EFFECTS OF DEFICIT IRRIGATION ON YIELD AND QUALITY OF ONION CROP

BY

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DECLARATION

DECLARATION BY THE CANDIDATE

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DEDICATION

I dedicate this study to my dear wife, Willitter, sons Jonathan and Immanuel, nephew Kevin and niece Sheila, who supported and encouraged me throughout the period of this study.

ABSTRACT

There is shortage of onions in Uasin Gishu and Nandi counties during dry season from October to March when the demand is high. Rainfall during the period is inadequate for crop development. This study aimed at testing Deficit Irrigation technology as an appropriate irrigation management strategy that could improve crop water productivity and give optimum Onion crop yield. A field trial was conducted in Nandi County with drip irrigation system and six irrigation treatments replicated three times in a randomized complete block design. Full supply of crop water requirement to meet 100% ETc (T100) acted as a control. The crop was subjected to five stress levels T90, T80, T70, T60 and T50 at vegetative and late season growth stages. Establishment and yield formation stages were given adequate water to meet normal crop water demand (ETc). The treatments were protected from receiving extra water from the rain. The yield, biomass, quality and irrigation water use efficiency were determined. The data collected were statistically analyzed using ANOVA. The variation in yield ranged from 34.4 ton/ha to 18.9 ton/ha and that of quality from 64 mm to 35 mm diameter for T100 and T50 respectively. The treatments T90, T80, T70, and T60 gave yields of 33 ton/ha, 32 ton/ha, 25 ton/ha and 23 ton/ha with corresponding bulb diameter of 60 mm, 58 mm, 53 mm and 40 mm. Water stress of 20% led to optimum yield with water saving of 10.7%. The results obtained from the field trial were used to calibrate and validate the performance of AquaCrop Model using separate data sets. Statistical indices, Model efficiency (E), root mean squared error (RMSE), coefficient of residuals (CRM) and coefficient of determination (R^2) were used to evaluate the performance of AquaCrop model in simulating yield, biomass, canopy cover and soil moisture parameters. The model performance statistical index was found for R^2 as 0.912 for canopy and 0.798 for soil moisture in confirming model calibration. Similarly, the index (R^2) for confirming model validation for canopy and soil moisture was 0.892 and 0.616 respectively. The model was applied to derive full (T100) and deficit (T80) irrigation schedules for three weather regimes from October-March growing seasons between 2003 and 2012 giving rise to 34 and 30, 38 and 34, 45 and 40 irrigation events each of 13 mm respectively. It was concluded from the results that deficit irrigation (DI) at vegetative and late growth stages significantly influenced yields. DI influenced the size and size distribution of fresh Onion bulbs significantly (Fcalculated = 96.28, Fcritical = 3.12). However, it did not significantly affect the shape of onion. AquaCrop model performance in simulating yield, green canopy cover and soil moisture declined at higher stress levels. The model is useful in developing irrigation schedules for different weather regimes that can be applied by farmers through extension services. It was recommended that the model be used to simulate yield at lower stress levels and adopted for irrigation scheduling by farmers and field extension staff. DI technology should be adopted for optimum yield and maximum water productivity.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
CERES	Crop Environmental Resource Synthesis
CRM	Coefficient of residuals
DI	Deficit Irrigation.
E	Model Efficiency in simulation.
DSSAT	Decision Support Systems for Agro- technology Transfer
EIA	Eldoret International Airport
EPIC	Environmental Policies and Institutions for Central Asia
ETc	Crop Evapotranspiration
ETo	Reference Evapotranspiration
IWUE	Irrigation Water Use Efficiency
Kc	Crop Coefficient
Ky	Yield response factor
MOA	Ministry of Agriculture
R^2	Coefficient of determination
RMSE	Root Mean Squared Error
SWAP/WOFOST	Soil Atmosphere Plant System
WP*	Water Productivity

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CHAPTER ONE
INTRODUCTION

1.1. Background Information

It is stated by UNEP (2006) that thirty percent of the world's population live in countries where there is water scarcity. A country is categorized as water scarce if it has an annual water supply per capita of less than 1,000 cubic meters which is considered to be the global standard benchmark for a country to be termed as water sufficient. Kenya is classified as a water scarce country because its current per capita water availability is 586 m^3 as per the National Water Master Plan 2030 (JICA Report, 2013). Half of the world population that is rapidly growing live below absolute poverty line and therefore exerts a lot of pressure on natural resources including fresh water (UNESCO, 2006).

Under traditional system of irrigation, water availability is not considered. However, rising demand for water calls for changes in the management of irrigation and scheduling to improve crop water use efficiency thus saving the scarcely available water for agriculture. Three methods are however available for enhancing vegetable production in a country. Allocating more area, developing and adopting new technologies and utilizing the available resources more efficiently (Bakhsh et al., 2007). It is unsustainable to allocate more area to vegetable production due increasing pressure on land as a result of increasing population. Deficit Irrigation (DI) being a new irrigation technology that utilizes water resources efficiently is a suitable option. In DI the crops are subjected to a certain degree of water stress during specific growth stages or throughout the whole growing season, without significant reduction in yields compared with the benefits gained through diverting the saved water to irrigate other crops (Kipkorir et al., 2001).

Onion is one of the vegetable crops whose yield and quality are responsive to careful irrigation scheduling and maintenance of optimum soil moisture (Shock et al., 1998). Efficient irrigation technology that can prevent plant water stress and reduce deep percolation shall play an important role in view of water saving and improving water productivity. Drip Irrigation is considered as an effective way of saving water and enhancing onion water productivity because it can supply small and frequent water application depths (Shock et al., 2000).

1.2. Statement of the Problem

The report by Horticultural Crops Development Authority (HCDA, 2012), indicated that Kenya's domestic demand for bulb onion outstrips supply resulting in imports from India, Egypt and Tanzania. During rainy season in Uasin-Gishu and Nandi Counties, farmers cultivate mainly cereal crops for local consumption and export to other counties for income. Harvesting of these crops take place from September to November when fields become available for other crops. This period coincides with the onset of dry season (Figure 1.1) when there is water scarcity (365 mm) for vegetable production in Nandi and Uasin Gishu counties which runs from October to March when the market prices of onion are high (upto Kshs 50 per Kg). Prices of onion rise between January and June when there is shortage of onions due to low supply from imports especially from Tanzania (Hortinews, 2014). Production is mainly under irrigation with little quantities being produced under rain fed conditions.

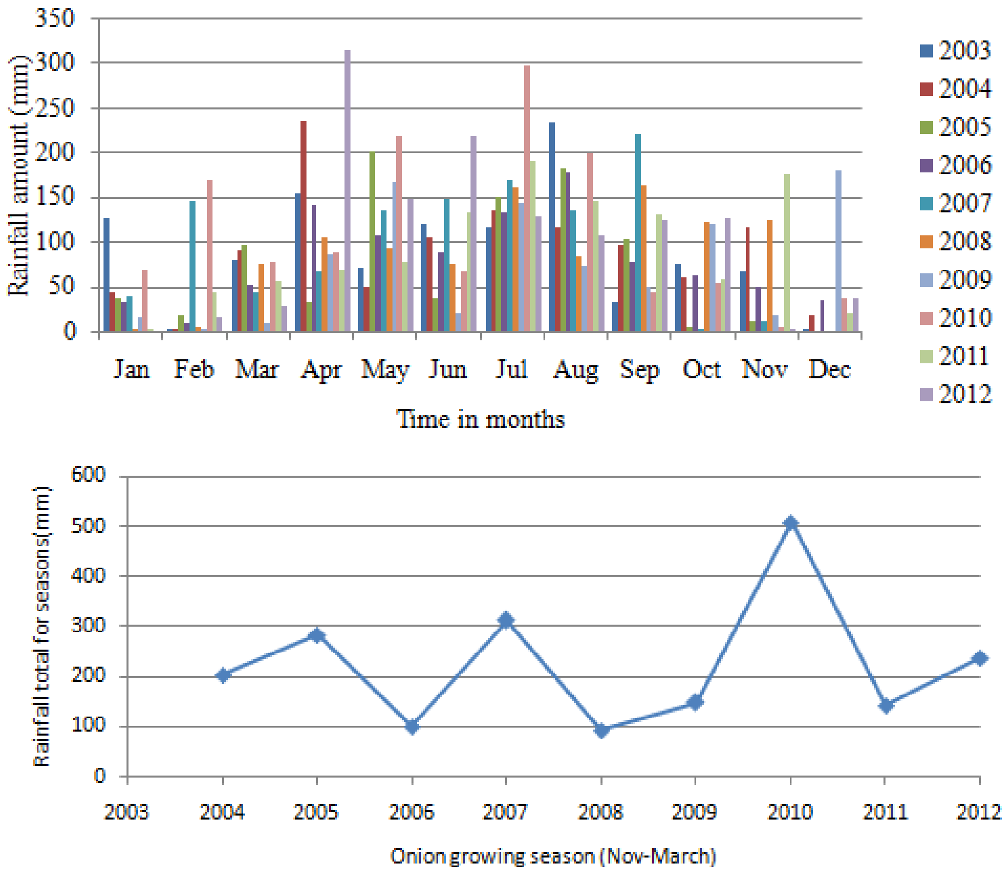

Figure 1.1: Rainfall pattern for Uasin Gishu county and Nandi north.

(Source: Kapsoya meteorological weather station).

The scarcity of water for vegetable production in the study area as depicted in Figure 1.1, calls for increased productivity of the available water through adoption of new irrigation scheduling technology. Deficit Irrigation technology was identified for use in the study because it saves some water at stress tolerant stages of the crop leading to increased water productivity and optimized production.

1.3 Objectives of the Study

1.3.1. Broad Objective

The broad objective of the study was to determine the effect of Deficit Irrigation or DI on the yield and quality of onion in Nandi and Uasin Gishu Counties.

1.3.2. Specific Objectives

The specific objectives which were addressed to achieve the general objective were:

a) To determine Onion yield in response to various water deficit application levels.

b) To determine the effect of Deficit Irrigation on the quality of onion based on yield physical characteristics.

c) To evaluate the performance of AquaCrop Model in simulating Onion yields as response to limited water supply.

d) To apply AquaCrop in deriving Irrigation Schedules.

1.4. Hypothesis

H_0: Deficit Irrigation at stress tolerant stages of Onion maximizes crop water productivity without reducing crop yield and quality significantly.

H_1: Deficit Irrigation at stress tolerant stages of Onion maximizes crop water productivity but reduces yield and quality significantly.

1.5. Justification and Significance of the Study

Onion farmers in Uasin-Gishu and Nandi Counties will be able to grow Onions during dry season by utilizing the little available water efficiently through Deficit Irrigation technology as opposed to traditional methods of irrigation which lead to water losses resulting in lower efficiencies and crop water productivity. This will improve vegetable production in the region.

Since onion crop will be grown during dry season when supply is low and prices are high, farmers will fetch high market prices thereby improving their economic strength. The results will also be a frame of reference for further research of onion production using Deficit Irrigation in Kenya.

AquaCrop was selected for use in this study since it uses a relatively small number of parameters and tries to balance simplicity, accuracy, and robustness. It also has a user-friendly interface and could therefore be used by non-specialists to develop scenarios.

1.6. Scope of the Study

The experimental study consisted of primary and secondary data collection from various sources. Primary data collected included some crop and soil characteristics. Soil texture and profile, pH and fertility for the experimental plot were determined. Secondary data (climatic) were collected from nearby meteorological weather stations (Kapsoya and Eldoret International Airport). The study covered six crop water application levels and three replications. The variable parameter was the quantity of irrigation water applied at various application levels and growth stages through drip irrigation system. The crop was temporarily covered against rainfall. The trial was carried out beginning from planting of the crop to harvesting after a growing period of about 150 days. The crop was subjected to deficit irrigation at stress tolerant growth stages to varying levels. The performance of AquaCrop in simulating yield in response to water stress at different treatment levels was evaluated at the end of the trial to ascertain if it could be used to simulate Onion yield and quality parameters.

1.7. Limitations and Assumptions

Onion crop does well under specific range of weather conditions above or below which physiological development is adversely affected. Optimum daily temperature favourable for the crop lies between 15^{o}C and 25^{o}C. The unpredictable environmental and weather changes outside these temperatures might have therefore negatively affected the development of the crop. Strong winds sometimes threatened to rip off the rain shelter. It was assumed that soil fertility, water quality, soil permeability, soil pH and all other factors other than water levels which were being tested for their effect on yields and quality were effectively controlled. While using ANOVA, it was assumed that each of the samples was drawn from a normal population and that each of these populations had the same variance.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

This chapter focuses on the reviewed literature relevant to the current study. It covers the detailed information on onion crop, agronomic practices, and climatic requirements for successful crop development, crop growth stages, yield and quality. Types of irrigation available for water application and the preferred deficit type of irrigation for this study were also highlighted. Information on the effects of various factors on yield and quality were also reviewed and presented. Crop modeling on onion response to deficit irrigation was also covered.

2.2. Onion Crop

2.2.1. Climate and soil

Onion (*Allium cepa*) is a shallow rooted crop whose roots are mostly found in the upper 30 cm of soil and with a few roots extending to 60 cm deep (Figure 2.1). The crop performs well under a wide range of climatic conditions ranging from temperate to tropical. For optimum crop development, the mean daily temperature vary between 15^{o}C and 20^{o}C before bulbing and 20^{o}C and 25^{o}C for bulb development is preferred. Crop development slows down when the temperatures rise beyond 27^{o}C (FAO, 1986).

Bulb Onions are highly influenced by the length of days and nights. Short day Onion varieties take a shorter period (11 to 13 hours) of daylight to bulb while long day varieties require a longer period (14 hours per day or more) to form bulbs. Long day varieties do not bulb under short day climatic conditions, but short day varieties on the other hand performs well and develops bulbs if planted under long day conditions. Short day varieties require a certain critical period of light to bulb beyond which no effect of light is impacted on the crop.

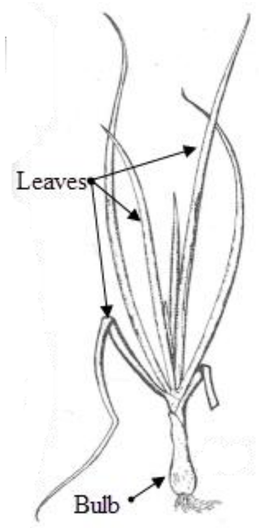

Figure 2.1: Onion plant at bulbification stage

(*Source: FAO, 1986*).

The crop is sown in a well prepared nursery where it takes about 30 to 35 days before being transplanted into the field. Seeds can also be sown directly into the field. The crop is planted in rows spaced at 0.3-0.5 x 0.05-0.1 m. The soil temperature favourable for germination is from $15^{o}C$ to $25^{o}C$. Bulbs are ready for harvesting between 130 and 175 days from transplanting depending on climate (FAO, 1986).

The crop performs well on medium textured and well drained soils of high fertility with a pH range of 6 to 7. However, onions grown in sandy soils require more frequent irrigation applications and such a crop usually mature early because bulbs are particular about the density of the soil and do not grow well if they are not able to expand easily. Sandy loams to clay loam soils are generally suitable for onion cultivation. Alkaline and saline soils are unsuitable for onion cultivation. Salt concentration above 4 mmhos/cm^2 inhibits vegetative growth of most of the onion cultivars. Soils which experience water logging problem can cause crop development failure. Onion performs well and produces optimum yield under application of 350 to 550 mm of water throughout the growing season. Water stress affects onion development during transplanting, yield formation (3), and during flowering period for seed crop (Figure 2.2). The crop is less sensitive to water deficit during vegetative growth period (1) and late season stage (FAO, 2012).

2.2.2. Growth stages of onion

The growth stages and crop coefficients used for water management of an onion crop with a growing period of 100 to 150 days in the field are depicted in Table 2.1 and Figure 2.2.

Table 2.1: Crop Coefficients (Kc) of Onion

Crop characteristics	Stages of Development				
	Initial (1)	Crop development (2)	Mid-season (3)	Late season (4)	Total days
Growth stage length (days)	15-20	25-35	25-45	35-45	100-150
Depletion coefficient, p	-	-	-	-	0.3
Root depth (m)	-	-	-	-	0.6
Crop coefficient, Kc	0.40-0.60	0.70-0.80	0.95-1.10	0.85-0.90	-
Yield response factor, Ky	0.45	-	0.80	0.30	1.10

(Source: FAO Water Development and Management Unit, 2012).

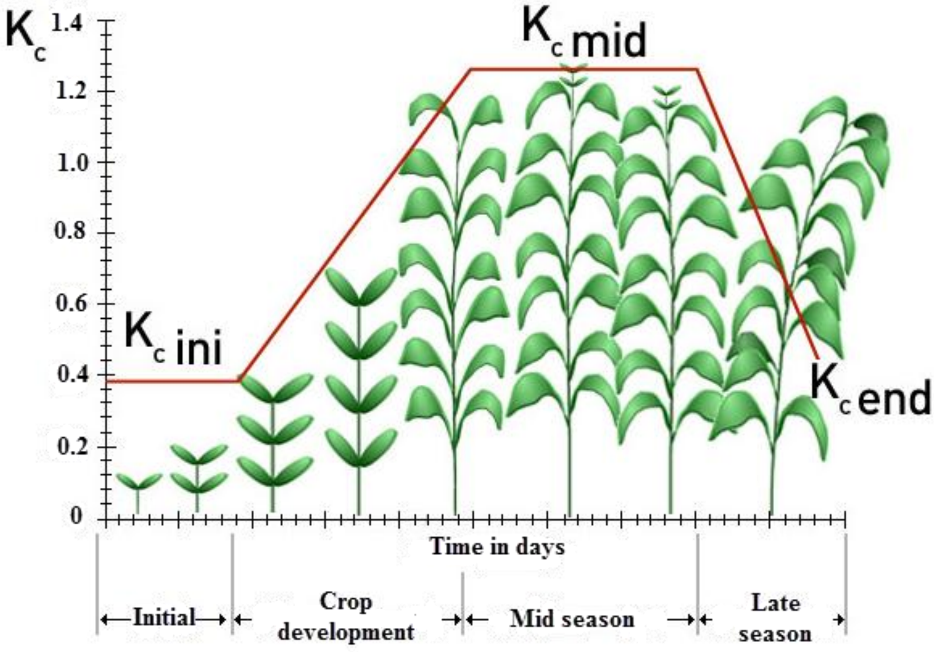

Figure 2.2: Crop stages of onion

(Source: Allen et al., 1998).

