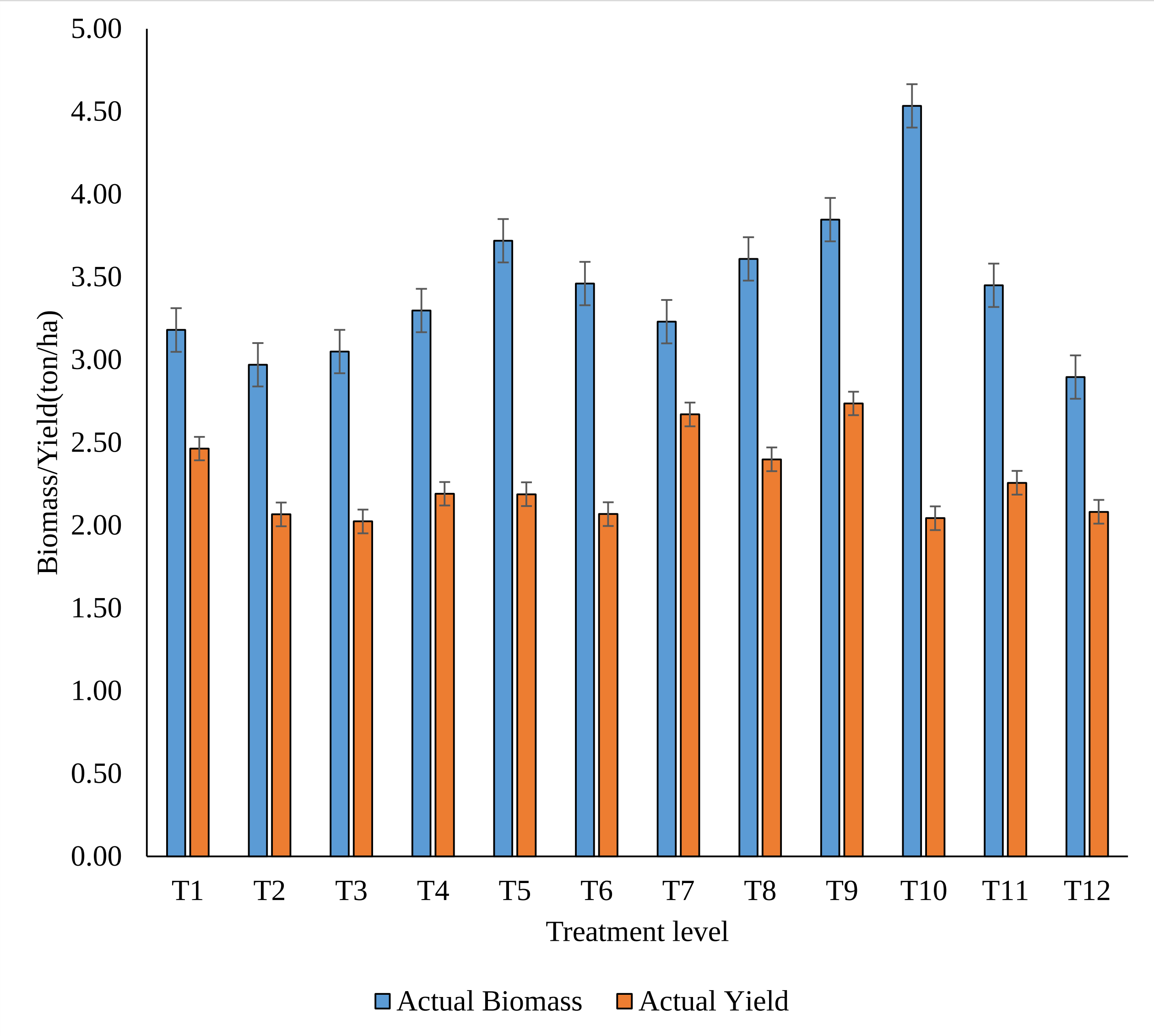
4.2 Effect of Deficit Sub-Surface Drip Irrigation and Mulching on Water Productivity

Tomato water productivity was estimated from the tomato yields and the total water used. The tomato yields/biomass obtained from the different treatments in the field was as shown in Figure 4.6.



where: Treatments T1 to T12 are described in Table 3.1

Figure 4.6: Biomass/Dry yield against treatment levels

It can be seen from Figure 4.6 that the highest and the lowest tomato dry yields were obtained at treatments T9 (60 % ET_c with 1.0 kg/m^2 of mulch) and T3 (60 % ET_c with no mulch) respectively. The yield at treatment T9 (60% ET_c with 1.0 kg/m^2 of mulch) was higher than that at treatment T1 (100 % ET_c with no mulch by 11.4%. This shows the positive impact of mulching, which was effective in reducing evapotranspiration component and thus increasing

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yield per volume of water used. The yield at treatment T4 was lower than that in treatment T1 despite the use of 0.5 kg/m^2 of grass mulch in T4 and this may be attributed to the uneven distribution of the mulch in the plots. This may also be attributed to the scarcity and scattering of the grass mulch in the plots. Olaniyi and Atanda (2017) carried out a study in Ogbomoso and Mokwa, Nigeria and their results revealed the highest tomato yields at grass mulch application rate of 1.5 kg/m^2, while in this study, under the same conditions, the highest yield was obtained at 1.0 kg/m^2. This may be attributed to the sub - surface drip irrigation incorporated in this study unlike in their study where surface drip irrigation was practiced or probably it was due to the variations in the weather conditions in the different study areas, unlike in this study where a controlled environment was used. Sub – surface drip irrigation was able to reduce evapotranspiration significantly. From Figure 4.6, the highest and the lowest biomass production was at treatments 100 % $ET_{C,}$ 1.5 kg/m^2 of mulch and 60 % $ET_{C,}$ 0.5 kg/m^2 of mulch respectively. It can be seen that mulching has the potential of increasing the biomass production significantly.

Tomato crop evapotranspiration and water productivity for the different treatments was estimated using Equations 3.1 and 3.2 respectively and the results are as presented in Figures 4.7 and 4.8 respectively.

