Effect of supplemental irrigation on growth, yield and economic returns of onion *(Allium cepa)* and tomato *(Solanum lycopersicum)* in Kibwezi District, Eastern Kenya

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Declaration

This thesis is my original work and has not been presented for award of a degree in any other university.

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Dedication

To my dearest mother, brother Joseph, and other siblings, all of whom encouraged me to do what they never had a chance to do themselves.

To Mercy, whose daily motivations are priceless.

Angie and Roche, they will be proud of this work someday.

My friends, who encouraged and wished me well

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List of Abbreviations and Acronyms

ACZ	Agro-climatic Zones
AIC	Agricultural Information Resource Centre
ANOVA	Analysis of Variance
ASALs	Arid and Semi-arid Lands
CBO	Community Based Organization
CHE	Commission for Higher Education
CPE	Cumulative Pan Evaporation
DAT	Days after Transplanting
ERS	Economic Recovery Strategy
ET	Evapotranspiration
ET_o	Reference Evapotranspiration
ET_c	Crop Water Requirement
FAO	Food and Agricultural Organization
GM	Gross Margin
GoK	Government of Kenya
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Panel on Climate Change
IWUE	Irrigation Water Use Efficiency
KARI	Kenya Agricultural Research Institute
kc	Crop coefficient
kPa	Kilo Pascal

KVDA	Kenya Voluntary Development Association
LSD	Least Significant Difference
MDGs	Millennium Development Goals
MC	Moisture Content
MoA	Ministry of Agriculture
MOARD	Ministry of Agriculture and Rural Development
NWOG	Ndiwa Women Group
OM	Organic Matter
RBD	Randomized Block Design
RH	Relative Humidity
SAR	Sodium Adsorption Ratio
SAT	Semi-arid Tropics
SI	Supplemental Irrigation
SLM	Sustainable Land Management
SSA	Sub-Saharan Africa
UNDP	United Nations Development Programme
USDA	United States Department of Agriculture
WUE	Water Use Efficiency
SWT	Soil Water Threshold

Abstract

Water availability, amount and distribution throughout the year is very crucial to sustained agricultural production in the water-scarce arid and semi-arid lands (ASALs). That water is scarce in the ASALs is undisputable. It is on this premise that water has been the most important and most limiting resource to agricultural productivity of Kibwezi District, mostly resulting from a combination of low and erratic rainfalls. Skillful water management is, therefore, the key to survival in these drylands. If no appropriate measures are taken, the harder and more expensive it will be to salvage the resource bases. Rainfed agriculture, consequently, need to be supplemented with irrigation to realize the potential of our soils.

Trials were conducted in Kikumbulyu location of the new Kibwezi District (Makueni County) to examine the effects of supplemental drip irrigation on growth and yield characteristics and economic feasibility on tomato (*Solanum lycopersicum* var. cal J) and onion (*Allium cepa* L. var. red Creole). A 4-day irrigation (supplemental) interval was adopted for the research. The trials involved two modes of supplemental irrigation: twice -a-day (T1) and once-a-day (T2) water application to both tomato and onion fields, and a control (rainfed, T3). Treatments were laid out in a completely randomized block design (CRBD) with three replications.

Two seasons of tomato trials were conducted. The first experiment in 2009 coincided with onion trials. The second experiment was carried out in 2010. A total of 206.3 mm of rain was received during the first tomato season, against the total season crop requirement of 415.01 mm. In the second season, total rainfall was 328.9 mm against the crops' requirement of 394.97 mm. The supplemented amounts (for T1 and T2) were 202.76 and 207.75 mm in season 1 and, 114.15 and 126.12 mm in season 2. Onion required 390.08 mm, but only 234.8 of rainfall was received during the growth period. T1 and T2 plots were thus supplemented with 182.8 and 184.74 mm, respectively.

For tomato season 1 and 2, the measurable parameters (plant height, numbers of leaves and numbers of branches per plant) were monitored at three stages, flowering, fruit setting and maturity. The same parameters, except number of branches, were monitored in onion at 30, 60, and 90 days after transplanting (DAT). These parameters responded positively to the supplemental irrigation in both onion and tomato. There were significant differences ($p \leq 0.05$) in the growth characteristics of T1 and T2 plots when compared to those of T3. Supplemental irrigation also had a remarkable effect on increasing crop yields based on the fruit/bulb yield analysis for the two crops. When compared to T3, T1 and T2, respectively, represented a 78.91% and 63.14% increase in tomato (season 1) marketable yields. The effect of supplemental irrigation over rainfed agriculture was even more outstanding on onion, resulting to a yield increase of 153.16% and 137.97% in T1 and T2 plots, respectively. Onion water use efficiency increased with increasing water application, with the results obtained in T1 and T2 being significantly higher ($p < 0.05$) and different from those of T3. However, tomato results showed a deviation from this trend, irrigated treatments T1 and T2 had significantly lower WUE compared to T3. The trials' results for both crops also demonstrated that the twice-a-day supplemental irrigation mode at 4-day interval (T1) was comparatively effective in enhancing yields than supplementing at once-every-day (T2).