2.2.3. Varieties of Onions

Common varieties of onion fall into three categories each of which has different characteristics of colour, texture and shape (Plate 2.1).

Red onion: The red onion has red outer skin and red purple white flesh (Kenya seed company Ltd., 2012). It is preferred for fresh use since its colour and texture is attractive to the eye. It is also mostly used in grilling and char-boiling.

Yellow onions: The yellow onions are considered to be all-purpose and are often used in cooking. They have a yellow-brown papery skin on the outside and a white flesh. They turn to rich, dark brown in colour when cooked.

White onions: The white onions have an all-white skin and an all-white flesh. They have a thin golden skin when cooked. They are similar to yellow onions in flavour (Mower and Chris, 2013). They have a slightly milder flavor than the yellow onion and are a substitute if a mild flavour is required. White onions are commonly used in Mexican cuisines.

Plate 2.1: Colour of common onion varieties, 1) Red,2) Yellow,3) White.

(Source: Mower and Chris, 2013)

2.2.4. Propagation

Onion seedlings are raised in nursery beds from onion seeds. The surface of the beds should be smooth and well leveled. Raised beds are necessary to avoid the problem of water-logging in heavy soils. In sandy soils, however, sowing can be done in flat beds as there is no possibility of water-logging unless there is an underlying impervious layer. Sowing should be done in rows spaced at 5cm to 10cm apart (FAO, 1986). Spacing of the seedlings is dictated by the yield and quality of the produce required.

2.2.5. Yield

A well managed onion crop produces yield of 35 to 45 ton/ha under irrigation and a spacing of 30cm x10 cm depending on the variety. The water use efficiency of harvested crop containing 85% to 90% moisture lies between 8 and10 kg/m^3 (FAO, 2012).

2.2.6. Onion Quality

The quality of onion is determined based on various parameters. The parameters include pungency percentage, reducing sugar, total sugar, total soluble solid, moisture percentage, weight of onion, circumference of onion or diameter, length of onion and eye-sight grade (Murthy, 2007). The United States Department of Agriculture (October, 1995), however specifies the grades/quality of onion into five classes as shown in Table 2.2.

Table 2.2: Onion bulb size classification

Size designation	Minimum diameter (mm)	Maximum diameter (mm)
Small	25.4	57.2
Repacked/Prepacker	44.5	76.2
Medium	50	82.6
Large or Jumbo	76.2	-
Colossal	95.3	-

(Source: United States Department of Agriculture, 1995).

The onion bulbs can also be classified into three grades namely; Large: >60mm, Medium: 45 – 60mm, Small: <45mm (Ministry of Economics and External Trade, 1992). The quality of onion in this study was determined using bulb diameter, moisture content, bulb mass, colour, texture and shape index measurements.

2.3. Irrigation Scheduling

The crop has a shallow root system with roots concentrated in the upper 0.3 m soil depth. In general 100 percent of the water uptake occurs in the first 0.3 to 0.5 m soil depth. To meet full crop water requirements the soil is provided with sufficient moisture to sustain reference evapotranspiration rate of 5 to 6 mm/day. The rate of water uptake starts to reduce when about 25 percent of the total available soil water has been depleted ($p = 0.25$, where p is the fraction of soil water depletion) (FAO, 2012).

The crop requires frequent, light irrigations which are applied when about 25 percent of available water in the first 0.3 m soil depth has been depleted by the crop. The common practice is to apply irrigation every 2 to 4 days before harvesting or when 20-30% of the tops collapse. Over-irrigation sometimes causes spreading of diseases such as mildew and white rot. Irrigation can be discontinued 15 to 25 days before harvest (FAO, 2012).

2.4. Deficit Irrigation

Deficit Irrigation is a strategy of optimization whereby irrigation is applied during drought-sensitive growth stages of a crop. Irrigation is limited or even unnecessary during these stages, if rainfall supplies a minimum quantity of water. Water stress is confined to drought-tolerant phenological stages, which are usually the vegetative and the late ripening stages. Total irrigation application is therefore not proportional to irrigation requirements throughout the crop cycle. Although this leads to plant drought stress and eventually yield reduction, DI maximizes irrigation water productivity, which is the main limiting factor (English and

Nakamura, 1989). The objective of DI therefore is to optimize yields while maximizing crop water productivity rather than maximum yields (Zhang and Oweis, 1999).

DI can be used to increase the ratio of yield to crop water consumption where crops have phenological stages in which they are tolerant to water stress (Geerts and Raes, 2009). This occurs through either reducing the water loss by unproductive evaporation, and/or by increasing the proportion of marketable yield to the totally produced biomass (harvest index), and/or by increasing the proportion of total biomass production to transpiration due to hardening of the crop, although this effect is limited due to the conservative relation between biomass production and crop transpiration, (Steduto et al., 2007) and/or due to adequate fertilizer application (Steduto and Albrizio, 2005) and/or by avoiding bad agronomic conditions during crop growth, such as water logging in the root zone, pests and diseases (Pereira et al., 2002).

Leskovar (2010) reported that results of onion trials indicated that while marketable yields and the number of bulbs increased at higher plant density, the bulb size decreased. The higher the plant density the more the number of plants per unit area, but their roots are confined to a small area leading to competition for light, water and nutrients, hence decrease in bulb sizes. Results also showed that DI at the 50 percent of ETc had a significant impact on yield, while the yield from DI at 75 percent was not significantly different from 100 percent and produced a similar bulb size. He further concluded from the study that it would be possible to produce onion by adjusting their planting densities and water-conservation practices to a 75 percent ETc rate, as a means to target high-price bulb sizes without reducing quality. However, DI should be avoided during the yield formation stage (3) for high yield to be achieved. Saving of some water can be made during the vegetative development stage (1) and the late season period (4).

2.5. Irrigation Systems

2.5.1. Surface Irrigation

Surface irrigation refers to a group of irrigation methods in which water is applied and distributed by gravity over the surface of the field. These methods of application include basin, border strip and furrow irrigation. Water is applied at the high point or along the edge of a field and allowed to cover the field by overland flow. The efficiency and uniformity of irrigation is dependent on soil uniformity, quality of land grading, field topography and control of the relationship between stream size, soil infiltration rate and duration of application. The disadvantage of this system is the inability to evenly apply small depths of water with high application efficiency (FAO, 1989).

2.5.2. Sprinkler Irrigation

Sprinkler irrigation is the method of irrigation by which water is sprayed on the land surface in the form of artificial rain in a way similar to natural rainfall. Water is distributed through a system of pipes usually by pumping. It is then sprayed into the air through sprinklers so that it breaks up into small water drops which fall to the ground. The pump supply system, sprinklers and operating conditions are designed to enable a uniform application of water. Evaporation losses vary, but can be in the 1-20 % range, depending on the nozzle type, height of trajectory, climate conditions, extent of wetting of the crop canopy, and numerous other factors.

2.5.3. Drip Irrigation

Drip irrigation is a method of crop water application which uses low-flow emitters connected either on the surface or below the surface to directly supply water to a plant's root system, thereby reducing water loss and improving efficiency. This method of water application reduces its loss, by upto 30% to 50% less than surface irrigation. In addition to conserving water, drip irrigation reduces salinization and water-logging problems. Drip systems have been shown to achieve water efficiency of up to 95% as shown in Table 2.3. In water scarce environments, drip irrigation may allow for agriculture in areas where furrow or flood irrigation would not be possible. However, the irrigation systems are expensive, energy intensive, and require clean water to prevent the clogging of the fine delivery tubes (Pimentel *et al*., 2004). It is therefore apparent that drip irrigation system is the most efficient compared to surface and sprinkler irrigation systems (Table 2.3).

Table 2.3: Indicative values of the field application efficiency

Irrigation Efficiencies	Method of Irrigation		
	Surface (%)	Sprinkler (%)	Drip (%)
Conveyance Efficiency	40-50 (canal) 60-70 (well)	-	-
Application Efficiency	60-70	70-80	95
Surface water moisture evaporation	30-40	30-40	20-25
Overall Efficiency	30-35	50-60	80-95

(Source: Howell, T.A., 2003).

2.6. Effect of Various Factors on Yield and Quality

2.6.1. Irrigation Water Levels

In a field study conducted to determine the effects of deficit irrigation regimes on onion yield and water productivity, Nagaz *et al*., (2012) applied five water treatments as follows; SWB-100 – 100% ETc applied readily available water in the root zone after it had been depleted, 60% ETc (DI-60) and 80% ETc (DI-80), continuous deficit irrigation, SWB100-MDI60- applied water from transplanting to the mid-season stage, to supply 100% ET*c*, followed by 60% of ET*c* application till harvest. A fifth irrigation treatment comprised the farmer method of application which involved the application of a fixed quantity of water to the crop at fixed interval of 5 days from transplanting to harvesting. It was observed that the full irrigation (SWB-100), continuous and regulated DI (DI-80 and SWB100-MDI60) strategies gave reasonable advantage for both onion yields and WUE. The initial moisture content of the trial plots before transplanting was raised to field capacity. The results of the trial are given in Table 2.4.

Table 2.4: Yield of onion under different irrigation treatments.

Treatments	Bulbs fresh yield (ton/ha)			Bulbs dry yield(ton/ha)		
	2008	2009	Mean	2008	2009	Mean
SWB-100	24.29	26.10	25.20	3.045	3.272	3.16
DI-80	23.17	24.98	24.08	2.906	3.132	3.02
DI-60	22.40	23.44	22.92	2.808	2.938	2.87
SWB100-MD160	23.50	25.64	24.57	2.946	3.214	3.08
Farmer method	18.97	21.18	20.08	2.378	2.665	2.67
LSD (5%)	1.443	2.198		0.311	0.280	

(Source: International Scholarly Research Network, ISRN Agronomy Volume 2012).

2.6.2. Fertilizer Application Rates

A study conducted to find out the optimum fertilizer application of onion for Faridpur region in India (Amin *et al.*, 2007) concluded that in soils with low N and P, but high K., yields increased gradually to 15.04 ton/ha, 15.04 ton/ha, 15.14 ton/ha and 15.04 ton/ha with increasing levels of N, P, K and S upto 100 kg/ha, 80 kg/ha, 50 kg/ha and 30 kg/ha respectively beyond which yields decreased (Table 2.5).

Table 2.5: Yield of onion as affected by different levels of nutrients.

Fertilizer level (Kg/ha)	Bulb Yield (ton/ha)			Mean (ton/ha)
	2001	2002	2003	
N level				
0	7.52	7.68	7.05	7.42
75	13.25	13.50	12.53	13.09
100	14.85	15.42	14.85	15.04
125	14.20	14.22	12.77	13.73
CV%	11.50	12.70	10.90	
P level				
0	10.95	9.70	7.98	9.54
60	14.10	14.55	12.83	13.83
80	14.85	15.42	14.85	15.04
100	13.97	14.17	13.00	13.71
CV%	12.10	11.50	9.80	
K level				
0	11.70	11.55	11.94	11.73
50	15.00	15.48	14.96	15.14
100	14.85	15.42	14.85	15.04
150	14.78	15.32	14.72	14.94
CV%	11.70	12.40	10.50	
S level				
0	11.00	10.45	9.28	10.24
15	13.45	13.48	11.57	12.83
30	14.85	15.42	14.85	15.04
45	14.10	14.20	13.36	13.89
CV%	12.30	11.80	10.70	

(Source: Amin, M. R. et al., 2007).

Similar results were observed by Ali and Haque, (1994) and Gupta and Gaffar, (1990) who found the highest yield of 16.00 ton/ha with 100 kg/ha in Fadipur soil. Gupta and Gaffar, (1990) found the highest yield of onion bulb (16.6 ton/ha) by the application of 54 kg P/ha. Ahmed *et al.,* (1987) observed that the performance of *Taherpuri* onion variety at Rajbari was 8.42 ton/ha with 65 kg K/ha, while Ahmed et al., (1988) reported that the diameter and weight of bulbs were significantly improved with the application of S up to 24 kg/ha. The nutrient dose that maximized yield as well as profit were (107-72-90-33 kg NPKS/ha) and (95-50-70-32 kg NPKS/ha) respectively.

2.6.3. Planting Density

Farooq *et al*., (1990) observed that seeds of onion crop variety 'Desi Red' planted at a varying density of 20, 30 and 40 plants/m^2, gave rise to reduced mean bulb weight with leaves to 1.80-1.70 kg/10 bulbs and without leaves to 1.61-1.50 kg/10 bulbs (Table 2.6).

Table 2.6: Effect of planting density on growth and yield of onion bulbs

Planting density (Bulbs/m^2)	No. of leaves per bulb	Bulb diameter (cm)	Neck diameter (cm)	Weight of 10 bulbs (Kg)		Yield (Kg/m^2)
				with leaves	without leaves	
20	12.67	6.82	1.91	1.80	1.61	2.16
30	12.67	6.72	1.66	1.75	1.50	2.75
40	11.67	6.67	1.61	1.70	1.50	3.56

(Source: Muhammad Farooq Ch. et al., 1990).

Bulb and neck diameters equally decreased from 6.82 to 6.67 cm and 1.91 to 1.61 cm, respectively. Increase in planting density resulted in increased yield per unit area. The highest planting density of 40 plants/m^2 led to the production of maximum yield of 3.56 kg/m^2. The results of this study were similar to the findings of Vagai *et al*., (1976), Rashid and Rashid (1977), Miccolis *et al*., (1984), but did not compare with that of Mc Geary (1985).

2.7. Crop Simulation Modeling

Crop simulation modeling involves the use of computer software to predict growth, development, and yield of agricultural crops. Data on weather, soil, crop characteristics and crop management are input and processed to predict crop yield, maturity date, efficiency of fertilizers and other factors of crop production. The calculations in the crop models are based on the existing information on the crop characteristics and the responses to the environment. By simulating the effects of different influencing factors on crop production, models allow to better understand the mechanism behind improved water use efficiency, to schedule the necessary irrigation applications during the drought sensitive crop growth stages, considering the possible variability in climate, to test DI strategies of specific crops in different regions, and to investigate the effects of future climate scenarios or scenarios of altered management practices on crop production (Raes *et al*., 2009). Models are frequently used to evaluate the effect of climate change on crop production and to assess the impact of potential adaptation strategies (Aerts and Droogers, 2004).

Some of the frequently used agricultural models are, CropWat, AquaCrop, CropSyst, SWAP/WOFOST, CERES, and DSSAT. Each of these models is able to simulate crop growth for a range of crops. The main differences between these models are the representation of physical processes and the main focus of the model. Some of the models mentioned are strong in analyzing the impact of fertilizer use (WOFOST), the ability to simulate different crop varieties (CropSyst, DSSAT), farmer practices (CROPWAT), etc. The three models that are specifically strong on the relationship between water availability, crop growth and climate change are CropWat, AquaCrop and SWAP/WOFOST. The three models have a user-friendly interface, but comparatively AquaCrop uses a relatively small number of parameters and tries to balance simplicity, accuracy, and robustness (Steduto *et al*., 2009). Its interface is user-friendly and can therefore be used by non-specialists to develop scenarios. Based on these qualities, AquaCrop was selected for use in this study.

2.8. AquaCrop Model description

AquaCrop model is a water driven growth engine which was developed by FAO for crop water productivity simulation (Steduto *et al*., 2009). It translates transpiration into biomass using conservative, crop specific parameters. The model uses green canopy cover instead of leaf area index (LAI) as the criteria for calculating transpiration and separating soil evaporation from transpiration. It relates its soil-crop-atmosphere components through its soil and its water balance, the atmosphere, crop conditions and field components in order to generate its output components (Raes *et al*., 2009; Steduto *et al*., 2009). Transpiration is related to canopy cover which is proportional to the extent of soil cover whereas evaporation is proportional to the area of soil not covered. The crop responds to water stress through four stress coefficients namely leaf expansion, stomata closure, canopy senescence, and change in harvest index.

The normalized crop water productivity (WP*) is considered constant for a given climate and crop. WP* for C3 crops is set between 15 and 20 g/m^2 (Raes *et al*., 2009). Using the normalized crop water productivity, AquaCrop calculates the daily above ground biomass production (Steduto *et al*., 2009). Yield is calculated as the product of the simulated biomass and the adjusted harvest index (HI). The adjustment of HI in relation to the available water depends on the timing, severity and duration of water stress (Raes *et al*., 2009; Steduto *et al*., 2009). Harvest Index is adjusted for five water stress coefficients namely coefficient for inhibition of leaf growth, for inhibition of stomata, for reduction in green canopy duration due to senescence, for reduction in biomass due to pre-anthesis stress and for pollination failure (Raes *et al*., 2009; Steduto *et al*., 2009). The model calculation scheme is as shown in Figure 2.3.