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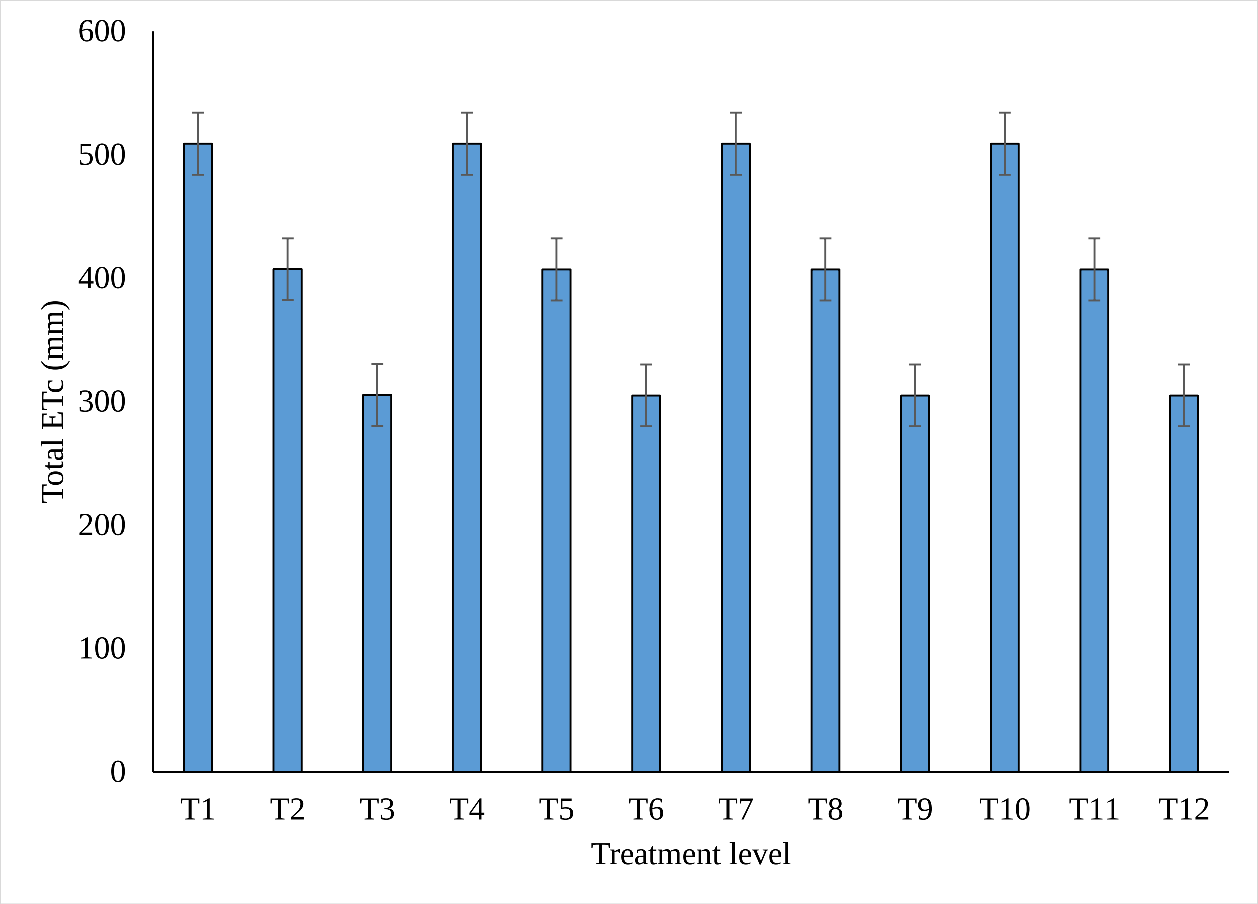

Figure 4.7: Crop evapotranspiration (ET_C) against treatment levels

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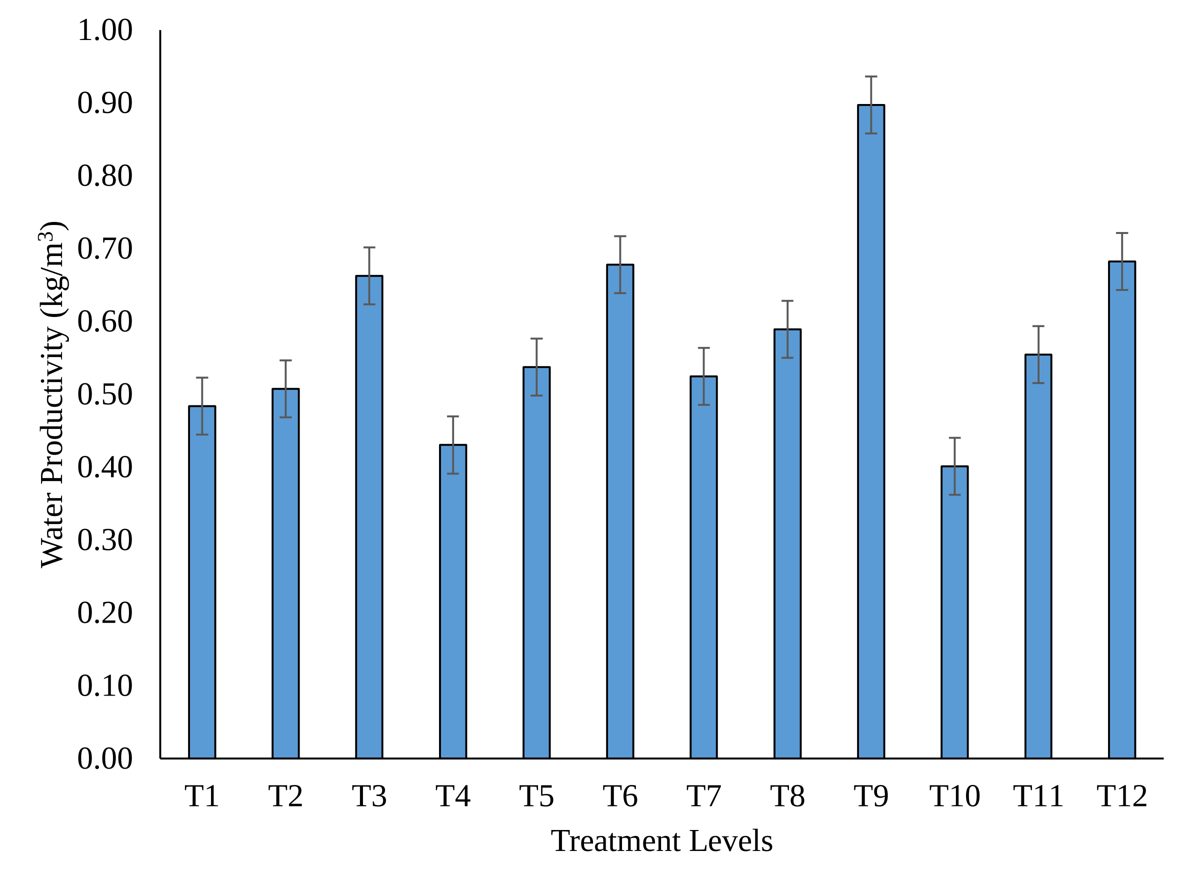