When the gross margin analysis was carried out for the supplemental irrigation system (SI) and compared to the current rainfed agriculture, it could be adduced from the results that potentially higher benefits in terms of yield increases can be obtained through the combination of supplemental irrigation and other appropriate agronomic practices specific to the crops grown. The yield increases for both crops with supplemental irrigation alone was sufficient to compensate for the investment of input and capital in the system.

Since the current rainfed production system would most definitely result into an economic loss to the farmers, it would be wiser to encourage farmers to invest in supplemental irrigation as a means to cushion against losses. What are needed are efforts towards enhancing farmers' willingness to act with self-interest towards its adoption. It would also be more prudent if vigorous rural extension services were initiated to encourage culture change among small-scale farmers so that they can shift to growing high value crops like tomato and onions, as opposed to traditionally grown low-yielding crops like maize. Supplemental irrigation, in general, requires that the crop be of high value in order to pay for the extra investment.

Chapter One

Introduction

1.1 Background information

One in seven people in the world live in semi-arid regions. These people (more than one billion) are both cause and victim of increasing degradation of the fragile environment. Almost two thirds of these people have been affected by the direct and indirect effects of deteriorating conditions, including insufficient fresh water (ILRI, 2006). Recent studies indicate that semi-arid Africa may experience large scale water stress and yield reductions and may result to 50% increase in undernourished people in less than 30 years time (Morton, 2007).

Most of the countries currently classified as water-stressed are in Africa, and their numbers are likely to increase, independent of climate change. This is due to increases in demand resulting from population growth, degradation of watersheds caused by land-use change, and siltation of river basins and reduction in precipitation. This scenario does not auger well with respect to agricultural productivity and subsequent food security. The extreme weather conditions associated with climate change will further aggravate the situation (Hay, 2007).

Climate change, especially as indicated by protracted drought, is one of the most serious climatic hazards affecting the agricultural sector of the continent. As most of the agricultural activities in African countries hinge on rainfed, any adverse changes in the climate would have a devastating effect on the sector, and the livelihood of the majority in the region (IPCC, 2007). Climate change also threatens irrigation by shifting the world's rainfall patterns, changing river flows, among other threats and consequences.

The reality on the ground is that there would still be persistent crop failures in semi-arid areas which dominate most countries in Sub-Saharan Africa (SSA), a key indicator of poverty. Poverty mapping in the developing world by Thorton et al. (2003) indicated that numbers of poor people were greatest in SSA, particularly in the mixed rainfed farming systems. Poverty and household survey data for east Africa in general, and Kenya in particular indicated that many poor households were confined in the arid and semi-arid lands (ASALs) (Thorton et al., 2003). Kenya has close to 590,000 km^2 of land mass. Only about 16% of this is classified as medium and high potential (MoA, 2005). Over 80 % of the country falls under ASAL environments (Willem van Cotten, 2007).

The ASALS in Kenya are predominantly characterized by low and variable rainfall, which rarely exceeds 750 mm (Ngigi, 2003; GoK, 2004b). The ASALs are prone to harsh weather conditions rendering the communities within this region vulnerable to natural hazards, mainly droughts. The water resource in these areas is limited and many of the streams only flow during the wet seasons and remain dry for most of the year. These areas, therefore, may not support sustainable and productive agriculture under their natural conditions. Meaningful agriculture may, however, be realized if the scarce water resource can be properly utilized for supplemental irrigation or dry-season irrigation.

Continued water scarcity will definitely worsen the food security. According to available data the world's irrigated area was at 277 million hectares in 2001(Gilland, 2002). Surprisingly, in sub-Saharan Africa, only 4% of the total arable land is under irrigation. Kenya's irrigation potential is close to 1.3 million hectares. Only 21% of that potential has been developed so far (GoK, 2003). It is, however, predicted that by the year 2030, 70% of the world's cereal grains will come from irrigated land (Gilland, 2002). This means the same opportunity exists for the production of high value crops like tomato and onions. As most governments signal a shift towards irrigation-based farming, the question of water security arises. The scarce water resources continue to be transferred to non-farm uses because of rapidly growing demands of industries and cities.