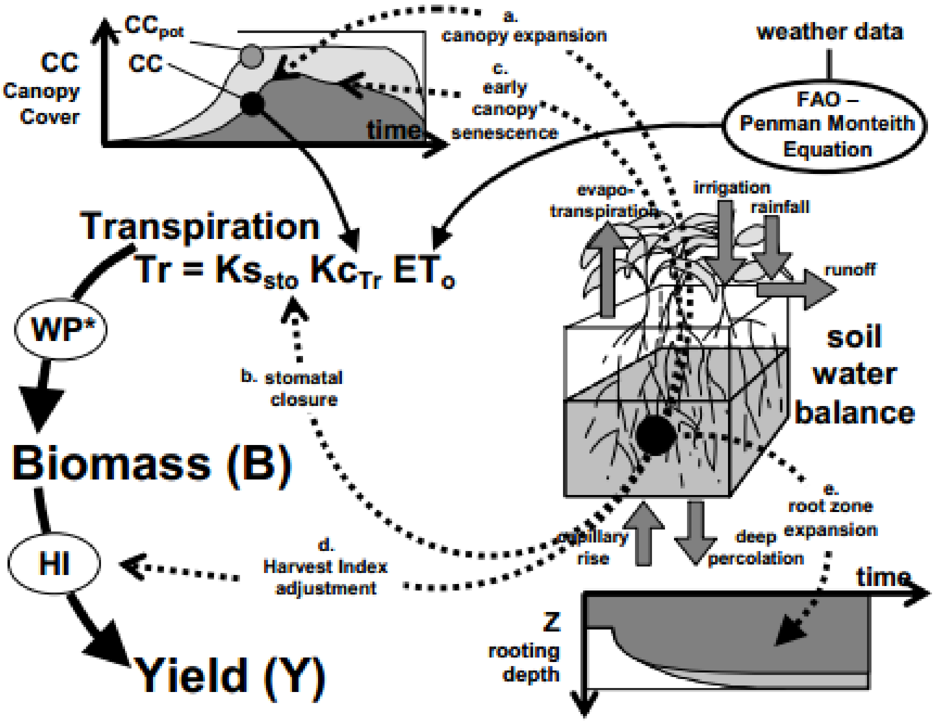

Figure 2.3: Calculation scheme of AquaCrop

(Source: Raes D. et al., 2011).

CHAPTER THREE
MATERIALS AND METHODS

3.1. Introduction

This chapter presents the materials and methods used to collect data from the field trial. It also describes the study area, materials used, experiment layout, irrigation scheduling, field management and methods of data analysis.

3.2. Study area characteristics

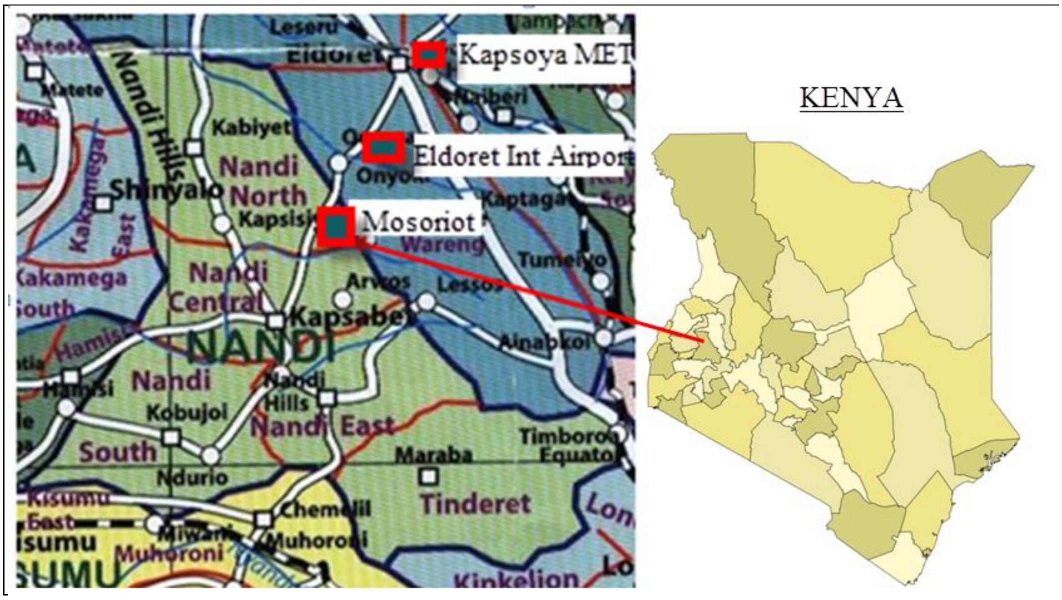

Figure 3.1: Location of study area

(Source: http://mapsof.net/map/kenya-districts-colored).

The study was conducted at Mosoriot Teachers College in Nandi County (Figure 3.1) near the border with Uasin Gishu County, from March to July 2013. The site is located at 35°10’E longitude, 0°19’N latitude and at an altitude of 2117 m above sea level. The soil texture is described as sandy loam, deep red, well drained with good fertility. The area experiences a bimodal type of rainfall with mean annual rainfall of 1365 mm. The mean annual minimum and maximum temperatures are 10°C and 24°C, respectively (Ralph and Helmut, 1983). Climatic data observed during the season were acquired from the nearby Eldoret International Airport meteorological station (Figure 3.1) for calibration of AquaCrop model. The temperature during the season from the data ranged from 14^{o}C to 28.5^{o}C and when compared to those for Onion production, it indicated that the weather was favourable.

3.3. Soil Sampling

Soil samples for analysis of physical and chemical properties were collected from seven points within the experimental plot whose approximate area was 0.01 ha in a zigzag pattern (Figure 3.2).

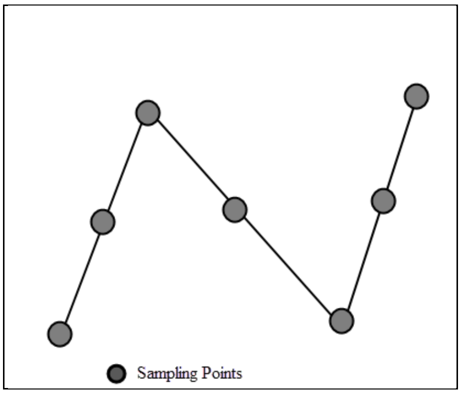

Figure 3.2: Soil sampling pattern used in the trial field.

(Source: Author, 2013)

The method was chosen as it was convenient for a small area. It is a conventional sampling method that best represented the field, accounting for known sources of variability. It avoids arranging sampling points in a straight line and provides for fairly complete sampling of the field and a good estimate of the need for single uniform fertilizer application rate to be applied to the entire field, (CropNutrition.com). Samples were taken from 0-60 cm depth and bulked before taking a representative sample for physical and chemical analysis. The tests were carried out at the Ministry of Transport and Infrastructure at Eldoret, University of Eldoret Soil Science Department and the Crop Nutrition laboratory.

Soil physical properties were determined (Plate 3.1) according to Brady, (1990) whereas soil water content at saturation (θ_{sat}) was determined using pedotransfer function (Saxton and Rawls, 2006) after determining field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}) in the laboratory. Soil moisture content was determined every decade by volumetric method. The soil chemical properties obtained were used to recommend the type and quantity of fertilizer and soil amendments applied. The bulk density was also determined using the procedure outlined by Okalebo et al., (2002).

Plate 3.1: Soil texture analysis.

(Source: Author, 2014)

3.4. Materials

The trial plot was sited near a borehole which acted as a source of water for the trial. The plot was fenced off to provide security against interference from livestock and other external intruders. A rain shelter structure (Plate 3.2) was constructed over the plots to protect the crop from receiving additional water from rainfall.

The structure measured 12 m long by 8 m wide with 1m buffer zone between the edge of the shelter and the boundary of the plots, all around the structure. A polythene sheet was used as a cover over the structure to keep off rainfall at night and whenever there was rainfall during the day. Drainage channels were excavated around the site to discharge rainwater away from the site. A polythene sheet was inserted into the soil all round the trial site to prevent water seepage under the plots.

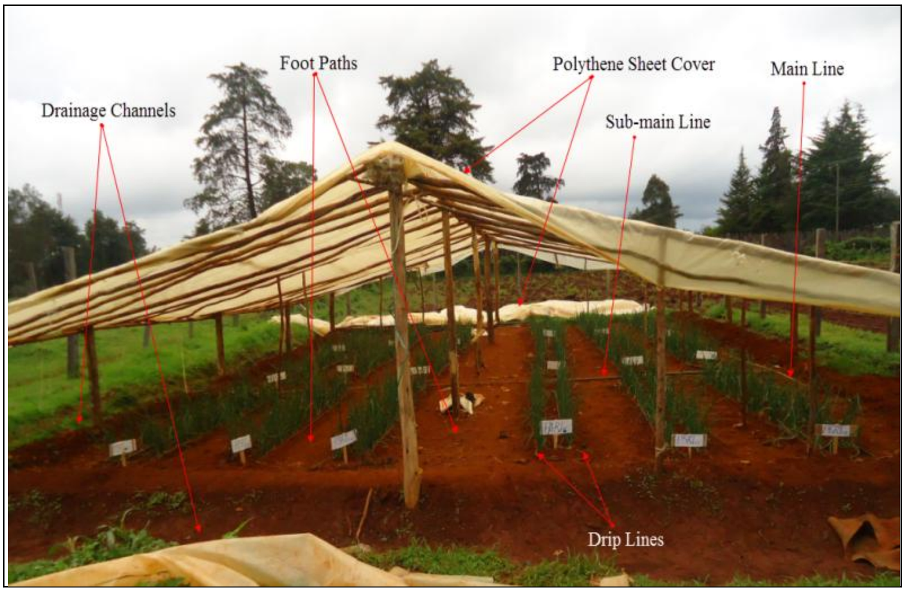

Plate 3.2: Rain shelter structure used in the field trials

(Source: Author, 2014)

The quality of water was obtained from the existing records and was found to be suitable for irrigation of Onion (ECw = 0.5 ds/m). Water was pumped from the borehole and stored in a masonry tank situated 15 m away from the plots. The dimensions of the tank were 15 m in diameter and 2.5 m high. The water was tapped from the base of the tank and piped to the plots by gravity through a main line of 25 mm diameter fitted with a filter to protect the drip emitters from clogging. The main supply pipe branched into three sub-mains to supply eighteen sets of laterals which separately served each of the eighteen plots. Rainfall was measured at the nearby Eldoret International Airport (EIA) station as 939 mm during the season from March to July, 2013 (Figure 3.3).

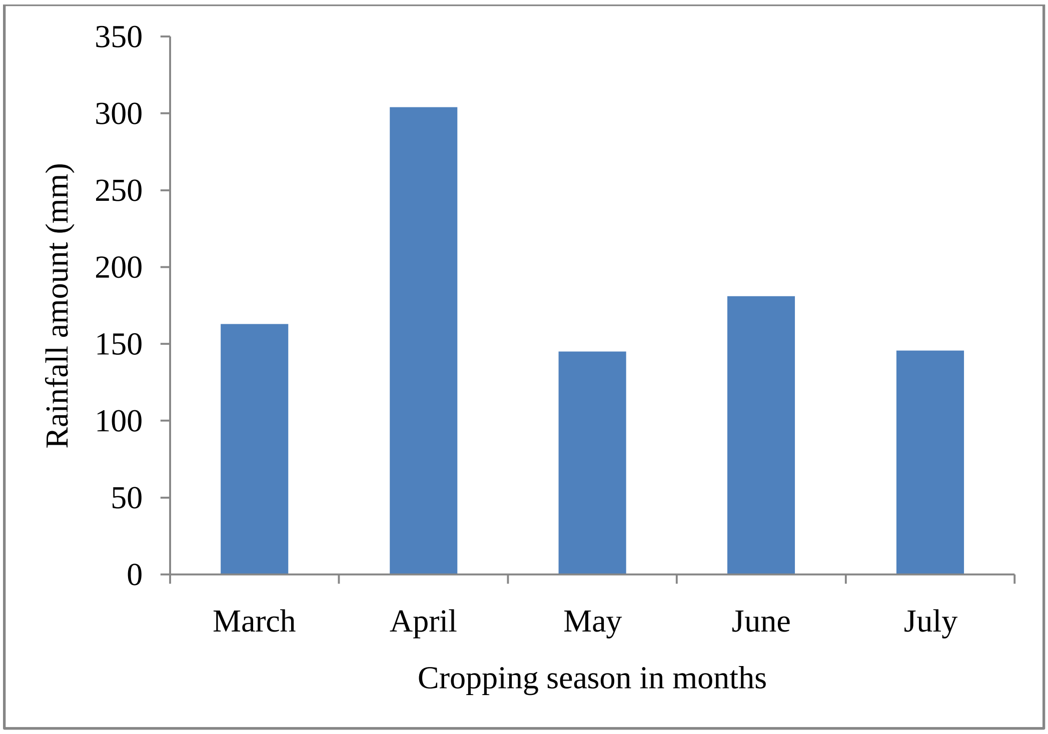

Figure 3.3: Rainfall amount received during the cropping season.

(Source: Author, 2013)

Flow from the sub-mains to the laterals (drip lines) was controlled using in-line control valves which regulated the supply of water to the crops during full and deficit application of water to various plots. Drip pipes with perforations at regular spacing ran along the rows of onions which were spaced at 30 cm apart by 240 cm long. On the main line, before the sub-mains branched, a filter was installed to guard the emitters from blockage caused by dirt and soil particles leading to poor uniformity of irrigation water application. Details of the setup are presented in Plate 3.3 and Figure 3.5.

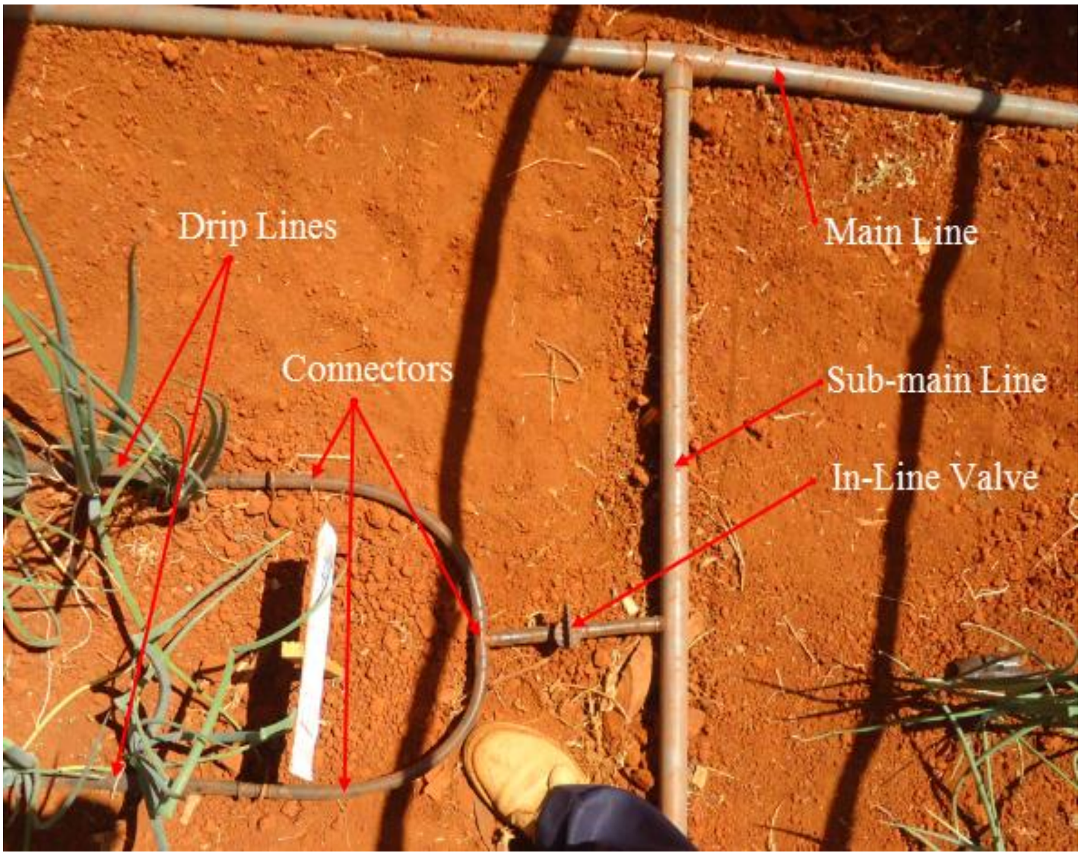

Plate 3.3: Setup of drip irrigation components.

(Source: Author, 2013)

Inputs composed of Red Creole onion variety seeds (the most commonly grown in the area), fertilizer, pesticides, and disease control chemicals were used during the trial. Inputs for soil pH and fertility amendment were applied to the soil as recommended. After transplanting, the crop, specified irrigation schedules per plot were applied to each treatment and required crop management practices were implemented during the growing season.

For irrigation scheduling, long term climatic data were acquired from Kapsoya meteorological station in Eldoret (Figure 3.1). Reference Evapotranspiration

(ETo) was computed for irrigation scheduling from climatic data by means of the FAO Penman-Monteith equation in ETo calculator version 3.1 (Allen et al., 1998). Linear measurements for rain shelter structure, crop spacing, soil depth and plot dimensions were determined with a tape measure. Discharge from the drip system was regularly measured with transparent graduated cylinders to ascertain the accuracy of the drip system at regular intervals. After harvesting the crop, yield and quality/grade were determined. Colour and texture were determined through CIE colour system (Figure 3.4) which is more precise in color measurement than the Munsel and Ostwald systems.