Figure 4.8: Water productivity of tomato crop against treatment levels

It can be seen from Figure 4.8 that the highest water productivity was observed at treatment T9 (60 % ET_C and 1 kg/m^2 of grass mulch) while the lowest was observed at treatment T10 (100 % ET_C and 1.5 kg/m^2 of grass mulch). This concurs with the results of Zhang *et al.* (2017) who conducted a study at Hitao Irrigation District, Inner Mongolia, China where the authors observed a higher processing tomato water productivity at 60 % ET_C irrigation level. Luvai *et al.* (2014) carried out a study in Kitui county, Kenya and their results showed the highest water productivity at 80 % ET_C, contrary to the highest water productivity at 60 % ET_C in the present study. This is because of the reduced evapotranspiration as a result of sub – surface drip irrigation and mulching. The study by Amare *et al*. (2017) carried out in Amhara Regional State, Ethiopia revealed the highest water productivity at 80% ET_C with sugar cane mulch while in the present study the highest water productivity was obtained at 60% ET_C with grass mulch. This shows that grass mulch, which is a readily available material has the potential of saving up to 10% of irrigation water when compared to sugar cane mulch which is not a readily available material in most parts of Kenya.

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4.3 Modeling Tomato Water Productivity

The input files to the Aquacrop model were soil, crop, climate, irrigation and field management as described in Section 4.3.1 to Section 4.3.3. The calibrated files were used as input to the Aquacrop model.

4.3.1 Soil Files

The soil data created for the soil files were collected from the experimental site and the results are presented in Table 4.3. The soil analysis was carried out at the Department of Agricultural Engineering, Soil Laboratory and the Department of Crops, Horticulture and Soil laboratory.

Table 4.3: Soil hydraulic properties

Bulk density (g/cm^3)	Volumetric water content at saturation (%)	Texture analysis				Hydraulic conductivity (m/day)	Field capacity (%)	Permanent wilting point (%)	Soil salinity (dS/m)
		% sand	% clay	% silt	Textural class				
1.34	61.00	29.80	28.20	42.0	Sandy clay loam	11.17	30.7	15.9	1.25

From Table 4.3 the textural class of the soil in the study area was classified as sandy clay loam and salinity of 1.25 dS/m. The other soil hydraulic parameters are presented in Table 4.3. The calibrated soil files were used as input to run the model.

4.3.2 Crop Files

The tomato crop data were collected during the growing period from the experimental site at Tatton Agriculture Park, Egerton University and the results are shown in Table 4.4.

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Table 4.4: Crop data of tomato during the growing period

Treatment / crop data	Dry Yield (ton/ha)	Biomass (ton/ha)	Green canopy cover (%)	Harvest index	Effective rooting depth (m)	Flowering time (days)	Maturity time (days)
T1	2.463	3.18	0.90	0.57	40	30	75
T2	2.066	2.97	0.83	0.60	45	30	75
T3	2.024	3.05	0.80	0.74	35	30	75
T4	2.191	3.30	0.77	0.58	35	30	75
T5	2.188	3.72	0.85	0.79	40	30	75
T6	2.068	3.46	0.85	0.66	30	30	75
T7	2.670	3.23	0.82	0.58	37	30	75
T8	2.398	3.61	0.88	0.65	73	30	75
T9	2.736	3.85	0.77	0.74	65	30	75
T10	2.043	4.53	0.93	0.66	45	30	75
T11	2.257	3.45	0.92	0.63	35	30	75
T12	2.082	2.90	0.92	0.63	45	30	75

The tomato crop was transplanted on 12th January 2019 with the maturity period being 75 days and the entire growing period being 135 days. The plant density of the tomato crop was 2.25 plants/m^2 and the canopy size of the transplanted seedling was 5 cm^2/plant. The initial canopy cover was 0.34% while the maximum canopy cover for the different treatments was as presented in Table 4.4. The averages of the other crop data obtained during the tomato growing period after transplanting to the experimental site for the calibration of the crop file are as shown in Table 4.4. The calibrated crop files created were used as input to run the Aquacrop model.

4.3.3 Climate Files

The climate files of the experimental site for the growing period of the tomatoes are presented in Table 4.5 and included rainfall, maximum temperature, minimum temperature and reference evapotranspiration.

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Table 4.5: The climatic parameters for the 2019 growing season

Month/Climatic parameter	January	February	March	April	May
Maximum Temperature (^{O}C)	24.8	26.8	27.2	27.1	24.9
Minimum Temperature (^{O}C)	9.8	10.0	11.0	12.0	11.5
ET_O (mm)	4.5	5.0	5.3	5.0	4.4

The climatic parameters in Table 4.5 were collected from the Department of Agricultural Engineering, Egerton University weather station for the tomato growing period that was January to May 2019. The climatic parameters formed the calibrated climate files and were used as input to run the Aquacrop model.

4.3.4 Irrigation files

The irrigation file calibrated composed of the irrigation method which was sub – surface drip and the irrigation events which included the irrigation dates and the amount of irrigation water. The calibrated irrigation file was used as input to run the Aquacrop model.

4.3.5 Field Management Files

The field management practices calibrated include the soil fertility which is non limiting, mulches which varied in the different treatments as 0.0, 0.5, 1.0 and 1.5 kg/m^2. The relative cover of the weeds was maintained at 0%. The calibrated field management file was then used as input to run the Aquacrop model.

4.3.6 Simulation of Tomato Water Productivity Using Aquacrop Model

The crop data, climatic parameters, soil data and the management practices were input to the Aquacrop model to simulate the tomato water productivity during the growing period. The actual versus simulated yield are as shown in the Figure 4.9.