Current global concerns on attainment of food security and poverty alleviation require new strategies with marked potential for water conservation and yield increase. The challenge in the ASALs in Kenya and the rest of SSA is to develop an innovative approach to sustainable land management (SLM) where resource conservation and land rehabilitation can be combined with improved livelihoods and income generation for local communities and farmers/herders (Ngigi et al., 2005). Continuing to ignore the specific needs of ASALs will result in increased food insecurity, poverty and environmental degradation. Willem van Cotten, (2007) envisaged that such trend would result in close to 50% increase in undernourished people in less than 30 years time.

With regard to agricultural production and water, and in reference to climate change, Bates et al. (2008) recommended some adaptation measures including: a) adoption of varieties and species of crops with increased resistance to heat stress, shock and drought; b) modification of irrigation techniques, including amount, timing or technology (e.g. drip irrigation systems); c) improved water management to avert waterlogging, erosion and nutrient leaching; d) adoption of water-efficient technologies to 'harvest' water, conserve soil moisture (e.g. crop residue retention, zero-tillage), and reduce siltation and saltwater intrusion, among other measures.

To respond well to weather vulgarities and to sustain crop production for smallholder farmers, selective agriculture where high value crops are preferred over the traditional varieties should be encouraged. This study, therefore, sought to examine the effect of supplemental irrigation on growth, yield and economic returns of onion *(Allium cepa)* and tomato *(Solanum lycopersicum)* in the semi-arid environment of Kibwezi District, Eastern Kenya.

1.2 Problem Statement

Kibwezi District forms part of the arid and semi-arid lands in Kenya; which are home to more than 30% of the country's population (GoK, 2004b). Since the people of Kibwezi are dependent on rainfed agriculture for their livelihood and to ensure food security, vulnerability here is high due to unreliability of rainfall (UNDP, 2002).

Persistent crop failures in ASALs, which dominate most countries in sub-Saharan Africa, have been significantly attributed to climate change and its negative consequences such as increase in pest and disease incidents, insufficient and unreliable rainfall, protracted drought, flash floods. Protracted drought, unpredictable and unreliable rainfall has had a drastic change on the local agriculture. Most of the Kibwezi District is classified as semi-arid with a low rainfall range of 300 and 700 mm per annum. The district is hot and dry with an evapotranspiration rate sometimes higher than twice the annual rainfall (Ngigi, 2003; GoK, 2004b). Rainfall patterns in the district are unpredictable and are subject to high variations in time and space. This is a phenomenon that warrants immediate attention from all concerned.

Drought is a major cause of poverty in the district and the most vulnerable are women, children, and the aged and persons with disability (GoK, 2008). Money that could be gainfully invested is spent on relief food during the dry period. Despite this, there is high potential for irrigation along the seasonal rivers/streams that can lead to increased food crop production for local consumption and commercial purpose

But the effects of climate change and its negative consequences and/or deteriorating environmental conditions alone are not to be blamed for diminishing agricultural returns. There are a number of clearly distinguished human and management failures that, too, need be addressed both at individual and community levels. Low-cost drip irrigation has already been successfully implemented in SSA (Mvungi et al., 2005), but there is generally low level of awareness and low acceptance of such new technologies among the small-scale subsistence farmers. Despite the perceived positive impacts the adaptation of this technology could have on the local agriculture, there is still lack of investment on the same. In a few places where irrigation projects have been initiated, there are low social responsibility and ownership of such projects at individual and corporate levels on environmental matters (GoK, 2008).

Unsustainable resource use, including inappropriate land use and poor management of the scarce water are realities in the district. Over the decades the inhabitants of this region have maintained their old tradition subsistence farming, mostly growing cereals (maize) as the main food crop, putting none or little emphasis on growing other high value crops like tomato and onions. Nonetheless, the production of these main food crops in the district has been fluctuating over the years due to the low, unpredictable, erratic and inadequate rainfall. This has created food insecurity among the general population (GoK, 2008). This is a big challenge since agricultural productivity of an area is a critical constituent that needs to acclimatize in the face of both climate and socio-economic pressures.

The current situation in the region is not sustainable since water resources are scarce and, where available are under-utilized or, in most cases, excessively utilized without a sense of conservation by those who have access to it. The result is repeated water shortage and poor management as demand for water increases. Even if water could be plentiful in this region, its efficient use and proper management would still be necessary. Owing to increasing human and livestock populations, it has become difficult to allocate sufficient water for agricultural demands without competing with other pressing needs for fresh water such as domestic and industrial water use in water scarce regions.