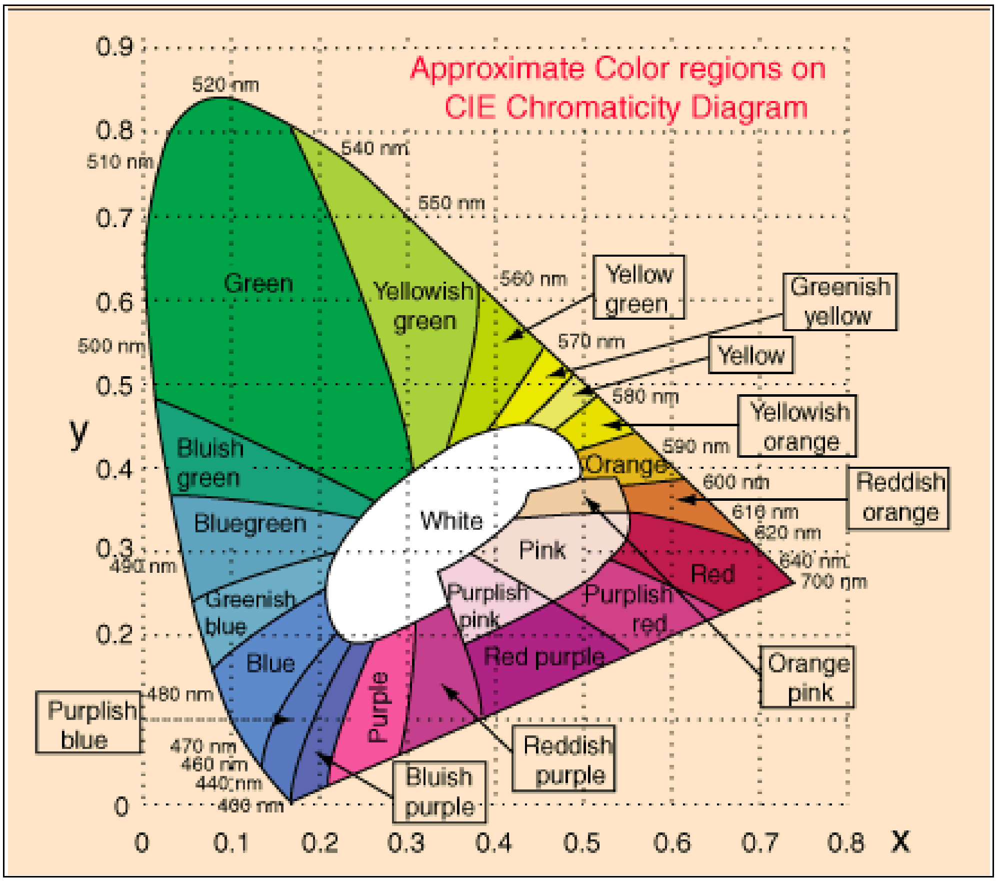

Figure 3.4: CIE colour system chart

Source: ***http://hyperphysics.phy-astr.gsu.edu/HBASE/vision/cie.html***

3.5. Layout of the Field trial

The field trial was laid out in a Randomized Complete Block Design (RCBD) with three replications under each treatment. There were six treatments in each block of replicates of varying water application levels consisting of T50 (50% ETc), T60 (60% ETc), T70 (70% ETc), T80 (80% ETc), T90 (90% ETc) and T100 (100% ETc) and applied at specific growth stages. The treatments consisted of full irrigation throughout the growing season, five treatments with 10%, 20%,30%, 40% and 50% water deficit application at two (development and late season) different crop growth stages considered to be drought tolerant.

The blocks were named after the three replications designated as R1, R2, and R3 and the plots in each replication as P1, P2, P3, P4, P5, and P6 giving rise to eighteen (3x6=18) plots. DI levels were named according to a combination of the replicate position (R1, R2, R3) and plot number (P1, P2, P3, P4, and P5) together with a subscript denoting the quantity of water applied as a percentage of ETc. The six levels of application within block R1 appeared as $R1P1_{0.9}$, $R1P2_{0.5}$, $R1P3_{0.6}$, $R1P4_{1.0}$, $R1P5_{0.7}$ and $R1P6_{0.8}$. The same applied to the second and third blocks of replications which were also named as $R2P1_{1.0}$, $R2P2_{0.7}$, $R2P3_{0.9}$, $R2P4_{0.8}$, $R2P5_{0.5}$, $R2P6_{0.6}$, and $R3P1_{0.5}$, $R3P2_{1.0}$, $R3P3_{0.7}$, $R3P4_{0.9}$, $R3P5_{0.6}$ and $R3P6_{0.8}$ respectively.

The six levels of water application were randomly assigned to the plots in each block of replicates. Each of the possible samples in the first block of replication were written on slips of paper and mixed thoroughly in a container. A slip was then drawn at random and assigned to the plots starting with the first plot (P1) of replication one (R1). The remaining five slips were then thoroughly mixed again before drawing another slip to be assigned to the next plot. The exercise continued progressively to the last plot of the block. The procedure was repeated for the remaining two blocks of replications. The detailed layout of the field trial used is given in Figure 3.5.

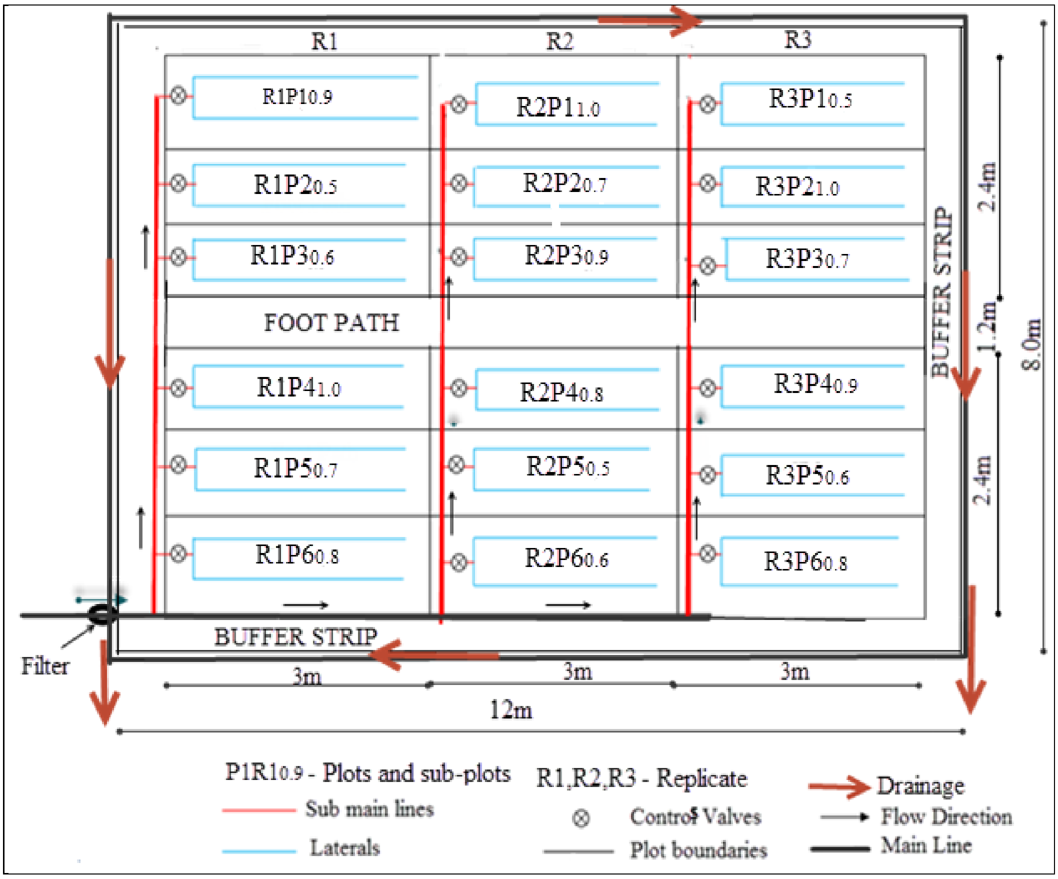

Figure 3.5: Layout of trial plots showing irrigated plots and drip pipes.

(Source: Author, 2013)

3.6. Irrigation Scheduling

The main objective of irrigation scheduling for crops is to decide when to irrigate and how much to irrigate depending on the crop water needs (FAO, 1989). Optimal irrigation scheduling leads to maximum yields and good bulb quality while under-irrigation stresses the crop causing losses in total yield and market grade. Over-irrigation causes soil erosion, bulb disease susceptibility, water loss, extra energy costs for pumping, Nitrogen leaching leading to ground water pollution, and increased crop nitrogen needs. Scheduling therefore was carried out following the steps outlined below:

1. Estimation of the length of all growth stages of the crop in days from literature. The crop duration of Red Creole onion (150 days) was divided into four growth stages (initial, development, mid-season and late season) each with specific duration in days.

2. Determination of ETo values. These were calculated from climatic data from Kapsoya meteorological station (Figure 3.1). ETo calculator which employs the FAO Penman Monteith equation (Allen et al., 1998) was used to compute the values using Equation 3.1.

$$\mathbf{ETo} = \frac{\mathbf{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}}{\mathbf{\Delta + \gamma(1 + 0.34U_2)}} \tag{3.1}$$

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

3. Estimation of the crop coefficients (Kc), (Allen et al 1998) for each of the decades during the growing season. The estimation is made from growth stages curve (Figure 3.6) with an assumption that the humidity and wind speed were medium.

4. Calculation of the crop water need (ETc) on decade basis using the expression:

$$ETc = ETo \times K_c \left(\frac{mm}{day}\right) \quad (3.2)$$

5. Estimation of the net and gross irrigation depth in mm/day as outlined below (Gupta and Larson, 1979):

Total Available Water; $TAW = (FC - PWP)$ (3.3)

Where FC - Field capacity and PWP - Permanent wilting point.

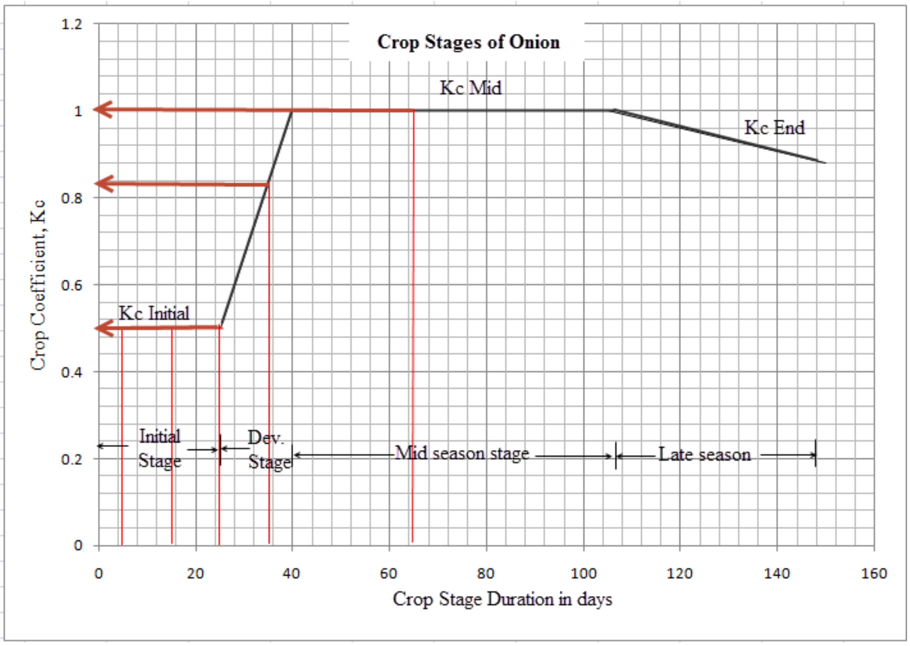

Figure 3.6: Crop growth stages curve and respective kc for onion.

Source: Allen et al., (1998)

6. Equivalent depth of available water, d;

$$d = TAW \times D_b \times Zr \quad (3.4)$$

Where Db - Bulk density, Zr - Root zone depth (30 cm).

Readily available water, $RAW = d \times p$ (3.5)

Where p is allowable moisture depletion (p = 25%).

7. Net irrigation application depth, I_{net} (mm) = RAW. (3.6)

RAW is the maximum allowable depletion based on the rooting characteristics of the crop.

8. Gross irrigation depth, $I_{gross} = \frac{I_{net}}{Ea}$ (mm) (3.7)

Where Ea - application efficiency for drip system, 70-95% (Howell, 2003). For this calculation, 85% was considered.

9. Irrigation application interval, $i = \frac{I_{net}}{ETc}$ (days) (3.8)

10. The volume (V) of water to be applied to meet the demand of the crop was:

$$V = A \times I_{gross} \text{ (litres)} \quad (3.9)$$

Where A – area wetted by an emitter (Plate 3.4).

11. Then the irrigation time, $T = \frac{V}{Q}$ (mins) (3.10)

Where Q - drip emitter discharge in litres per hour.

The integrity of drip discharge was regularly checked by recording the time taken for the discharge to fill a vessel of known volume.

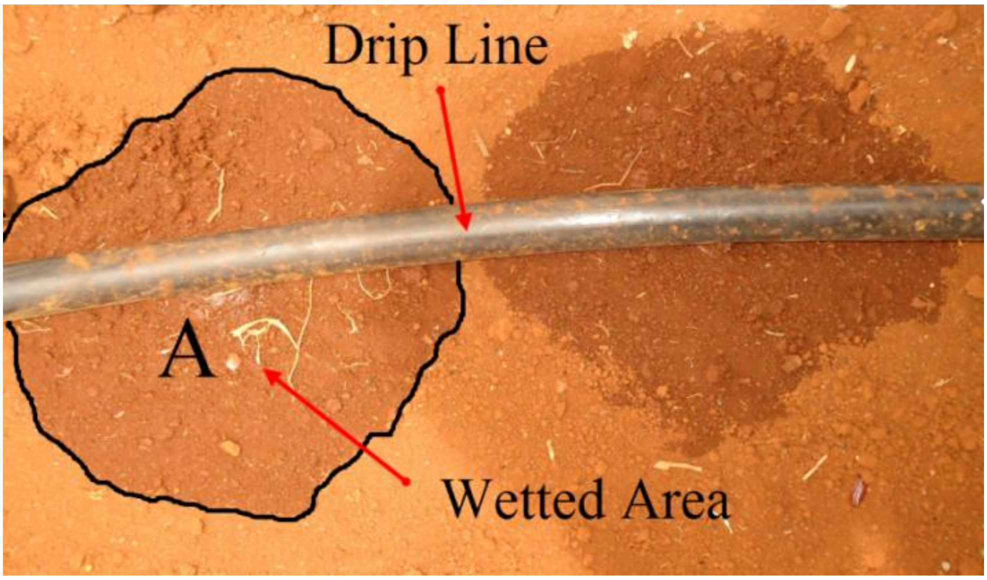

Plate 3.4: Area wetted by an emitter denoted by A

(Source: Author, 2013)

3.7. Field and Crop Management

The crop was transplanted one month after applying soil amendments to the soil in the trial plots (Plate 3.5). The type and rate of application was based on the laboratory results of soil analysis (Malakouti, 1999). The amendments and rates of application were as follows; Calcitic Lime – 3300 kg/ha, Dolomitic Lime – 2500 kg/ha, Mijingu Rock Phosphate – 240 kg/ha, Manure/Compost – 5000 kg/ha, and Magnesium Sulphate – 40 kg/ha.

Before transplanting, at a spacing of 10 cm by 30 cm, water was applied to raise the soil moisture content to field capacity as the soil was very dry. Di-ammonium phosphate (DAP) fertilizer was applied at a rate of 160 kg/ha at transplanting. Onion management after transplanting involved timely weed control, top dressing, pests and disease control and timely water application according to the irrigation schedule.

Plate 3.5: Soil amendment for pH improvement.

(Source: Author, 2013)

Weeds were controlled through regular cultivation. Care was taken to avoid root damage which could slow plant growth. Weed control was particularly important during the first two months of growth when plants were growing slowly and competed poorly. Top dressing with calcium ammonium nitrate (CAN) was done after three weeks of transplanting. Onion diseases and pests were controlled as they could destroy the crop leading to failure to achieve the aim of the trial. The most common pests were thrips and onion fly.

The crop was harvested 150 days after transplanting when bulb onions were mature and the leaves had collapsed or bent over and left to dry for 10-12 days**.** Mature bulb onions were manually uprooted from the soil and cured in the sun for 10-14 days before taking measurements of yield and quality parameters. Dried leaves were cut off at 3.5 cm from the bulb. During harvesting, two bulbs were left out in each row, one at each end. Off-types were removed together with small bulbs resulting from gap-ups. The remaining ranged from 35 to 45 bulbs per plot out of which 30 bulbs were randomly picked for determination of yield and quality.

3.8. Data Collection

The study required various types of data for both irrigation scheduling, determination of yield and quality, and evaluating the performance of AquaCrop model. Climatic, soil, crop and management data were collected from various sources.

3.8.1. Climatic Data

Two different sets of climatic data with the same parameters were collected from two different meteorological stations located near the trial site. The data collected from Kapsoya in Eldoret and EIA (Figure 3.1, Section 3.2), were used for irrigation scheduling and modeling respectively. The parameters collected included maximum and minimum air temperature (˚C), rainfall (mm), humidity (%), wind speed (km/day) and sunshine (hours). Reference evapotranspiration (mm/day) was determined using all these climatic parameters except rainfall (Raes et al., 2009, Steduto et al., 2009). Data for modeling and irrigation scheduling covered 4.5 and 10 years from 2009 to 2013 and 2003 to 2012 respectively.

3.8.2. Soil Data

The soil parameters collected from field trial for both irrigation scheduling and modeling using AquaCrop consisted of the number of soil layers, soil texture for each layer (clay, loam, sand in %), saturated hydraulic conductivity (K_{sat}), volumetric water content at saturation (θ_{sat}), Field capacity (θ_{FC}), Permanent wilting point (θ_{PWP}) and Initial soil water content with depth (% on volumetric basis) and bulk density.

3.8.3. Crop Data

Onion yield and quality characters

Onion bulbs were harvested 150 days after transplanting and cured for 10-14 days before data was collected. This was after the bulbs had attained moisture content for storage.

(a) Yield

(i) Fresh bulb yield

The total weight in ton/ha was estimated by weighing 30 randomly picked Onion bulbs from each treatment harvested from an area of 1 m^2 and converted to yield in ton/ha

(ii) Dry bulb yield

Ten randomly selected bulbs from each treatment were weighed, chopped and dried in an oven at 70^o C until a constant weight was achieved (ton/ha).

(b) Quality characters

Thirty onion bulbs were randomly selected from each treatment to determine some quality parameters composed of size represented by the equatorial diameter, colour and texture, moisture content and shape index.

(i) Bulb diameter

The equatorial diameter (mm) of onion bulbs were measured using a digital vernier caliper (Plate 3.6). The diameter measured was the maximum width of the onion in a plane perpendicular to the pole. Bulb diameter was determined as one of the parameters of the crop quality (Murthy, 2007).

Plate 3.6: Onion bulbs diameter measurement.

(Source: Author, 2013)

(ii) Colour and texture

The colour and texture of onion bulbs vary according to varieties which are normally available in three colours namely yellow, red and white. The colour and texture of the skin and inner flesh of harvested onion bulbs were established through CIE colour system. Red variety was used in the trial.