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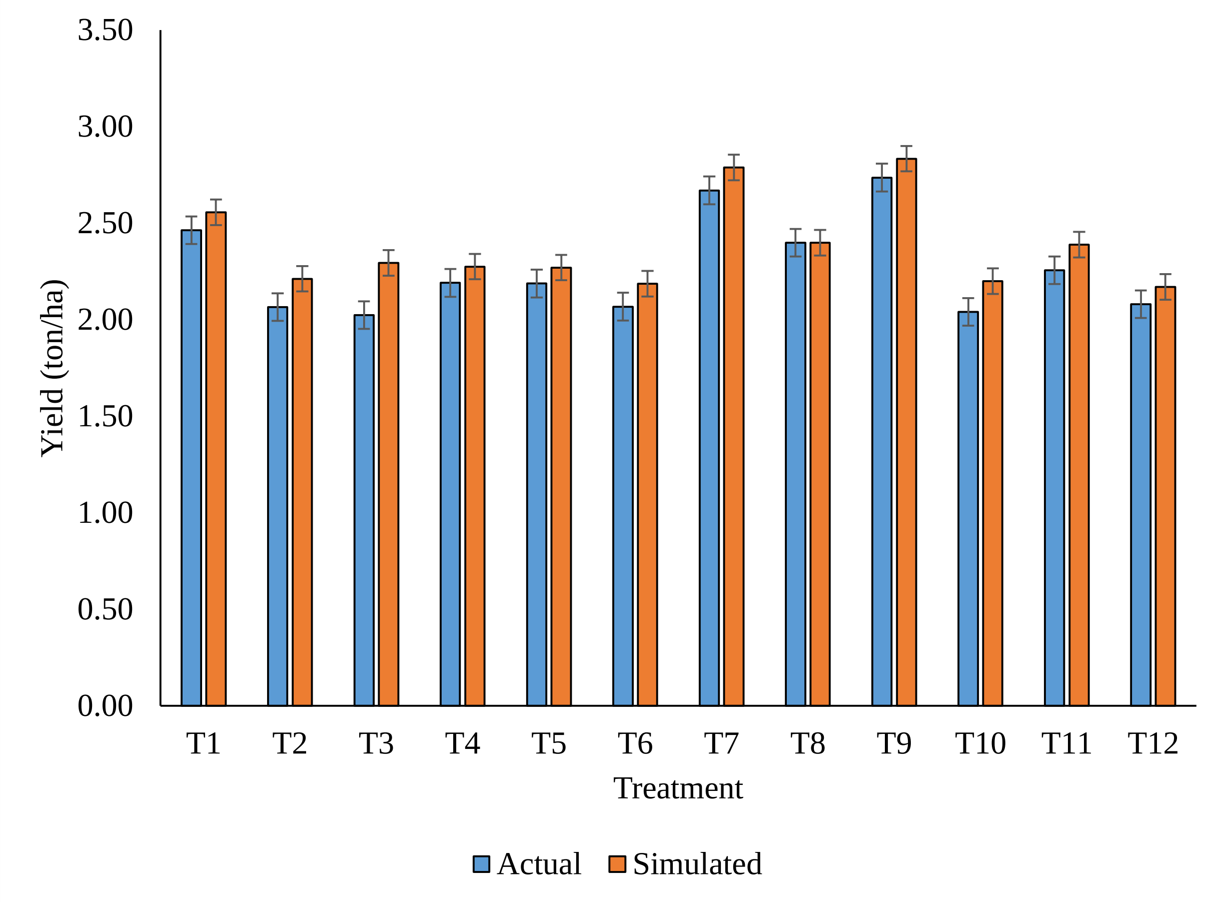

Figure 4.9: Actual versus simulated dry yield

It can be seen that Aquacrop model was able to accurately simulate yield response to water as indicated by the graph presented in Figure 4.9. The performance of the model was found to be good as described by the Nash and Sutcliffe efficiency (NSE) of 0.636, Root mean square error (RMSE) of 0.130 and Coefficient of correlation (R^2) of 0.937. The results concur with those of Algharibi *et al.* (2013) who conducted a research in Muscat, Oman where the performance of the Aquacrop model to simulate yield response to water was found to be good as determined by the NSE of 0.77, and R^2 of 0.83. The results also concurs with those of Paredes *et al.* (2015) who conducted a research on soybean in North China Plain and revealed a better Aquacrop model performance with an R^2 value of 0.83. Jin *et al.* (2014) conducted a study in North China Plain and revealed a consistency in the measured yield to the Aquacrop model simulated yield with an R^2 value of 0.93.

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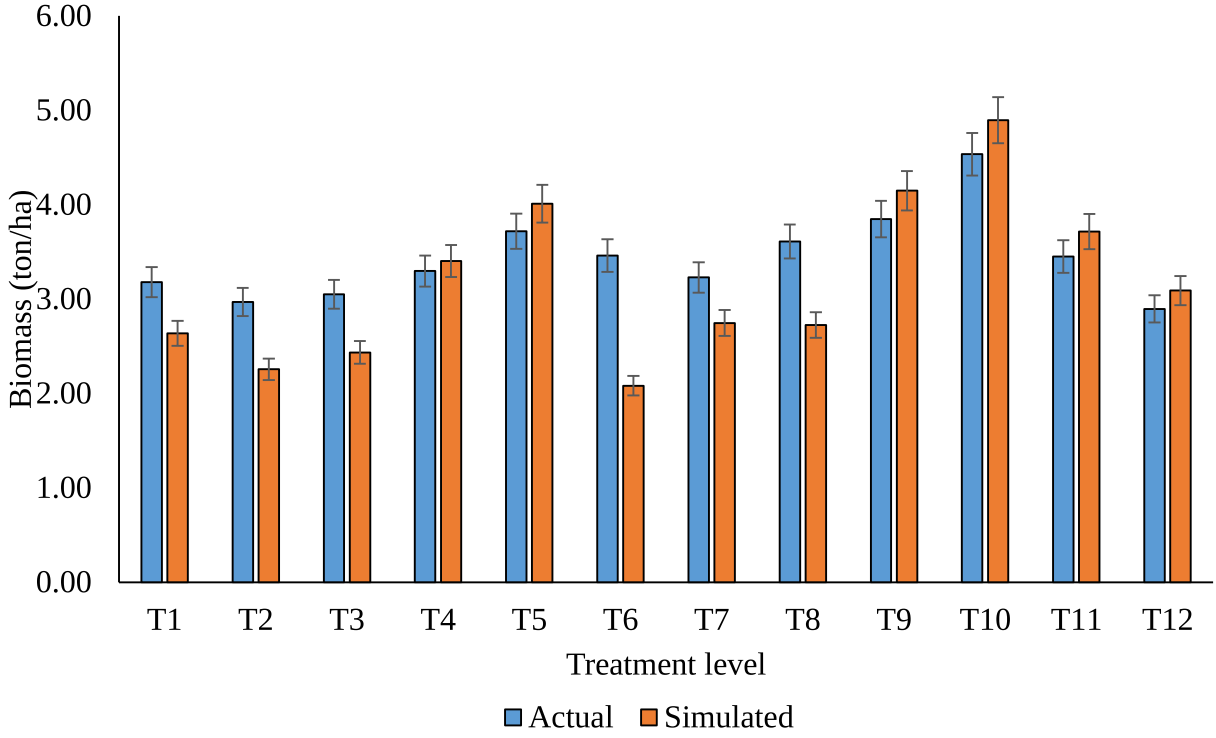