1.3 Justification

Food security and rural livelihoods are intrinsically linked to water availability and use. Food security is determined by the options people have to secure access to own agricultural production and exchange opportunities. These opportunities are influenced by access to water (Coulter 2008; Holzmann et al., 2008). Settlement in the ASALs can be made more successful with appropriate design of water collection and storage systems and efficient water use, for both domestic and agricultural use.

In view of the escalating levels of poverty and the need to improve livelihoods in the ASALs, priority for irrigation should be given to high value crops such as tomatoes and onions. The Vision 2030 for Kenya and the Economic Recovery Strategy (ERS) for wealth and employment creation (GoK, 2003) recognized the crucial role of supplemental irrigation and rehabilitation of the ASALs in contributing to economic growth, poverty eradication, and improved human nutrition.

That water is scarce in the ASALs is undisputable. It is on this premise that water has been the most important and most limiting resource to agricultural productivity of Kibwezi District, mostly resulting from a combination of low and erratic rainfalls. Skillful water management is, therefore, the key to survival in these drylands. If no appropriate measures are taken, the harder and more expensive it will be to salvage the resource bases. Rainfed agriculture, consequently, need to be supplemented with irrigation to realize the potential of our soils.

On a classification based on moisture availability, Kibwezi District is classified as having the probability of being 80-100% ASAL (GoK, 2004a). However, it should be noted that the issues facing Kibwezi District, and several other districts in Kenya, may be intricate, but the solutions to them can come from simple interventions. Since the majority of farmers and other local water users are not knowledgeable of the concept and/or technologies to improving yield per unit area of land, the findings of this study will lead to general awareness of the concepts of improved water use efficiency, thus ensuring optimum utilization of the scarce water resources. In particular, the demonstrations carried out in the two experimental seasons were meant to empower the targeted group (Ndiwa Women Group) with knowledge on sustainable farming besides meeting the research objectives cited below:

1.4 Study Objectives

1.4.1 Overall objective

The overall objective of the study was to examine the effect of supplemental irrigation on growth, yield and economic returns of onion (*Allium cepa*) and tomato (*Solanum lycopersicum*) in the semi-arid Kibwezi District, Eastern Kenya.

1.4.2 Specific objectives

To achieve this, the specific objectives addressed were to:

(a) Investigate the effect of supplemental irrigation on growth and development of onion and tomato;

(b) Determine the yield response of onion and tomato to different methods of supplemental irrigation;

(c) Determine the effect of different watering regimes on water use efficiency of onion and tomato;

(d) Evaluate the effect of supplemental irrigation on economic returns of onion and tomato.

Chapter Two

Literature review

2.1 Role of water availability on agriculture

Water is one of the major constrains to increasing crop production. Water stress has become a common phenomenon in a number of countries in sub-Saharan Africa. The main contributors to this situation being insufficient and unreliable rainfall and changing rainfall patterns. As a result, yields obtained by small-scale farmers in SSA are often less than half of the potential yields (Barron and Okwach, 2005).

The response of crops to water is complex since it is affected by the physical, chemical, and biochemical processes of environment, that are site specific (Payero et al., 2008) Yield response to water deficit can vary among variety of the same crop. In general, high quality varieties are also the most sensitive to water stress. Low quality ones are less responsive, hence more suitable for rainfed crop production in areas that are prone to drought (Passioura and Angus, 2010).

Quantifying crop yield versus water use relationship is important in matching crops and varieties to suitable rainfall regimes. It also offers guidelines on timing and levels of irrigation for maximizing returns (Sammis et al., 2000). When water supply does not meet crop water requirement, water stress will develop in the plant which will adversely affect crop growth and ultimately crop yield

Water deficit during the crucial crop growth stages together with low input interact to reduce yields. Yield losses due to drought are highly variable, depending on timing, intensity, and duration, coupled with other location-specific environmental variables, such as irradiance and temperature (Kijne et al., 2003a). Drought may cause complete crop failure or lead to varying amounts of reduction in biomass yields

Several researchers (Rockstrom and Fox, 2003; Tesfaye et al., 2008) have reported that most annual crops can be sustained through irrigation which plays a vital role in ensuring continuity of production and good quality crops. Supplemental irrigation can have a substantial effect to increase crop yield Crops response to irrigation depends on the water application regime that includes timing and the depth of irrigation The marginal response of crops to irrigation such as the increase in growth or yield due to additional units of irrigation water provides a basis for assessing the economic returns of irrigation. Despite the level of crop water requirement, there is a limit beyond which additional water is not economically justified (Payero et al , 2008).