(iii) Moisture content

Randomly selected bulbs at storage moisture content from each treatment were weighed, chopped and dried in an oven at 70^{o} C until a constant weight was achieved. Moisture content was calculated as follows;

$$MC\% = \frac{W_w - W_d}{W_w} \times 100 \qquad (3.11)$$

Where W_w – wet bulb weight, W_d – dry bulb weight.

(iv) Shape index

The shape index is used to evaluate the shape of onion bulbs and was determined using the expression given below (Abd Alla, 1993);

$$\text{Shape Index} = \frac{D_e}{\sqrt{D_p \times T}} \qquad (3.12)$$

Where D_e – Equatorial diameter, D_p – Polar diameter and T - Thickness

A shape index greater than 1.5 indicates that the bulbs are oval while index lower than 1.5 shows a spherical bulb shape.

(v) Irrigation water use efficiency

Irrigation water use efficiency (IWUE) was determined according to Jensen (1983) as follows:

$$\text{IWUE} = \frac{\text{Onion yield}\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Irrigation water applied (mm)}} \qquad (3.13)$$

Water use efficiency (kg/ha mm) values were used to evaluate the effectiveness of the irrigation treatment practices on maximum water utilization by onion crops.

(vi) Yield response factor

Yield response factor (Ky) was determined based on the formula derived by Doorenbos and Kassam (1979) and given in equation 3.14:

$$\left(1 - \frac{Ya}{Ym}\right) = Ky\left(1 - \frac{ETc\,adj}{ETc}\right) \qquad (3.14)$$

Where Ky - yield response factor, ETc adj - adjusted (actual) crop evapotranspiration [mm/day], ETc - crop evapotranspiration for standard conditions (no water stress) [mm/day], Ya - actual yield (kg/ha), Ym - maximum yield (kg/ha), $(1-\frac{Ya}{Ym})$–decrease in relative yield, $(1-\frac{ETc\,adj}{ETc})$ - decrease in relative crop water consumptive use.

3.8.4. Data for AquaCrop

a) Climatic parameters

Daily climatic parameters collected for modeling from EIA included air temperature, relative humidity, wind speed and sunshine hours for period between January and August 2013.

b) Crop parameters

Crop specific parameters collected from the field trial included planting density, bulb yield, biomass, effective rooting depth, bulb formation and maturity time, green canopy cover (CC) and crop germination rate. Additional crop information included transplanting date, species and cultivar name, crop cycle duration (in days) and harvesting date. Canopy cover was determined through grid-estimation of shaded and un-shaded ground area. Estimation of shaded ground was made from photographs taken 1.2 m above the ground at solar noon when the sun was at its highest point above the horizon (Board *et al*., 1992, Egli, 1994) on decade time-steps. Biomass and final yield were determined after harvesting the crop. Rooting depth of the crop was monitored regularly through a section of excavated edge of the plots to expose a section of the roots. Plant density at emergence was estimated using plant spacing of the crop and germination percentage. Crop cycle duration was acquired from the supplier of the crop seeds and literature.

c) Soil parameters

Soil parameters collected included soil texture, field capacity, available water holding capacity and bulk density, number of soil horizons and indication of any restrictive soil layer. Soil moisture content was determined on decade time-steps when the crop was growing using direct method. Soil samples were taken from each treatment at depths of 0-10 cm, 11-20 cm, 21-30 cm and 31-40 cm. Soil moisture was removed by oven-drying the soil sample at 105°C for 24 hours in the laboratory until the weight remained constant. The moisture content (%) was then calculated (volumetric basis) using equation 3.15.

$$MC\% = \frac{W_2 - W_3}{W_3 - W_1} \times \frac{D_b}{D_w} \times 100 \qquad (3.15)$$

Where W_1- weight of tin (g), W_2 - weight of moist soil + tin (g), W3 - weight of dry soil + tin (g), D_b – bulk density of soil (g/cm^3), D_w – density of water (g/cm^3).

3.9. Data Analysis

Statistical analysis methods were used to analyse the data obtained from the trial for effect of water stress on yield and quality components of onions. Analysis tools used comprised Analysis of Variance (ANOVA) and Solver from Microsoft Excel, 2007 , mean and standard deviation. The ANOVA technique performs simultaneous test of the significance of the difference among the means of more than two samples at the same time as opposed to z-test or the t-test which only deals with not more than two samples at the same time. Analysis of variance for the yield and quality components was carried out to determine the significance of the impact of water stress on yields and quality according to the randomized complete block design (RCBD) principle. The probability level for determination of significance was 5%.

3.10. AquaCrop Calibration and Validation

3.10.1. Calibration

The crop data from the no-water stress treatment (T100) was used to calibrate the model based on yield, biomass, canopy cover and soil moisture content while the remaining treatments under water stress, (T90,T80,T70,T60, and T50), were used in validating the model using determined model parameters in the calibration stage under the same conditions. Canopy growth coefficient and canopy decline coefficient were adjusted accordingly to match the observed canopy cover from the field results. Climatic data spanning seven months from Eldoret International Airport meteorological station was used for calibration.

3.10.2. Validation

The model validation is the confirmation that the calibrated model closely represented the real situation represented by the observed parameters. Validation consisted of a comparison of simulated output and observed data that had not been previously used in the calibration stage, (T90, T80, T70, T60, and T50). The input to the model under no-water stress conditions (T100) remained constant. Irrigation at five varying water stress levels (T50, T60, T70, T80, and T90) constituted five different simulations resulting in corresponding number of results. The results of the trial which included dry above and below ground biomass, green canopy cover, yield and soil moisture content were simulated, and the outcome compared with the observed.

3.10.3. Model Performance Analysis

The statistical analysis methods used for comparison of the model performance in predicting onion yield, canopy cover, soil moisture and biomass were the Nash-Sutcliffe coefficient, E, Coefficient of determination, R^2, root mean square error, RMSE, and Coefficient of residuals, CRM. The Nash Coefficient of efficiency, E, quantifies the proportion of variability on the observed or measured values accounted for by the model and is expressed as shown in equation 3.15. The value ranges from -∞ to +1 with better model simulation efficiency when values are closer to +1 (Nash and Sutcliffe (1970)).

$$E = 1 - \frac{\sum_{i=1}^{n}\left(Mi - Si\right)^2}{\sum_{i=1}^{n}\left(Mi - \overline{M}\right)^2} \qquad (3.16)$$

The root mean square error, RMSE, is a measure of the average magnitude of difference between measured and simulated values and ranges between zero and positive infinity. RMSE close to zero indicates the best model performance. It is calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Mi - Si\right)^2} \qquad (3.17)$$

The coefficient of determination, R^2, shows the proportion of the variance of simulated and observed values explained by the model and ranges from 0 to 1, with values close to 1 indicating a good agreement. It is calculated as:

$$R^2 = \left[\frac{\sum_{i=1}^{n} \left(Mi - \overline{M} \right) \left(Si - \overline{S} \right)}{\sqrt{\left(\sum_{i=1}^{n} \left(Mi - \overline{M} \right)^2 \sum_{i=1}^{n} \left(Si - \overline{S} \right)^2 \right)}} \right]^2 \qquad (3.18)$$

The coefficient of residuals, CRM, presents model tendency to over-estimate or under-estimate measured values of parameters. Values of the relative index CRM close to zero indicate the best fit of the model. CRM ranges from negative infinity to positive 1. The closer to 1 it is, the more robust the model is in simulation (Nash and Sutcliff, 1970).

$$CRM = \frac{\sum_{i=1}^{n} Mi - \sum_{i=1}^{n} Si}{\sum_{i=1}^{n} Mi} \qquad (3.19)$$

Where Si = simulated values, Mi = observed values, $\overline{M}$ = observed mean, $\overline{S}$ = simulated mean, n = number of observations.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents the secondary data, results of the field trials and discussion of the results. To analyze the data on the effect of full and deficit irrigation treatments on the final onion yield and quality, some parameters were considered which included fresh bulbs yield, dry bulbs yield, bulbs diameter, colour, shape index, moisture content, irrigation water use efficiency and bulb weight. Evaluation of the performance of AquaCrop model in simulating onion yield under water stress condition was also presented. Field application of AquaCrop model on irrigation scheduling was also presented and discussed.

4.2. Secondary Data

4.2.1. Soil Properties

Analysis of the soil collected from the study site to determine physical and chemical properties gave the results in Tables 4.1 and 4.2.

Table 4.1: Soil physical properties of the study area.

Depth (cm)	Sand (%)	Clay (%)	Loam (%)	Textural Class (USDA)	FC (Vol %)	PWP (Vol %)	AWC %
0-15	70.4	5.0	24.6	Sandy Loam	17.0	6.8	10.2
16-30	70.0	6.0	24.0	Sandy Loam	18.5	6.9	11.6
31-60	65.0	10.0	25.0	Sandy Loam	20.0	7.0	13.0
Average	68.5	7.0	24.5		18.5	6.9	11.6

NB: FC= Field Capacity, PWP= Permanent Wilting Point, AWC= Available water holding capacity.

(Source: Author, 2013)

The bulk density was found to be 1.47 g/cm^3 and the overall texture was sandy loam with field capacity and permanent wilting point values of 18.5% and 6.9% respectively.

Table 4.2: Soil chemical properties of the study area.

Laboratory	Parameter	Symbol	Test results		Optimum
			Before correction	After correction	
Crop Nutrition	pH	pH	4.63	5.10	5.80-6.80
	Phosphorus, ppm	P	5.16	9.14	20.0-60.0
	Potassium, ppm	K	318	401	191-510
	Calcium, ppm	Ca	540	1050	1630-2290
	Magnesium, ppm	Mg	140	217	196-314
	Nitrogen,%	N	0.25	-	0.2-0.5
	Sodium, ppm	Na	62.7	53.2	<188
	C.E.C., meq/100g	C.E.C	12.5	-	15-30
	E.C.(salts), uS/cm	EC(S)	77.0	-	<800
	ECw (dS/m)	ECw	0.4		0.0-1.0
University of Eldoret	pH	pH	4.94	-	5.50-6.5
	Carbon,%	C	4.55	-	> 2
	Phosphorus, Mg/kg	P	4.19	-	>10 ppm
	Nitrogen, %	N	0.54	-	-

(Source: Author, 2013)

The chemical properties of the soil in Table 4.2 determined the type and quantity of fertilizer and amendments applied during the study to meet crop nutrient requirement and create suitable environment for crop development.

4.2.2. Irrigation Scheduling

The calculated irrigation schedule for zero effective rainfall for the field trial during the entire growing period of the crop is given in Table 4.3.

Table 4.3: Irrigation schedule for the entire season.

Month	March			April			May			June			July		
Decade	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
ETo(mm /day)	5.2	5.3	5.1	5	4.9	4.2	3.6	3.8	3.4	3.4	3.5	3.3	2.8	2.7	2.7
Kc	0.5	0.5	0.6	0.7	0.8	0.9	1	1	1	1	1	0.97	0.95	0.92	0.89
ETc(mm /day)	2.6	2.7	3.0	3.3	3.8	3.9	3.6	3.8	3.4	3.4	3.5	3.2	2.7	2.5	2.4
Inet (mm)	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
Igross (mm)	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
Irrigation interval, i (days)															
% ETc	Initial (No stress)		Development (stress)			Mid-season (No stress)					Late season (stress)			Irrigation stopped	
100	5	4	4	3	3	3	3	3	3	3	3	4	4		
90	5	4	4	4	3	3	3	3	3	3	4	4	5		
80	5	4	5	4	4	3	3	3	3	3	4	5	6		
70	5	4	6	5	4	3	3	3	3	3	5	5	6		
60	5	4	7	6	5	3	3	3	3	3	6	6	8		
50	5	4	8	8	6	3	3	3	3	3	7	8	9		

(Source: Author, 2013)

4.3. Yield response of onion to water stress

4.3.1. Fresh Bulbs Yield

The crop in this experiment was subjected to water stress at vegetative and late season stages with six different treatment levels, five of which were water stressed to different degrees while one acted as control and was not stressed (T100, T90, T80, T70, T60, and T50) as given in Table 4.4.

Table 4.4: Irrigation water applied to the crop throughout the season.

Treatments	T100	T90	T80	T70	T60	T50
Applied Irrigation water (mm)	494	468	441	416	390	364
Irrigation Events	38	36	34	32	30	28
NB: Each event is equivalent to 13 mm of water						

(Source: Author, 2013)

Yield per unit area obtained from fresh onion in the experiment was found to increase with increasing irrigation water levels across the replications of various treatments (Table 4.5 and Figure 4.1).

Table 4.5: Yield of onion and water saving under different irrigation treatments

	Replications	Treatments					
		T100	T90	T80	T70	T60	T50
Yield (ton/ha)	R1	34.4	32.2	32.2	25.6	24.4	20.0
	R2	35.6	33.3	31.1	26.7	22.2	18.9
	R3	33.3	32.2	32.2	23.3	21.1	17.8
Mean (ton/ha)		34.4	32.6	31.9	25.2	22.6	18.9
SD		1.1	0.6	0.6	1.7	1.7	1.1
CV%		3.2	2.0	2.0	6.7	7.5	5.9
Yield Reduction (%)		0.0	5.2	7.3	26.7	34.3	45.1
Water saving %		0.0	5.3	10.7	15.8	21.1	26.3

(Source: Author, 2013)

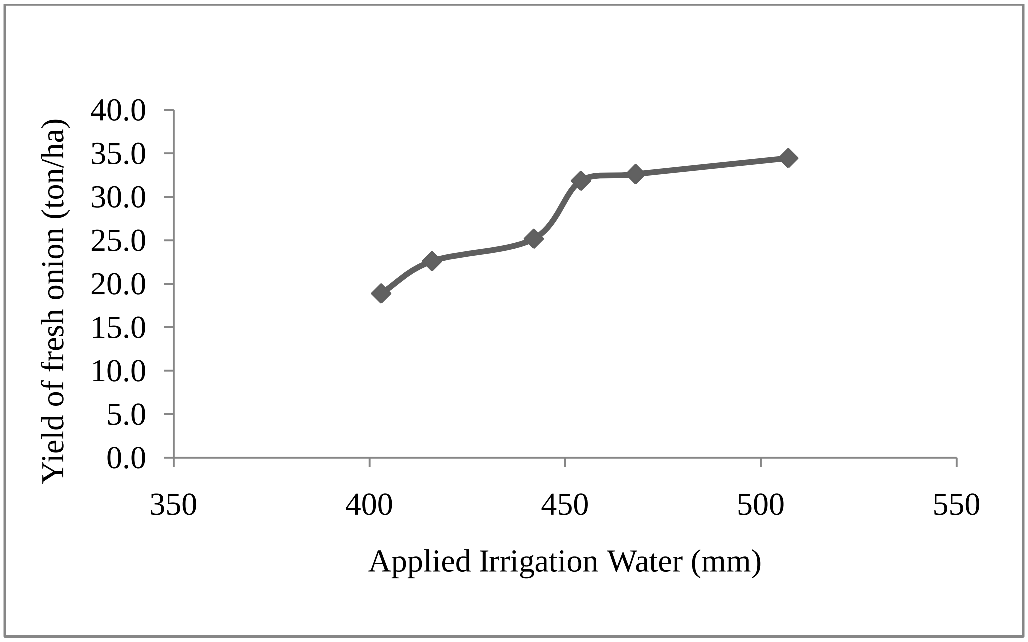

Figure 4.1: Yield of fresh onion under full and deficit irrigation treatments.

(Source: Author, 2013)

Yield from non-stressed treatments (T100) which acted as control was highest at 34.4 ton/ha while the most stressed treatment (T50) had the lowest yield of 18.9 ton/ha. The intermediate treatments T90, T80, T70 and T60 gave yields of 32.6, 31.9, 25.2, and 22.6 ton/ha respectively. The standard deviation varied between 0.6 and 1.7 ton/ha while the coefficient of variance ranged from 2% to 7.5% within the replications. The standard deviation within the treatments was low suggesting that yield was more clustered around the mean, hence reliable.

Analysis of variance across the treatments indicated that DI significantly affected yield (Fcalculated = 78.2, Fcritical= 3.11, $p<0.05$) at 5% probability. Calculated F is higher than the critical F in the tables leading to a high level of confidence in the accuracy of the relationship of water stress and yield. Coefficient of determination of 0.946 was strong and indicated a strong relationship between DI and yield meaning water as a variable influenced yield. This meant that water stress had a strong influence on yield. The effect was insignificant between T100 and T90 (Fcalculated=6.25, Fcritical=7.7), T90 and T80 (Fcalculated=2, Fcritical= 7.7), and T70 and T60 (Fcalculated=3.5, Fcritical=7.7) but was significant between T80 and T70 (Fcalculated=40.5, Fcritical = 7.7), and T60 and T50 (Fcalculated=10, Fcritical=7.7) to varying degrees at 5% probability.

The results also showed that yield reduction (Table 4.5) occurred significantly among the treatments which received minimum amounts of water (T70, T60 and T50) as opposed to those which received higher quantities (T100, T90 and T80). When water stress is imposed on the crop at the development and late stages of onion crop at varying levels, soil moisture tends to be depleted by the roots leading to reduced physiological activities which in turn affect root development.

If replenishment delays as in prolonged stress treatment, the crop wilts or recovers partially resulting in reduced yield and its components (Kirda and Kanber, 1999). Trials conducted on vegetables and cereals showed that the lowest yield was obtained during the full stress throughout the growing season (75% deficit). However, stressing the crops during the vegetative and late season stage of the growing season does not affect the crop yield significantly (Bazza and Tayaa, 1999 and Leskovar, 2010). This is because these growth stages are stress tolerant as opposed to initial and development stages which could result in significant drop in yield.

The results also showed that the effect of various treatments, influenced yields to different levels and the degree of recovery also varied according to the intensity of water stress as shown in Table 4.5. Yield decreased with increasing water stress signifying that the more stress the crop is subjected to, the slower it is for it to recover leading to progressively lower yields.

4.3.2. Dry Biomass Yield

Tables 4.6 and 4.7 gives the data for mean biomass yield for above ground, below ground and total dry weight.