Figure 4.10: Actual versus simulated biomass

From Figure 4.10 it can be seen that there was no significant difference between the actual and the simulated biomass in treatments T4, T5, T9, T10, T11 and T12 but there was a significant difference in treatments T1, T2, T3, T6, T7 and T8 as indicated by the error bars. The performance of the model was found to be fair as described by the Nash and Sutcliffe efficiency (NSE) of 0.16, Root mean square error (RMSE) of 0.60 and Coefficient of correlation (R^2) of 0.51. This goes in hand with the results of Abedinpour *et al.* (2012) who conducted a study in New Delhi where they found fair Aquacrop model performance in simulating biomass of tomato crop with a RMSE of 0.42 and R^2 of 0.91. The results also concur with those of Pawar *et al.* (2017) who carried out a research in India where the model was able to simulate biomass with a NSE of 0.96. A study by Lievens (2014) carried out in North Eastern Thailand revealed that Aquacrop model was able to relate fairly well the simulated to the actual biomass of sweet corn with a root mean square error (RMSE) of 0.56.

The actual and the simulated tomato water productivity using the Aquacrop model were as shown in Figure 4.11.

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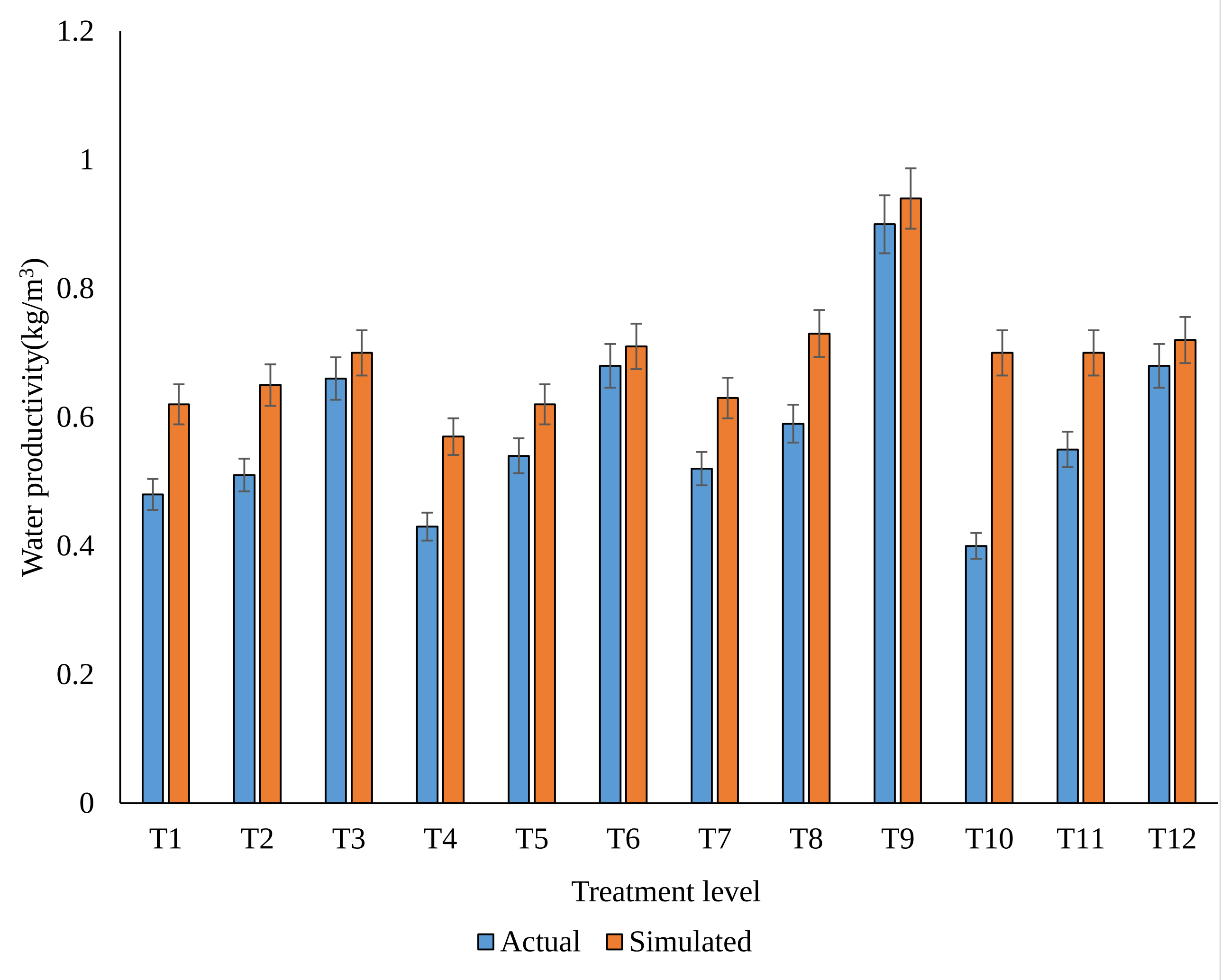

Figure 4.11: Actual versus simulated tomato water productivity

From Figure 4.11 it can be deduced that Aquacrop model was able to simulate tomato water productivity poorly. It can be seen that there was no difference between the actual and the simulate water productivity for treatments T3, T6, T9 and T12 while there was a significant difference in treatments T1, T2, T4, T5, T7, T8, T10 and T11 as indicated by the error bars. The performance of the model was found to be poor as described by the Nash and Sutcliffe efficiency (NSE) of 0.00, Root mean square error (RMSE) of 0.04 and Coefficient of correlation (R^2) of 0.72. The results contradict with a study conducted in Northern Serbia where they found good Aquacrop model performance in simulating water productivity with a root mean square error of 0.88 (Stricevic *et al.*, 2011). The results also contrsdict with those of Geerts *et al.* (2009) who carried out a study in Central Bolivian Altiplano on Quinoa crop where the simulated water productivity related well to the field measurements with a Nash and Sutcliffe efficiency of 0.82.