Table 4.6: Above-ground dry biomass yield

	Replications	T100	T90	T80	T70	T60	T50
Weight (ton/ha)	R1	1.8	1.4	1.2	0.9	0.9	0.8
	R2	1.3	1.1	1.0	1.0	0.8	0.6
	R3	1.2	1.1	1.0	0.9	0.9	0.8
Mean		1.4	1.2	1.1	1.0	1.0	0.7
SD		0.3	0.2	0.1	0.0	0.1	0.1

(Source: Author, 2013)

Table 4.7: Below-ground dry biomass yield

	Replications	T100	T90	T80	T70	T60	T50
Yield (ton/ha)	R1	5.8	5.7	5.6	5.1	4.4	3.7
	R2	5.7	4.9	4.7	4.0	3.7	3.4
	R3	5.8	5.3	5.2	4.8	4.1	3.7
Mean		5.8	5.3	5.2	4.6	4.1	3.6
SD		0.1	0.4	0.5	0.6	0.4	0.2

(Source: Author, 2013)

Analysis of variance indicated that the effect of various levels of water stress on total dry biomass yield was significant ($p<0.05$) and thus affected the production of biomass proportionally (Figure 4.2).

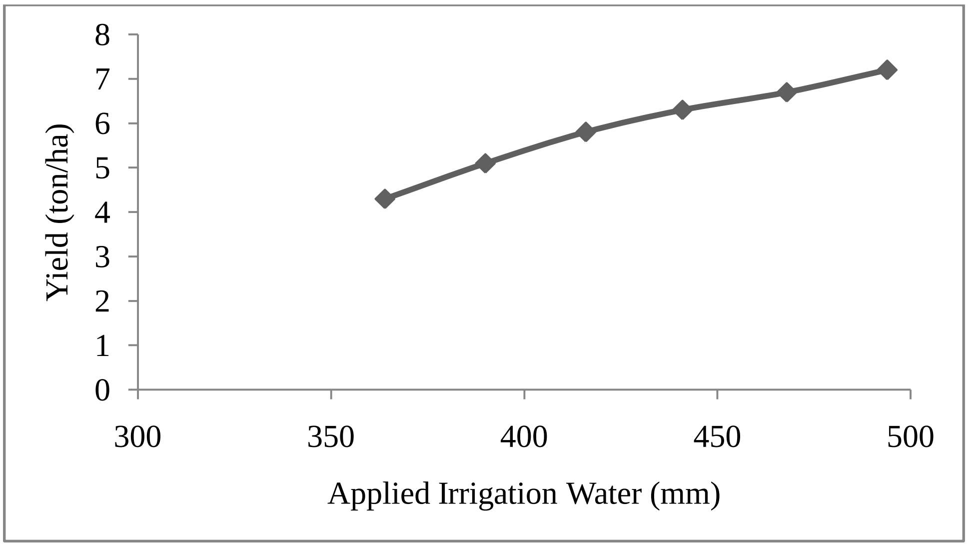

Figure 4.2: Effect of water stress on total dry biomass yield.

(Source: Author, 2013)

The lower the amount of water applied the lower the biomass yield. The intensity of moisture stress on the crop increased progressively from treatment T90 towards T50 reducing biomass production from a maximum of 7.2 t/ha to a minimum of 4.3 ton/ha. This observation was similar to the findings of Bagoury and Shaheen, **(**1977) who attributed reduced leaf and dry forage yield to water stress. Other findings (Tesfaye, 1997) also indicated that biomass production of haricot bean was reduced significantly by moisture stress.

Dry matter production is a result of interplay between photosynthesis and respiration. Any activity that tends to promote photosynthesis and reduce respiration increases production of dry matter. Therefore treatments which received higher amounts of water resulted in higher rate of photosynthesis and lower respiration rate leading to production of high dry matter. Sorensen and Grevsen (2001) concluded that water deficit resulted in higher dry matter percentage loss in bulbs. The analysis of optimum yield production level by use of linear programming model (solver) indicated that profits could be maximized at 20% water stress level (T80).

4.4. Quality Response of Onion to Water Stress

4.4.1. Onion Bulb Diameter

Onion bulb diameter was determined as an indicator of size and it was found to be significantly influenced by water stress (F calculated = 96.28, F critical = 3.12). The largest mean diameter (64 mm) was from T100 which received maximum amount of water (494 mm) while treatment T50 gave the smallest diameter (35 mm) having received the least amount of water at 364 mm (Table 4.8). Results indicated that bulb diameter varied proportionally with the quantity of irrigation water applied. There is therefore a linear relationship between bulb size and quantity of irrigation water applied. The coefficient of determination analysis between diameter and irrigation water applied was (R^2 = 0.927), indicating that the increase in bulb diameter in different treatments was attributed to increase in the quantity of water (Figure 4.3) hence quantity of water applied influences onion size.

The distribution of bulb sizes was such that large (>60 mm) formed 27 % of the total production, medium (45-60 mm) made 40% and the remaining 33% were small (<45 mm) as shown in Table 4.8. Large size was largely produced under treatments T100, T90, and T80 which received water amounts of 494 mm, 468 mm and 441 mm respectively. On the other hand standard deviation for the treatments varied with the highest being from T50 and the lowest T80. The low size variation of the bulbs as indicated by low standard deviation under T80 was an indication that the onion bulb diameters were more clustered closely around the mean under T80 than in other treatments. A similar effect of varied applied irrigation water levels on size of onion bulb was observed by Olalla et al. (2004) under drip irrigation. Leskovar (2010) indicated that it would be possible to adjust water conservation practices to a 75 percent ETc rate, as a means to targeting high-price bulb sizes without reducing quality. These results emphasize that adequate soil moisture content along the growing period encouraged the vegetative growth of the plant and enhanced the development of large and medium bulb size which is considered to be marketable.

Table 4.8: Onion bulb size as influenced by applied irrigation water level.

	Replication	Treatments					
		T100	T90	T80	T70	T60	T50
Onion diameter (mm)	R1	64.5	61.5	58.4	53.6	37.4	32.3
	R2	65.4	60.3	58.3	50.2	41.5	38.0
	R3	61.1	58.9	56.6	54.4	39.7	34.0
Mean (mm)		63.7	60.2	57.8	52.7	39.5	34.8
SD		2.3	1.3	1.0	2.2	2.1	2.9

(Source: Author, 2013)

Table 4.9: Onion bulb size (%) distribution in response to water stress.

Onion diameter distribution	Treatments						Proportion of Total (%)
	T100	T90	T80	T70	T60	T50	
>60 mm	80	57	27	0	0	0	27
45-60 mm	20	43	73	100	3	0	40
<45 mm	0	0	0	0	97	100	33

(Source: Author, 2013)

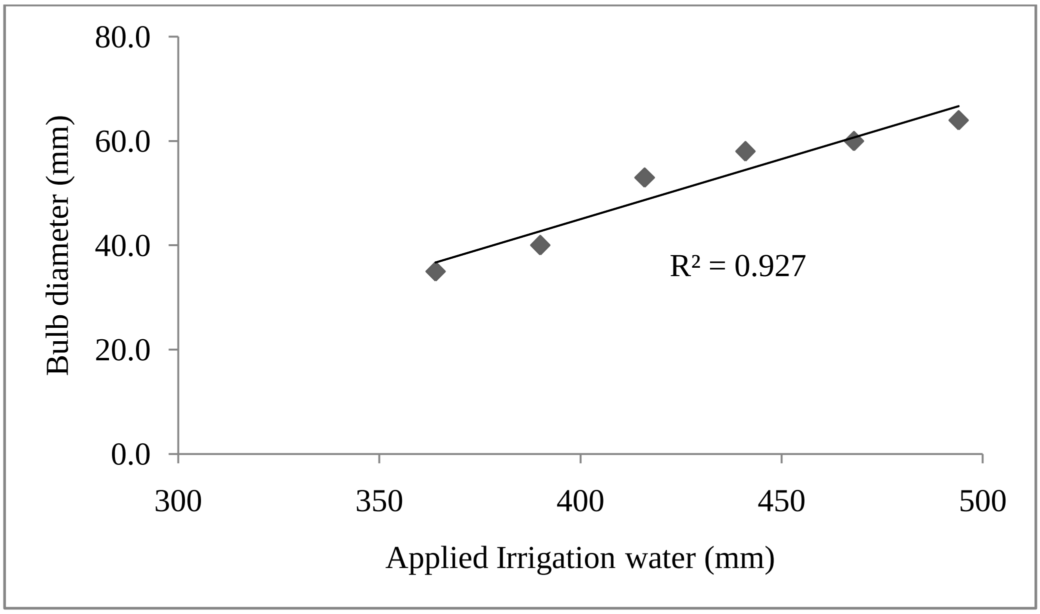

Figure 4.3: Effect of water stress on mean onion bulb diameter.

(Source: Author, 2013)

4.4.2. Mass of Onion Bulbs

Mean mass of onion bulbs is shown in Table 4.10. Fresh onion bulb mass across replicates was influenced significantly by DI treatments ($p<0.05$) at 5% probability with a coefficient of determination of 0.943 which suggests a direct relationship between DI and mass. The highest mean weight of bulbs (103 g) was obtained from treatment which received the highest supply of water while that which received the lowest quantity produced the least mean bulb weight (57 g).

There is a positive linear relationship between water stress and bulb mass. This means that water stress affects negatively the weight of individual bulbs (Figure 4.4).

Table 4.10: Mean mass of single fresh Onion bulbs

	Replications	Treatments					
		T100	T90	T80	T70	T60	T50
Bulb Weights (g)	R1	103	97	97	77	73	60
	R2	107	100	93	80	67	57
	R3	100	97	97	70	63	53
Mean		103	98	96	76	68	57
SD		4	2	2	5	5	3
CV		3.4	2.0	2.1	6.7	7.6	5.9

(Source: Author, 2013)

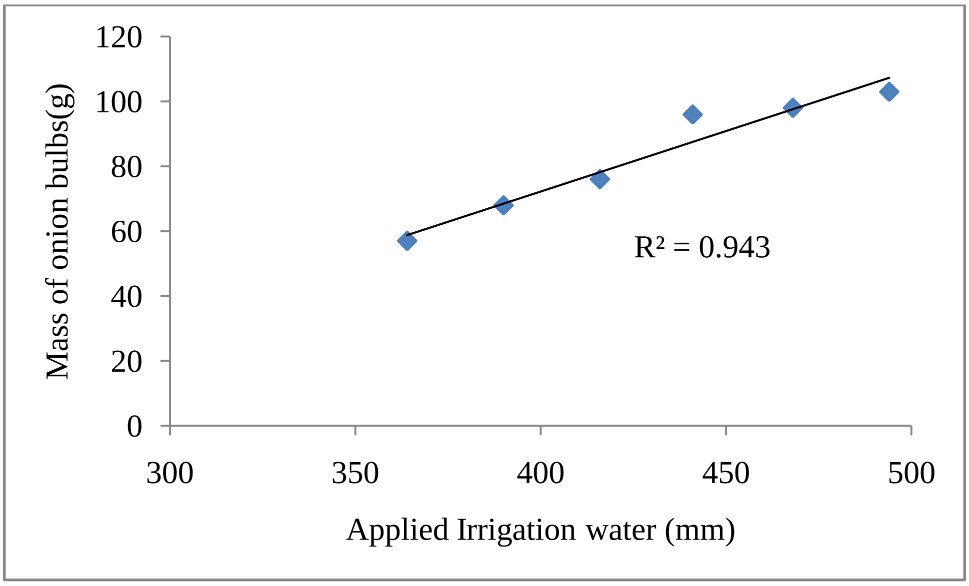

Figure 4.4: Effect of water stress on weight of fresh onion bulbs.

(Source: Author, 2013)

4.4.3. Moisture Content

The moisture content of onion bulbs as depicted in Table 4.11 do not vary substantially with treatments and range from 84% to 89%. The $F_{calculated}$ (3.97) was less than F_{table} (3.11) at 0.05 probability level. This means that the influence of water stress on onion moisture content was significant and hence the alternate hypothesis was accepted for this parameter.

Table 4.11: Moisture content of fresh onion bulbs under different treatments.

	Treatment	T100	T90	T80	T70	T60	T50
Moisture content (%)	R1	89	88	88	85	86	85
	R2	86	89	85	86	84	82
	R2	91	86	87	87	83	84
	Mean	89	88	87	86	84	84
	SD	2	1	1.5	1.5	1	0.6

(Source: Author, 2013)

4.4.4. Shape Index

The shape index data is presented in Table 4.12 and Plate 4.1. The results indicated that water stress at vegetative and late stages of growth of onion do not significantly affect the shape of onion bulbs. All bulbs were oval since the shape index is greater than 1.5. The null hypothesis was accepted for this parameter.

Table 4.12: Shape index of onion from the research trial

Treatment	D_e	D_p	T	SI
T100	63.69	42.02	21.63	2.11
T90	60.20	38.04	18.03	2.30
T80	57.79	36.46	15.31	2.45
T70	52.75	34.37	12.81	2.51
T60	39.52	33.81	9.81	2.17
T50	34.90	36.02	7.87	2.07

D_e - equatorial diameter, D_p - Polar diameter, T - Thickness, SI - Shape Index.

(Source: Author, 2013)

Plate 4.1: Shape and colour of onion bulbs under different treatments.

(Source: Author, 2013)

4.4.5. Colour and Texture

The colour and texture of the harvested crop of onion was red on the outer skin, purple white flesh and red inner scales (Plate 4.2). This description was determined using CIE colour system which indicated that the skin colour of the produced Onion bulbs matched the description of red onion by the supplier. It was therefore apparent that water stress treatment on onion did not affect colour and texture of onion skin and flesh. The colour and texture remains attractive to the eye and is appealing to the consumer. The null hypothesis holds for this onion quality.

Plate 4.2: Colour and texture of onion bulbs as influenced by treatments.

(Source: Author, 2013)

4.5. Irrigation Water use efficiency

Irrigation water use efficiency (IWUE) refers to the relationship between units of yield produced by a crop and the quantity of irrigation water applied (Steduto, 1996). Data on the amounts of applied irrigation water under different irrigation treatments are presented in Table 4.13. Full irrigation treatment (T100), was used as the reference point for comparison of irrigation treatments in saving water.

The net saving in irrigation water from T90, T80, T70 T60, and T50 were 5.3 10.7, 15.8, 21.1 and 26.3% respectively. IWUE values decreased with increasing water application level. The highest IWUE was obtained from treatment T50, 16.2 kg/ha/mm while the lowest was T100 with 13.1 kg/ha/mm. The relative decrease in IWUE was initially low up to T70, when it increased with increasing irrigation water application. Table 4.13 shows the IWUE values in the field trial expressed in kilograms of total dry bulb yield produced per mm of irrigation water applied and total water received from planting to harvesting.

IWUE for T80 and T70 were almost the same at 15.8 and 16.1 kg/ha/mm while the difference in dry bulb yield was 0.7 ton/ha .Water saving for these two treatments (T80 and T70) was 10.7% and 15.8 % respectively. Optimum yield is achieved by balancing between IWUE, yield reduction and water saving. These findings indicate that T80 results in 10.7% water saving without substantial negative effect on irrigation water use efficiency of the crop (Table 4.13 and Figure 4.5).

Table 4.13: Irrigation water use efficiency

Treatment	T100	T90	T80	T70	T60	T50
Irrigation water applied (mm)	494	468	441	416	390	364
Total DFY (ton/ha)	7.2	6.5	6.3	5.6	5.1	4.3
IWUE (Kg/ha/mm)	13.1	14.7	15.8	16.1	15.9	16.2

(Source: Author, 2013)

From the results the water stress applied to onion crop through deficit irrigation at vegetative and late growth stages had an overall negative effect on both fresh and dry biomass yields. Onion bulb diameter was equally affected by water stress giving rise to various respective bulb sizes. It is possible to predetermine the grades to produce for different market segments, by selecting appropriate water stress level to apply that does not compromise the yield per unit area. Irrigation water use efficiency decreased with increasing water stress upto optimum point at T80 where a balance exists between water saving and yield reduction without substantial decline in water use efficiency. There is also low size variation of the bulbs at this point. Producing at T80 saves 10.7% irrigation water but results in fresh bulb yield reduction of 2.5 ton/ha. The water saved is adequate to expand 0.12 ha of land and produce additional 3.8 tons of onions giving a total of 35.7 tons with the same quantity of water which could have yielded 34.4 tons/ha at full irrigation treatment. The hypothesis based on these results can be accepted to the extent that water stress affects yields negatively without substantially reducing yields at water stress level T80. At this level water saving (10.7%) resulted in low yield reduction (7.3%).

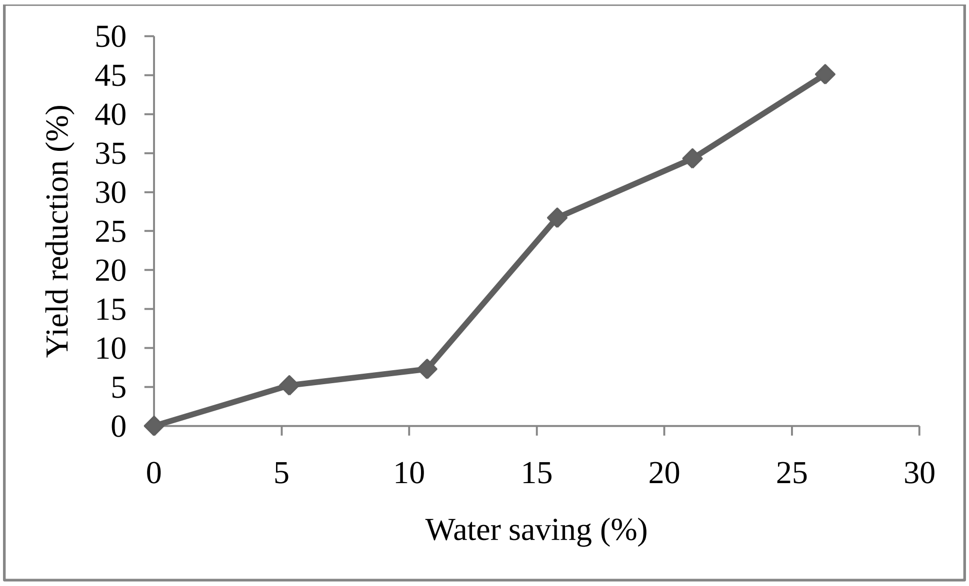

Figure 4.5: Optimum production based on water saving and yield reduction.