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4.4 Aquacrop Model Sensitivity Analysis

The water level parameter sensitivity to Aquacrop model output was determined and is described by Figure 4.12.

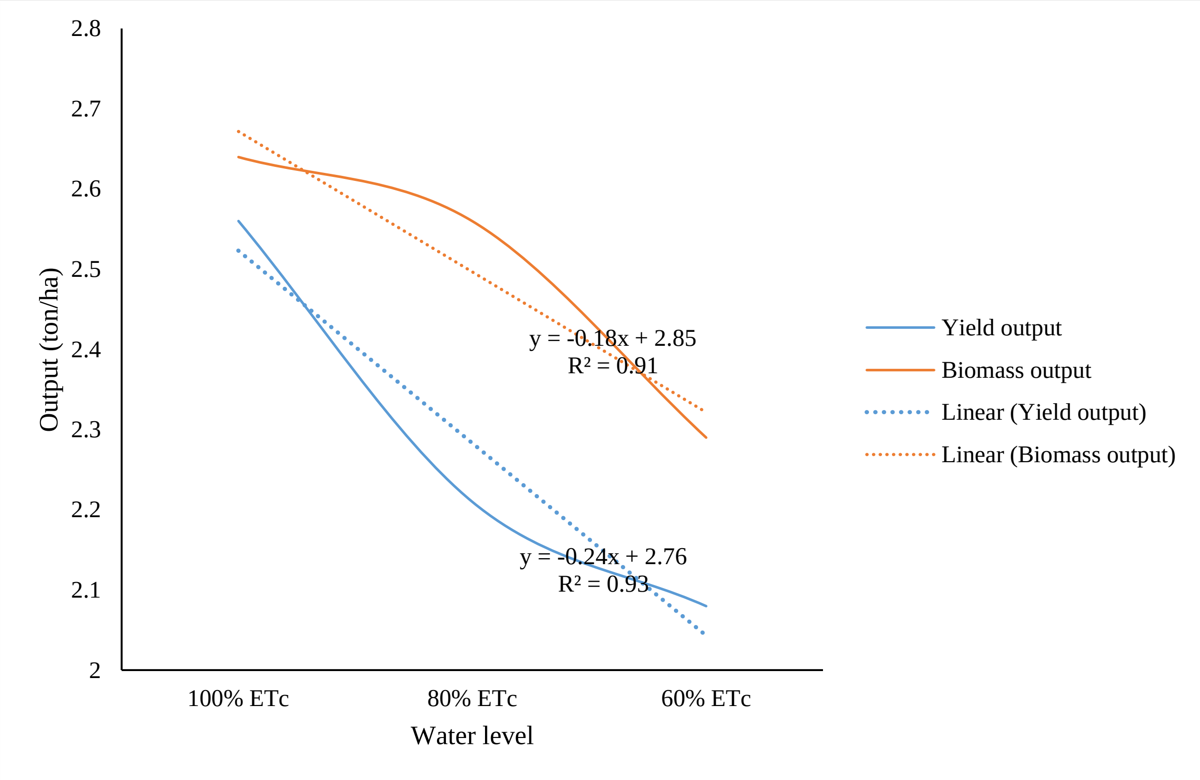

Figure 4.12: Sensitivity of water level to Aquacrop tomato yield

According to Figure 4.12, the most sensitive variable to the water level input was yield followed by the biomass as described by the gradient of the graphs. The magnitude of the gradient for the yield curve is 0.24 which is higher than 0.18 for the biomass. The higher the magnitude of the gradient in the equation/graph the higher the sensitivity. The findings in this research are not in conformity with what was given by Jin *et al.* (2018) who conducted a study in China and found that the biomass production by Aquacrop model is more sensitive to the water. The results concur with those of Lievens (2014) who carried out a study in North Eastern Thailand that the yield output is less sensitive to the water level as compared to biomass output. Similarly, the results of Martini (2018) who carried out a research in South of Brazil revealed that both the biomass and yield output are sensitive to the water levels.

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CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions were drawn from the study;

i. The total tomato crop evapotranspiration under full irrigation for Njoro Sub County was estimated to be 509 mm with the allocations for the initial, development, middle and late stages as 63, 144, 209.7 and 92.3 mm respectively.

ii. Yield is not directly proportional to biomass produced and from the results therefore the best combination of management practices that increases the water productivity of tomato crop in Njoro Sub County is the application of 60% ET_C of water in combination to 1 kg/m^2 of grass mulch.

iii. Aquacrop model was not able to simulate yield and biomass of tomato crop not relating well to the field measurements as described by the Nash and Sutcliffe Efficiency, Root Mean Square Error and the Coefficient of Correlation.

5.2 Recommendations

The following recommendations were suggested for further studies;

i. The study to be carried out in other sub counties to determine the effect of rainfall patterns within the year and to also estimate the reference evapotranspiration for the region thus enabling the estimation of the crop evapotranspiration.

ii. The study to be elaborated to include water levels lower than 60 % ET_C that is 50 % ET_C and 40% ET_C to determine their effects on tomato water productivity.

iii. Further studies to be carried out on other crops at Njoro Sub County to determine the interactive effect of deficit sub – surface drip irrigation and other mulching systems on their water productivity using Aquacrop model.