(Source: Author, 2013)

4.6 Yield Response Factor

The yield response factor (Ky) relates relative yield reduction to the corresponding relative deficit in evapotranspiration (ETc). The relationship is linear in nature between the two salient factors of the decrease in relative water use and the decrease in relative yield. It is an indication of the response of yield to reduced water use. The seasonal yield response factor obtained from the trial was 1.5 (Figure 4.6). However, yield response factors have been found to be dependent on locations. Kipkorir et al., (2002) found the seasonal Ky of onion to be 1.28 while Doorenbos and Kassam (1979) gave the parameter as 1.1. The result of the field trial showed a high impact of DI treatment on onion yield. When Ky> 1, the crop response is very sensitive to water deficit with proportional larger yield reductions; Ky< 1, the crop is more tolerant to water deficit, and recovers partially from stress, exhibiting less than proportional reductions in yield with reduced water use; Ky = 1, the yield reduction is directly proportional to reduced water use

(Doorenbos and Kassam, 1979). Since the obtained Ky>1, the crop response was very sensitive to water stress with proportional larger yield reduction.

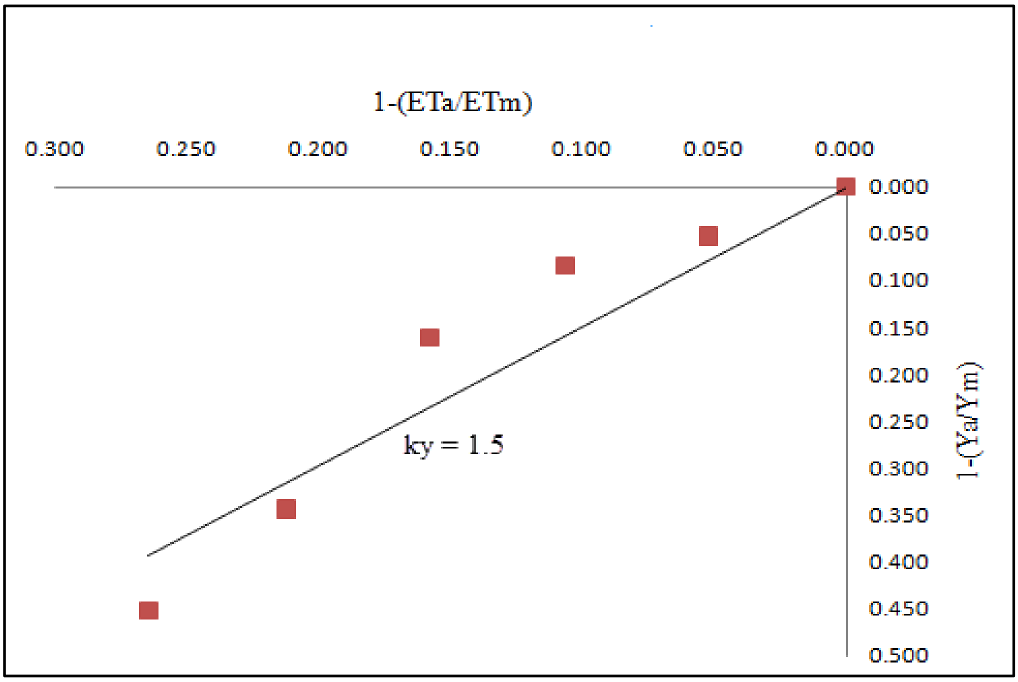

Figure 4.6: Relationship between relative yield decrease and relative crop evapotranspiration for onion throughout the growing season.

(Source: Author, 2013)

4.7. Crop Yield Modeling using AquaCrop

The data obtained from the field trials were used to calibrate and validate AquaCrop model for use in simulation of onion yield as a response to water stress under deficit irrigation conditions.

4.7.1. Model Calibration

The input data files consisting of meteorological data, plant, irrigation and soil information for the specific growing season of the crop, were first prepared before running the model. Calibration of the model was carried out by adjusting some of the model parameters to give the best matching results between observed and simulated output. The onion crop characteristics measured from the field trial was based on green canopy cover and yield. Calibration of the model is meant to reduce the parameter uncertainty (Salemi *et al*., 2005).

The crop modeling parameters used for calibrating and validating AquaCrop model in this study are presented in Table 4.14. The parameters were obtained from three main sources namely; calibration, estimation and field observation. Parameters obtained from calibration of the model consisted of canopy growth coefficient, canopy decline coefficient and normalized water productivity. Observed parameters included planting density, initial and maximum canopy cover, start of senescence, time to bulbification, time to reach maximum root depth and initial soil water content. Estimation provided optimum temperatures within which onion performs well, together with coefficient curve shapes and the threshold limits which are considered to be constant for C3 crops.

Table 4.14: AquaCrop model parameters for simulating onion development.

Description	Value	Units	Source
Base temperature	14	^oC	Estimated
Upper temperature	27	^oC	Estimated
Plant density per ha	333,333	-	Observed
Initial canopy cover per seedling (CCo)	10	cm^2	Observed
Canopy growth coefficient (CGC)	10.8	%	Calibrated
Canopy decline coefficient (CDC)	8.4	%	Calibrated
Maximum canopy cover (CCx)	80	%	Observed
Time to reach maximum canopy cover	60	days	Observed
Time to start senescence	120	days	Observed
Time to reach bulb formation	64	days	Observed
Time from transplanting to reach maturity	150	days	Observed
Maximum effective root depth	35	cm	Observed
Time from transplanting to maximum root depth	80	days	Observed
Reference harvest index (HI0)	80	%	Observed
Normalized water productivity	18	g/m^2	Estimated
Initial soil water content	Field capacity	%	Observed
Leaf growth threshold (P upper)	0.2	-	Calibrated
Leaf growth stress coefficient curve shape	3.0	-	Calibrated
Stomatal conductance threshold (Pupper)	0.55	-	Estimated
Stomata stress coefficient curve shape	3.0	-	Estimated

(Source: Author, 2013)

i) Green canopy cover

Calibration results of the model from the full irrigation treatment on canopy cover are presented in Figure 4.7. The simulated canopy cover for full irrigation treatment was compared with the measured canopy cover through statistical analysis tools (Table 4.15). The model simulated canopy cover fairly well based on the performance indices RMSE, E, CRM and R^2 of 5.73, 0.96, -0.07 and 0.91 respectively. RMSE of 5.73 is a sign of over-estimation of green canopy cover by the model. A negative value of CRM is an indication that the model over-estimated canopy cover. The efficiency of the model in simulating canopy cover was good at 0.96. The model can then be said to be robust in simulating this parameter. Similarly, the coefficient of determination of 0.91 indicates a good correlation between simulated and observed parameter.

Table 4.15: Statistical indices calculated for evaluating the performance of the model in simulating canopy cover for calibration.

Statistical index	RMSE	E	CRM	R^2
Optimal value	0	1.0	0	1.0
Canopy cover	5.73	0.96	-0.07	0.91

Key: RMSE-Root mean square error, E-Efficiency, CRM-Coefficient of residuals, R^2-Coefficient of determination.

(Source: Author, 2013)

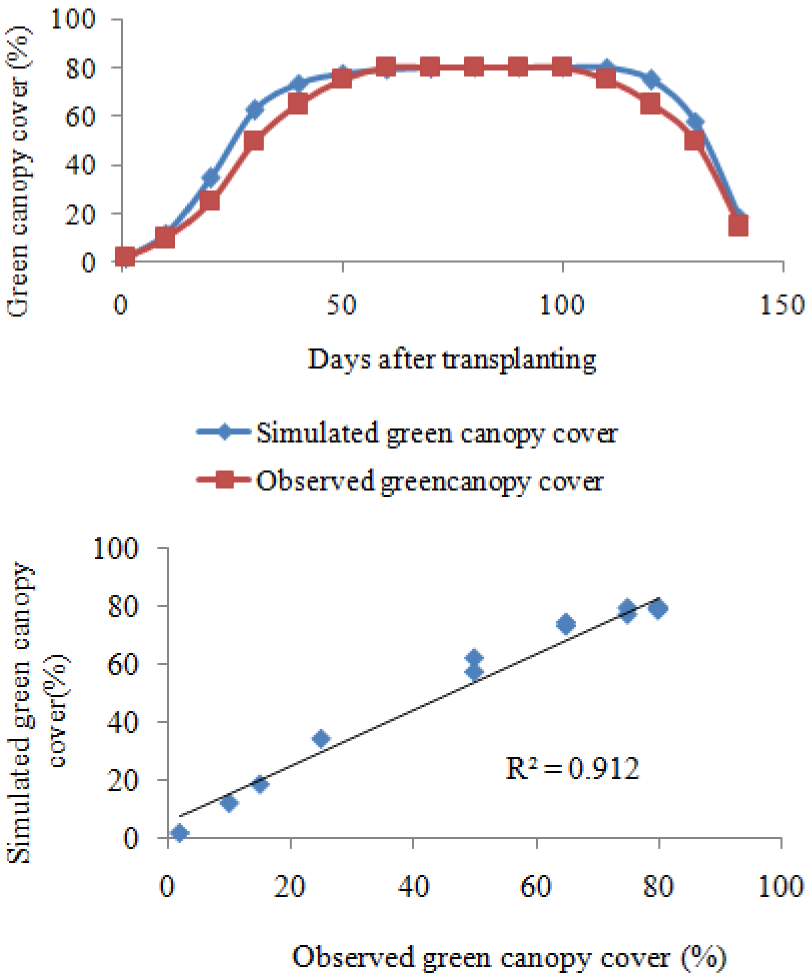

Figure 4.7: Observed and simulated green canopy cover T100

(Source: Author, 2013)

ii) Soil moisture

Soil moisture simulation results for calibration of the model for T100 are presented in Figure 4.8 and Table 4.16. Composite soil moisture content was computed from four compartments of soil depths. The statistical indices show that RMSE, E, CRM and R^2 were 0.95, 0.99, 0.04 and 0.798. The model under-estimated soil moisture as shown by a positive CRM. There was acceptable coefficient of determination as indicated by R^2 of 0.798 indicating an acceptable relationship between simulated and observed soil moisture. The efficiency of the model in simulating soil moisture was good as depicted by a positive value of 0.99. This means that the model over-estimated soil moisture content throughout the season and is evident in Figure 4.10. The reason for over-estimation of soil moisture was due to accumulation of irrigation water in the soil over time during the growing season.

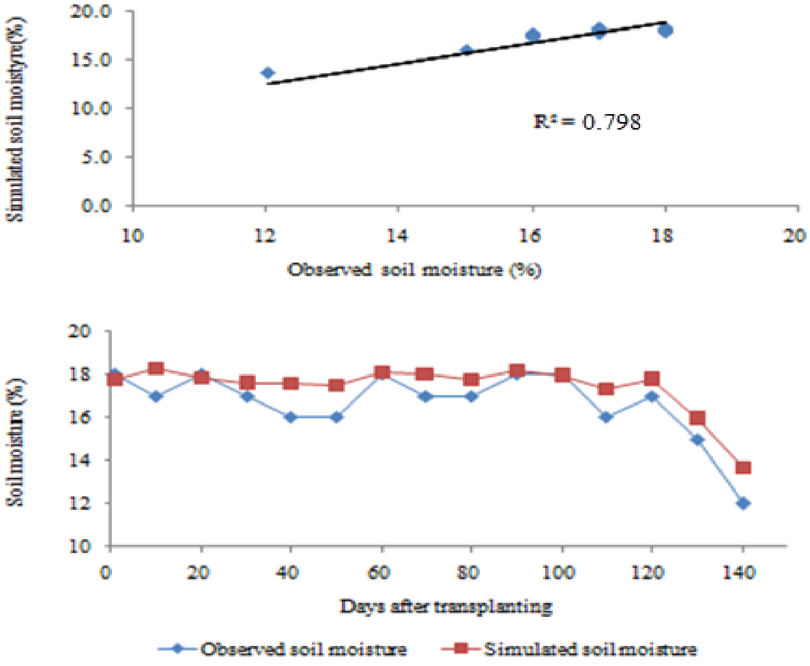

Figure 4.8: Observed and simulated soil moisture for T100

(Source: Author, 2013)

Table 4.16: Statistical indices calculated for evaluating the performance of the model in simulating soil moisture for calibration.

Statistical index	RMSE	E	CRM	R^2
Optimal value	0	1.0	0	1.0
Soil moisture	0.95	0.99	0.04	0.798

(Source: Author, 2013)

iii) Yield

Yield was obtained from the trial at the end of the season after harvesting. On running the model during calibration, the simulated results on yield and biomass under full irrigation were close to the observed data. The observed biomass and yield were 7.2 ton/ha and 5.8 ton/ha while the simulated results were 7.3 ton/ha and 5.8 ton/ha respectively. The model performed well on yield simulation.

4.7.2 Model validation

The results of validation of the model after calibration to confirm that the model closely represented the situation are presented in Figure 4.11, Figure 4.12, Figure 4.13, Table 4.17, Table 4.18 and Table 4.19.The observed and simulated data from green canopy cover and soil moisture content as tested by various statistical tools gave varying degrees of agreement although there was a central tendency for all the data of the two variables as shown in Figure 4.11 and Figure 4.12. Based on the coefficient of determination of 0.892 and 0.616 for all stressed treatments, the model was good in simulating soil moisture and canopy cover respectively in all the treatments.

(i) Green canopy cover

The discrepancy of simulated and observed canopy cover was minimal as depicted by a good R^2 for all treatments (Table 4.17). Coefficient of residuals (CRM) on the other hand clustered closely around zero but from the negative side except for T50. This was an indication that the model over-estimated the parameter, but was able to generate good fit results between the observed and simulated canopy cover. This finding is similar to those of Salemi et al., (2011) who found the model to have over-estimated canopy cover. The efficiency (E) of the model in simulating canopy cover was close to one (1) in all treatments with the highest being 0.96 while the lowest was 0.89. This means that the model is robust in simulating the parameter. The RMSE of the model in canopy cover simulation varied between 5.34 and 8.51. For the model to be considered as a best fit model, this value should tend towards zero from positive infinity. On this index the model is fair in simulation of canopy cover.

Overall from the indices considered, the model was able to simulate canopy cover based on its ability to separate transpiration and evaporation from evapotranspiration and translate the transpiration into biomass and attribute the loss of water from the uncovered ground to evaporation. Biomass production is related to yield through the harvest index of the crop. The model was able to predict both biomass and yield as close as possible to the measured quantity (Table 4.17 and Figure 4.9) with $p<0.05$ for both yield and biomass.

Table 4.17: Statistical indices derived for evaluating the performance of the model in simulating canopy cover for validation.

Statistical index	Treatment	RMSE	E	CRM	R^2
Optimal value		0	1.0	0	1.0
Canopy cover	T90	5.33	0.96	-0.06	0.98
	T80	6.96	0.94	-0.08	0.95
	T70	5.79	0.95	-0.07	0.97
	T60	6.96	0.93	-0.09	0.96
	T50	8.51	0.89	0.13	0.94

(Source: Author, 2013)

From the model calibration and validation results for simulation of yield as a response to water stress, the findings indicate that the model tends to over-estimate the development of green canopy cover as depicted by negative CRM. These findings are similar to what was found by Salemi et al, (2005) under deficit irrigation of wheat. It was further found that in East Africa, barley showed slightly lower performance under mild water deficit condition compared to full irrigation condition (Araya et al., 2010). According to Farahani et al., (2009), canopy cover simulation has to be done correctly as it is the core of AquaCrop performance which may affect rate of transpiration and in turn impact on biomass accumulation. For all treatments senescence is reached earlier in the observed than the simulated canopy cover. Similarly, maximum canopy cover for water stressed treatments was attained later progressively.

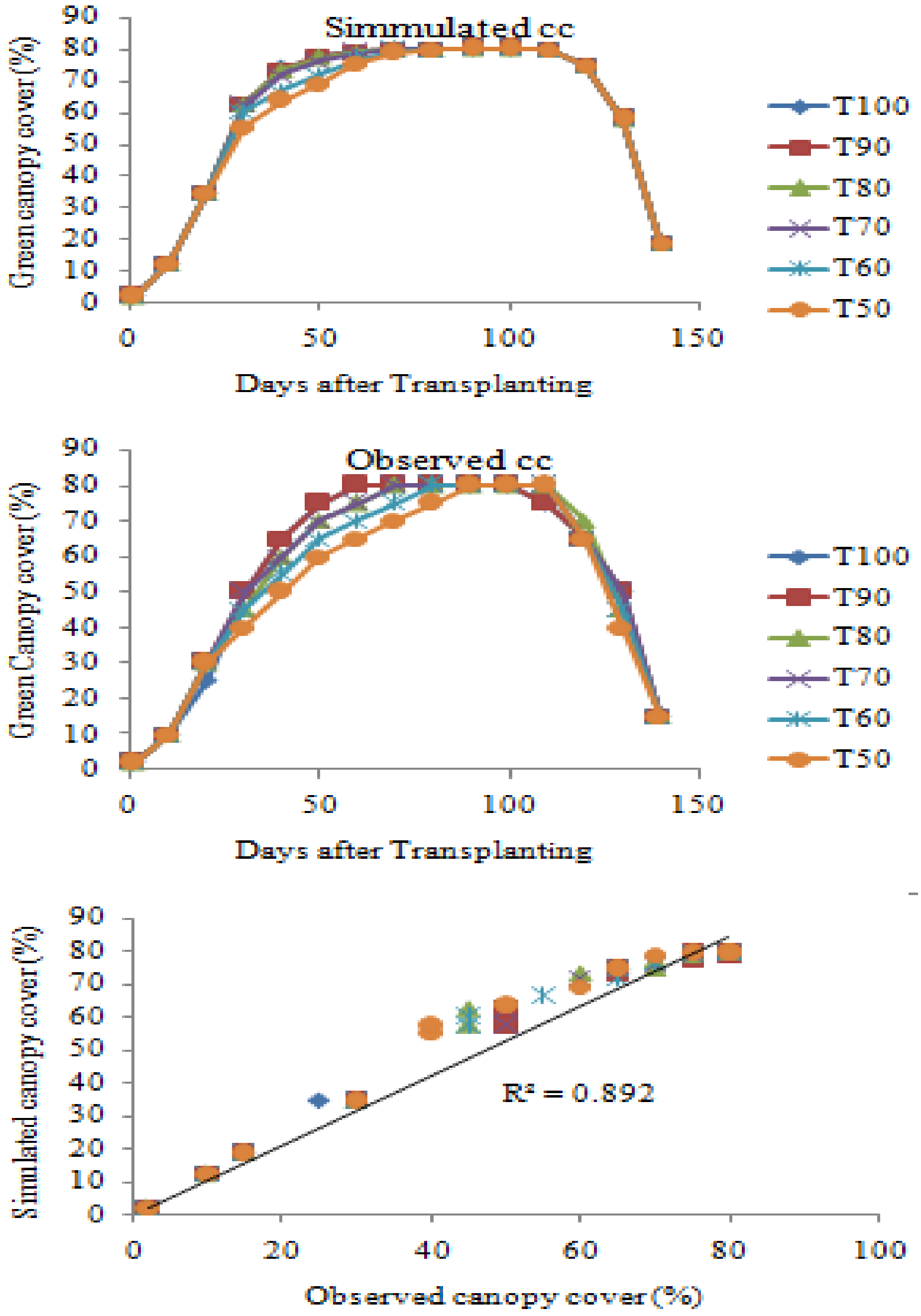

Figure 4.9: Comparison of simulated and observed green canopy cover from water stressed treatments.