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APPENDICES

APPENDICES A: PLATES

Appendix A.1: Sprinkler irrigation system (Ahaneku, 2010)

Appendix A.2: Furrow irrigation system layout (Akay, 2015)

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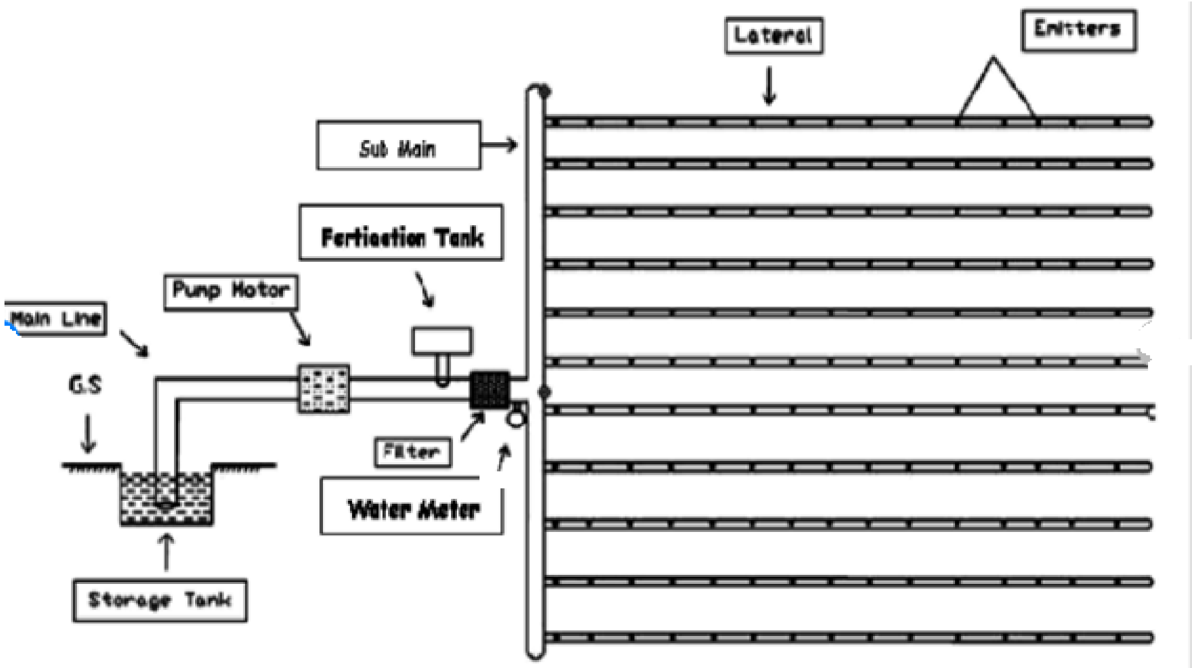
Appendix A.3: Drip irrigation layout (Keshtgar, 2012)



Appendix A.4: Drip irrigation set up

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Appendix A.5: Dripline layout

Appendix A.6: Mulch application

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Appendix A.5: Distribution tanks set up

Appendix A.8: Two weeks after transplanting

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Appendix A.9: One month after transplanting

Appendix A.10: Two months after transplanting

`

Appendix A.11: Three months after transplanting

Appendix A.12: Yield measurements

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Appendix A.13: Soil sampling

Appendix A.14: Sample of harvested tomatoes

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Appendix A.15: Dry yield and biomass measurements

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Appendix A.16: Agronomic parameters carried out

Tomatoes were transplanted on 12th January 2019

Chemicals applied

Karate 0.17g/m^2 – was applied immediately after planting to prevent the crops from cutworms.

Actara 0.06g/m^2 – was applied after every two weeks after transplanting to prevent the crop from whiteflies.

Foliar – was applied on 3rd February 2019 to facilitate root development and flowering.

Ridomil was applied after every two weeks to prevent the tomato crop from early and late blight

Weeding was done after every two weeks by uprooting and use of a scrapper

Tomato staking was done one month after transplanting to provide support to the plants

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APPENDICES B: TABLES

Appendix B.1: Mean daily percentage of annual day time hours for various latitudes (Ghosh & Biswas, 2016)

Latitude	North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	South	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60°		.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
55		.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
50		.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
45		.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
40		.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35		.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30		.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25		.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20		.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15		.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10		.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5		.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0		.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

Appendix B.2: Crop coefficients for specific crops (Allen *et al.*, 1998)

CROP	**Crop Development Stages**					**Total**
	Initial	**Crop development**	**Mid-season**	**Late season**	**At harvest**	**growing period**
Banana						
tropical	0.4-0.5	0.7-0.85	1.0-1.1	0.9-1.0	0.75-0.85	0.7-0.8
subtropical	0.5-0.65	0.8-0.9	1.0-1.2	1.0-1.15	1.0-1.15	0.85-0.95
Bean						
green	0.3-0.4	0.65-0.75	0.95-1.05	0.9-0.95	0.85-0.95	0.85-0.9
dry	0.4	0.7-0.8	1.05-12	0.65-0.75	0.25-0.3	0.7-0.8
Cabbage	0.4-0.5	0.7-0.8	0.95-1.1	0.9-1.0	0.8-0.95	0.7-0.8
Cotton	0.4-0.4	0.7-0.8	1.05-125	0.8-0.9	0.65-0.7	0.8-0.9

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Grape	0.35-0.55	0.6-0.8	0.7-0.9	0.6-0.8	0.55-0.7	0.55-0.75
Groundout	0.4-0.5	0.7-0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Maize						
sweet	0.3-0.5	0.7-0.9	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
grain	0.3-0.5	0.7-0.85	1.05-1.2	0.8-0.95	0.55-0.6	0.75-0.9
Onion						
dry	0.4-0.6	0.7-0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8-0.9
green	0.4-0.6	0.6-0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea, fresh	0.4-0.5	0.7-0.85	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
Pepper, fresh	0.3-0.4	0.6-0.75	0.95-1.1	0.85-1.0	0.8-0.9	0.7-0.8
Potato	0.4-0.5	0.7-0.8	1.05-1.2	0.85-0.95	0.7-0.75	0.75-0.9
Rice	1.1-1.15	1.1-1.5	1.1-1.3	0.95-1.05	0.95-1.05	1.05-12
Safflower	0.3-0.4	0.7-0.8	0.7-0.8	0.65-0.7	0.2-0.25	0.65-0.7
Sorghum	0.3-0.4	0.7-0.8	1.0-1.15	0.75-0.8	0.5-0.55	0.75-0.85
Soybean	0.3-0.4	0.7-0.8	1.0-1.15	0.7-0.8	0.4-0.5	0.75-0.9
Sugarbeet	0.4-0.5	0.75-0.85	1.05-1.2	0.9-1.0	0.6-0.7	0.8-0.9
Sugarcane	0.4-0.5	0.7-1.0	0.7-1.0	0.75-0.8	0.5-0.6	0.85-1.05
Sunflower	0.3-0.4	0.7-0.8	1.05-1.2	0.7-0.8	0.7-0.8	0.75-0.85
Tobacco	0.3-0.4	0.7-0.8	1.0-1.2	0.9-1.0	0.75-0.85	0.85-0.95
Tomato	0.4-0.5	0.7-0.8	1.05-1.25	0.8-0.95	0.6-0.65	0.75-0.9
Waterrnelon	0.4-0.5	0.7-0.8	0.95-1.05	0.8-0.9	0.65-0.75	0.75-0.85
Wheat	0.3-0.4	0.7-0.8	1.05-1.2	0.65-0.75	0.2-0.25	0.8-0.9
Alfalfa	0.3-0.4				1.05-1.2	0.85-1.05
Citrus						
clean weeding						0.65-0.75

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no weed control						0.85-0.9
Olive						0.4-0.6

Appendix B.3: Texture analysis

Sample no.	% sand	% clay	% silt
1	30.5	27.8	41.0
2	29.1	28.5	43.0

Appendix B.4: Bulk density

Sample no.	**Bulk density (g/cm^3)**
1	1.30
2	1.38

Appendix B.5: Anova for water productivity

SoV	**df**	**SS**	**MS**	**Fcal**	**Fcrit**
Total	36	567886			
Factor A	4	45866.4	15288.8	3.79	3.01
Factor B	3	209223	104611	17.31	3.4
Interaction AB	6	22732.4	3788.73	1.88	2.51
Error	24	290065	12086		

SoV = Source of variation Factor A = Mulching density   Factor B = Water level

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Appendix B.6: Water productivity of tomato crop

Treatment	Total ETc(mm)	Yd (kg/ha)	Yd (kg/m^2)	WP (kg/m^3)
100% No mulch	509	2463.333	0.246	0.484
80% No mulch	407	2065.958	0.207	0.507
60% No mulch	305	2023.583	0.202	0.663
100 % 0.5kg	509	2190.792	0.219	0.430
80 %0.5kg	407	2187.542	0.219	0.537
60% 0.5kg	305	2067.750	0.207	0.678
100% 1kg	509	2669.917	0.267	0.525
80% 1kg	407	2398.333	0.240	0.589
60% 1kg	305	2736.208	0.274	0.897
100% 1.5kg	509	2042.750	0.204	0.401
80% 1.5kg	407	2256.500	0.226	0.554
60 % 1.5kg	305	2081.500	0.208	0.682

Appendix B.7: Statistical analysis results

Parameter	NSE	RMSE	R^2
Yield	0.64	0.13	0.94
Biomass	0.16	0.60	0.50
Water productivity	0.00	0.04	0.72

`

Appendix B.8: Actual versus simulated dry yield

Treatment	100% No mulch	80% No mulch	60% No mulch	100% 0.5kg	80% 0.5kg	60% 0.5kg	100% 1kg	80% 1kg	60% 1kg	100% 1.5kg	80% 1.5kg	60% 1.5kg
Actual	2.463	2.066	2.024	2.191	2.188	2.068	2.670	2.398	2.736	2.043	2.257	2.082
Simulated	2.556	2.212	2.294	2.275	2.27	2.186	2.788	2.399	2.834	2.193	2.389	2.169

Appendix B.9: Actual versus simulated biomass

Treatment	100% No mulch	80% No mulch	60% No mulch	100% 0.5kg	80% 0.5kg	60% 0.5kg	100% 1kg	80% 1kg	60% 1kg	100% 1.5kg	80% 1.5kg	60% 1.5kg
Actual	3.18	2.97	3.05	3.30	3.72	3.46	3.23	3.61	3.85	4.53	3.45	2.90
Simulated	2.64	2.26	2.44	3.40	4.01	2.08	2.75	2.73	4.15	4.90	3.72	3.09

Appendix B.10: Actual versus simulated water productivity (kg/m^3)

Treatment	100% No mulch	80% No mulch	60%No mulch	100% 0.5kg	80% 0.5kg	60% 0.5kg	100% 1kg	80% 1kg	60% 1kg	100% 1.5kg	80% 1.5kg	60% 1.5kg
Actual	0.48	0.51	0.66	0.43	0.54	0.68	0.5	0.59	0.9	0.4	0.55	0.68
Simulated	0.62	0.65	0.7	0.57	0.62	0.71	0.6	0.73	0.94	0.7	0.7	0.72

APPENDICES C

Appendix C1: Research Permit

THIS IS TO CERTIFY THAT:
MS. HELLEN JEROTICH SANG
of EGERTON UNIVERSITY, 536-20115
Nakuru,has been permitted to conduct
research in *Nakuru County*

Permit No : NACOSTI/P/19/79189/29730
Date Of Issue : 28th May,2019
Fee Recieved :Ksh 1000

on the topic: *EVALUATION OF DEFICIT SUB - SURFACE DRIP IRRIGATION AND MULCHING SYSTEMS ON WATER PRODUCTIVITY: A CASE OF TOMATO CROP IN NJORO SUB COUNTY*

for the period ending:
27th May,2020

....
Applicant's Signature

....
Director General
National Commission for Science, Technology & Innovation

`

Appendix C2: Research Publication

Journal of Engineering Research and Reports

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ISSN: 2582-2926

Modeling Tomato Water Productivity Using Aquacrop Model in Njoro Sub County, Nakuru, Kenya

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Authors' contributions

This work was carried out in collaboration among all authors. Author HJS designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors RMW and JMR managed the analyses of the study and the literature searches. All authors read and approved the final manuscript.

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Original Research Article

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ABSTRACT

Aims: To model tomato water productivity under deficit sub – surface drip irrigation and grass mulch densities using Aquacrop model.
Study Design: The study was factorial experimental with twelve treatments.
Place and Duration of Study: Tatton Agriculture Park, Egerton University, Nakuru, Kenya between January to May 2019.
Methodology: Tomato (*Lycopersicon esculentum* mill) crop (Tylka F1) was used to determine the effect of deficit irrigation and mulching on its productivity. Aquacrop model was calibrated to simulate the tomato yield, biomass and water productivity. Aquacrop model was used to estimate the tomato water requirements, water productivity, yield and biomass under deficit irrigation and mulching. The study was carried out on 36 experimental plots measuring 2 by 2 m with the total area under study being 144 m^2.

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