(Source: Author, 2013)

(ii)Soil moisture

The model predicted the soil moisture content in the soil throughout the growing season of the onion crop (Figure 4.10) showing the variations corresponding to water application and stress events. It predicted soil moisture variation due to water stress subjected to the crop at vegetative and late season growth stages with some degree of variation (Table 4.18). Coefficient of determination (R^2) indicated that simulated and observed soil moisture content varied between 0.67 and 0.91 throughout all the water stressed treatments. CRM for all water stressed treatments was close to zero, with positive indices for all treatments, an indication that the model under-estimated the parameter. RMSE varied between 2.10 and 3.42, which are good indices. Efficiency of the model in simulation of the parameter was good across the treatments ranging from 0.31 to 1.3. This is an indication that the model is good at simulating the parameter.

Table 4.18: Statistical indices derived for evaluating the performance of the model in simulating soil moisture for validation.

Statistical index	Treatment	RMSE	E	CRM	R^2
Optimal value		0	1.0	0	1.0
Soil moisture content	T90	3.02	0.62	0.12	0.78
	T80	3.42	-1.3	0.14	0.67
	T70	3.00	-0.59	0.12	0.76
	T60	2.10	0.40	0.06	0.87
	T50	2.29	0.31	0.07	0.91

(Source: Author, 2013)

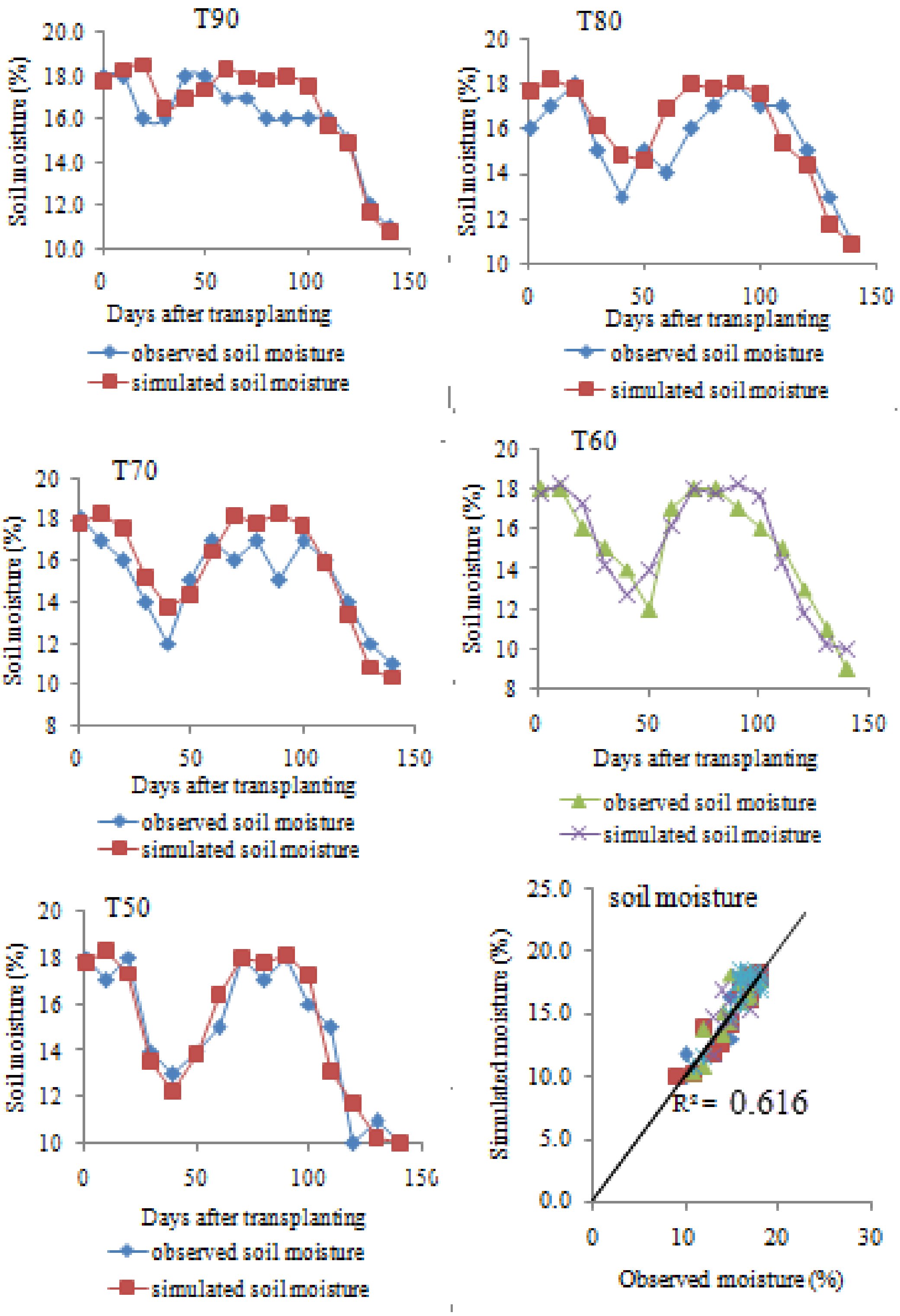

Figure 4.10: Comparison of simulated with observed soil moisture from water stressed treatments.

(Source: Author, 2013)

(iii)Yield

The results of yield and biomass (Figure 4.11) showed that the model performs best under full irrigation and declines with increasing water stress. From table 4.19, the model predicts yield and biomass fairly well upto treatment T70 before declining considerably. A similar observation was made by Heng et al., (2009). Accumulation of irrigation water in the soil over time before stressing a crop may affect the performance of the model under stress conditions (Salemi et al, 2005).

Table 4.19: Comparison of simulated and observed biomass and yield for stressed treatments.

Treatments		T90	T80	T70	T60	T50
Observed data(ton/ha)	Biomass	6.5	6.3	5.6	5.1	4.3
	Yield	5.3	5.2	4.6	4.1	3.6
Simulated data(ton/ha)	Biomass	7.2	7.2	7.1	6.6	6.4
	Yield	5.7	5.7	5.5	5.5	5.4

(Source: Author, 2013)

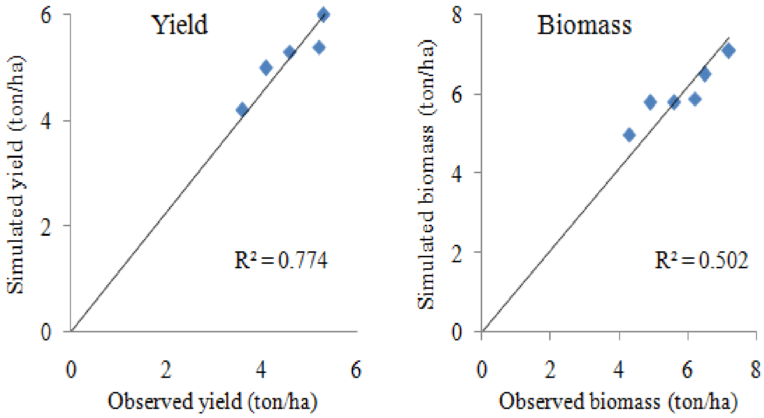

Figure 4.11: Yield and biomass of onion from all water stressed treatments *(Source: Author, 2013)*

4.8. AquaCrop Model Application

4.8.1. Introduction

Aquacrop model is an important tool for farmers and field extension workers. It can be used to derive irrigation schedules both for full and deficit irrigation application in light of decreasing water resources available for agriculture and the rising world population (Kijne et al., 2003). The model promotes timely irrigation application thereby improving irrigation efficiency and water productivity (Molden, 2003). The common practice of over-irrigation or under-irrigation experienced under traditional methods leads to consumption of excess or inadequate water, causing water loss and water stress to the crop respectively. These effects on water resources and the crops can be eliminated by using the model to generate irrigation schedules, hence ensuring that growing conditions are well maintained at optimal level throughout the growing season (Anac¸ et al., 1999). Guidelines therefore can be developed in summarized irrigation schedules and understandable formats for use by farmers and front line extension workers for specific crops of interest to the farmers. (De Nys et al., 2001).

4.8.2. Field Application of AquaCrop Model

Historical climatic data obtained from Kapsoya meteorological station for period between 2003 and 2012 were used in the calibrated model to develop irrigation schedules for three types of years namely dry, wet and normal. The rainfall frequency analysis was carried out on the historical climatic data using RAINBOW (Raes et al., 1996) to determine the homogeneity of the data and the three characteristic type of years with probability of exceedance of 20%, 50% and

80% corresponding to wet, normal and dry years respectively for the growing season between November and March for the years from 2003 to 2012. The findings are presented in Table 4.20.

Table 4.20: Simulated weather regimes

Type of year	Wet	Normal	Dry
Year	2006/07	2011/12	2010/11
Probability of exceedance (%)	20	50	80
Rainfall (mm)	338.1	240.1	142.1

(Source: Author, 2013)

The results pointed to the dry year to be 2010/11 with rainfall of 142.1mm, normal year 2011/12 with 240.1mm of rainfall and 2006/07 to be the wet year with rainfall of 338.1mm.Deficit irrigation schedules were then derived for the three characteristic types of years. With AquaCrop, the depth criterion representing a fixed irrigation application level was determined by considering various conditions consisting of irrigation method, crop and soil properties and local practices. Time criterion was selected to coincide with a fixed application interval in days.

Calibrated and validated model was run to simulate crop development from transplanting to maturity under rainfed conditions while generating irrigation schedules. The generated schedule was then compared with the observed deficit irrigation T80 where optimum water use efficiency was obtained in the trial and the stress levels adjusted at the two different growth stages to match.

4.8.3. Summarized Irrigation Schedules

Table 4.21 gives the summary of a simplified irrigation schedule for three weather regimes for onion crop under full and deficit irrigation (T80).

Table 4.21: Irrigation requirement for three weather regimes

Growth stages of onion (days)		Irrigation application Events					
		Wet Year (2006/07)		Dry Year (2010/11)		Normal Year (2011/12)	
		100% ETc	80% ETc	100% ETc	80% ETc	100% ETc	80% ETc
Establishment (0-20)		4	4	4	4	2	2
Development (20-50)		9	7	9	7	8	6
Mid season (50-100)		12	12	19	19	16	16
Late season(100-150)		9	7	13	10	12	10
Total no of events (13mm/event)		34	30	45	40	38	34
Applied Net irrigation water (mm)		442	390	585	520	494	442
Water saving (%)		11.8		11.1		10.5	
Production (ton/ha)	Biomass	6.72	6.52	8.54	8.25	8.97	8.31
	Yield	5.44	5.40	6.91	6.78	7.33	7.09
Production loss (%)	Biomass	3.3		3.40		7.47	
	Yield	0.74		3.04		4.50	

Irrigation application efficiency of 85% was used in the initial calculations.

(Source: Author, 2013)

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

It was concluded from the findings of the study that deficit irrigation at vegetative and late growth stages of onions influence yields in a positive linear trend with increasing quantity of irrigation water and decreasing water stress reaching optimum crop yield of 32.0 ton/ha at 20% water stress thereby saving 10.7% irrigation water. It was further concluded that production at this level optimizes water productivity without significantly affecting crop yields.

It was also found that deficit irrigation influenced the size and size distribution of fresh onion bulbs, with low size variation of the fresh bulbs at T80 as attested by low standard deviation of 1.0 as compared to other treatments. DI therefore can be used in deciding onion sizes to produce for a particular prevailing market.
Deficit irrigation does not affect the shape of onion bulbs as depicted by the shape index of more than 1.5. The colour of bulbs was also not affected by DI.

The AquaCrop model simulation of yield showed declining performance at higher stress levels in simulating green canopy cover, soil moisture content, yield and biomass. The model is useful in developing irrigation schedules for different weather conditions which can be applied by farmers through extension services.

5.2. Recommendations

1. DI technology is recommended for use by farmers and extension workers to optimize onion bulb yield and maximize crop water productivity by applying at vegetative and late season growth stages.

2. It is recommended that DI be used by onion producers in Uasin Gishu and Nandi counties in predetermining onion bulb sizes to produce for specific markets.
3. AquaCrop is a useful model recommended for use with acceptable level of accuracy for optimizing onion bulb yield production.

5.3 Recommendation for Future Research

Similar studies should be carried out with different irrigation levels of deficit irrigation to ascertain conclusively the influence of the same on yields and quality of onions.

The study should be replicated in different soils and agro-ecological zones in Nandi and Uasin Gishu counties.

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APPENDICES

Appendix I. Yield of onion bulbs from three replications for ANOVA analysis

Bulb No	Treatments					
	T100	T90	T80	T70	T60	T50
1	101	92	94	78	67	57
2	110	105	92	72	70	55
3	103	97	94	76	68	57
4	102	97	96	73	64	58
5	102	99	99	79	68	55
6	111	94	98	69	68	56
7	101	95	90	72	70	52
8	103	96	100	75	67	51
9	105	93	91	81	68	58
10	106	98	100	73	63	61
11	105	98	97	73	73	54
12	107	96	94	74	70	58
13	104	99	91	79	70	63
14	101	95	99	72	68	58
15	98	98	93	72	67	61
16	108	106	94	75	69	58
17	104	99	97	78	71	61
18	107	94	100	77	74	60
19	103	102	102	74	67	56
20	110	92	89	71	64	51
21	98	101	95	75	68	57
22	110	97	91	78	62	54
23	97	98	95	78	64	58
24	99	98	100	80	65	62
25	104	97	92	81	64	52
26	96	96	98	71	73	59
27	103	102	99	76	68	60
28	98	96	100	76	69	52
29	103	105	92	77	71	51
30	99	96	97	81	66	53
Mean weight of bulb (g)	103	98	96	76	68	57
Mean weight in ton/ha	34	33	32	25	23	19

(Source: Author, 2013)

Appendix II: Mean diameter of onion bulbs for ANOVA analysis.

Bulb No	Treatments					
	T100	T90	T80	T70	T60	T50
1	71.32	68.79	61.11	58.04	45.39	38.70
2	70.05	64.95	60.77	57.82	42.25	38.32
3	68.61	64.83	60.72	56.96	41.57	38.30
4	68.25	62.89	60.71	55.76	41.52	37.92
5	67.62	62.84	60.53	54.86	41.30	37.84
6	67.39	62.80	60.38	54.66	41.24	37.51
7	66.69	62.45	60.16	54.46	40.92	37.30
8	66.36	62.34	60.07	54.28	40.86	36.55
9	66.24	62.25	59.68	54.19	40.80	36.45
10	66.19	62.25	59.42	54.18	40.68	36.31
11	66.02	61.59	59.17	54.16	40.42	36.10
12	65.90	60.81	58.69	53.92	40.02	35.79
13	64.33	60.76	58.45	53.18	40.01	35.64
14	63.82	60.68	58.34	52.72	39.81	35.54
15	62.60	60.45	58.00	52.36	39.08	35.26
16	62.44	60.29	57.00	52.30	39.02	35.01
17	62.17	60.28	56.92	51.72	38.98	35.01
18	61.72	59.88	56.86	51.51	38.63	34.91
19	61.52	59.73	56.73	51.11	38.43	34.51
20	61.47	59.09	56.64	51.00	38.22	33.87
21	61.38	58.59	56.53	50.89	38.22	33.47
22	60.89	58.32	56.41	50.85	38.20	32.98
23	60.39	58.02	56.09	50.85	37.96	32.95
24	60.33	57.07	56.05	50.72	37.75	32.94
25	59.77	57.04	55.84	50.40	37.66	31.99
26	59.74	56.54	55.70	50.31	37.64	31.99
27	59.73	56.01	55.18	50.22	37.57	31.99
28	59.64	55.37	54.89	50.21	37.38	31.99
29	59.54	54.81	54.57	49.99	37.12	29.97
30	58.59	54.29	52.04	48.85	37.09	29.87
Mean Bulb diameter (mm)	64	60	58	53	40	35

(Source: Author, 2013)

Appendix III: Materials used in the study.

Plate 1A: Drip system filter ***(Source: Author, 2013)***

Plate 1B: Laboratory drying oven ***(Source: Author, 2013)***

Plate1C: Digital weighing balance ***(Source: Author, 2013)***

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Plate 1D: Soil particle distribution sieves ***(Source: Author, 2013)***

Plate 1E: Graduated measuring jug ***(Source: Author, 2013)***