The key to maximizing crop yield per unit of supplied water in dry areas is to ensure that as much as possible of the available moisture is used through plant transpiration and as little as possible is lost through soil evaporation, deep percolation and soil erosion (Sijali, 2001, Ngigi, 2003; Karuku and Gachene, 2006) One such promising technology for rural land use systems is drip irrigation (Sijali, 2001). Drip irrigation is capable of delivering water to the roots of individual crops as often as desired and at a relatively low cost and can achieve as high as 90-95% efficiency when compared with other irrigation systems.

2.2 Crop water requirements and sensitivity to water stress

2.2.1 Tomato water requirements

Moisture availability greatly influences tomato production and yields. Tomato needs adequate moisture during the early plant growth, fruit set and fruit enlargement stages (AIC, 2003). Studies reveal that approximately 550 mm of water is required by tomato to produce optimally.

A research by Imtiyaz et al. (2000) concluded that despite some variations, the overall result showed that a fixed amount of 18 mm of irrigation water application at cumulative pan evaporation (CPE) of 22 mm resulted in higher marketable yields and water use efficiency of tomato among other selected vegetable crops.

2.2.2 Tomato's sensitivity to water stress

The crop coefficient (k_c) relating reference evapotranspiration (ET_o) to water requirements (ET_c) for different development stages after transplanting are summarized in Table 1. Crops are more sensitive to water deficit during emergence, flowering and early yield formation than they are during early (vegetative) and late (ripening) growth periods (Payero et al., 2006b). Water stress during vegetative development reduces expansive growth of stems and leaves and results in reduced height, lower leaf area index and reduced internodes length. Kaziloglu et al. (2009) also observed this trend with corns.

Table 1: Crop coefficients (kc) for different development stages for tomato

Stages	Characteristic	Days	k_c ranges
Initial stage	germination and early growth when the soil surface is not or hardly covered by the crop	15-20	0.4-0.5
Crop development stage	from the end of the initial stage to attainment of effective ground cover	25-35	0.7-0.85
Mid-season stage	from the attainment of effective full ground cover to start of maturity (indicated by discoloring/falling leaves	25-45	1.05-1.2

	as in tomato)		
Late-season stage	from the end of mid-season stage until full maturity or harvest	35-45	0.85-1.1

Source: FAO (2002a)

Work conducted by Zegbe-Dominguez et al. (2003, 2006) showed that tomato grown using drip irrigation performed better under dry and sunny conditions than those grown under wet and humid conditions. Fruit rarely ripen fully during wet periods and production was generally higher during the dry season with irrigation (Rice and Tindal, 1994). Maximum fruit yields was reached when irrigation was performed at soil water threshold (SWT) of 35, 12 and 15 kPa during vegetative, fruit development, and maturation growth stages respectively (Wang et al., 2007). On-farm research in semi-arid locations in Kenya (Machakos District) and Burkina Faso (Ouagauya) indicated a significant scope for improving water productivity in rainfed farming through supplemental irrigation especially if combined with soil-fertility management (Rockstrom and Fox, 2003).

2.2.3 Onion water requirements

Onion with a shallow root system is very vulnerable to loss of moisture from the upper layer of the soil. Just like most vegetable crops, onion is sensitive to water deficit (AIC, 2003). Irrigation or supplemental watering must be provided if the crop is to maintain efficient growth (Bekele and Kitema, 2007). Juan et al. (2009) reported that onion growth in sandy soil under arid and semi-arid conditions must be adequately irrigated to meet the high evaporative demand and to assure maximum or near maximum yield with acceptable quality.

The crop requires frequent but light irrigations. The findings of several researchers (Bekele and Kitema, 2007; Juan et al., 2009) indicate that to meet full crop water requirements (ETc) the soil should be kept relatively moist; under a reference evapotranspiration (ETo) rate of 5-6 mm/day. The rate of water uptake starts to reduce when about 25% of the total available moisture in the first 30 cm soil depth has been depleted by the crop (p=0.25). Soil water depletion should, therefore, not exceed 25 % of available soil water in order to achieve high yields. Because they extract very little water from depths beyond 60 cm; most of the water is from the top 30 cm of soil. Irrigation application every 2-6 days is commonly practiced

Preliminary water requirement studies by Lema and Herath (1994), working in Ethiopia, revealed that a 5mm application at 4-6 days interval gave the highest yield with optimum water use efficiency. A range of between 350 - 550 mm of water is required by onion for optimum yield during its growing cycle.

2.2.4 Onion's sensitivity to water stress

For the sake of water use and management, onion crop in the field is categorized into stages (FAO, 2002a). The growth periods of an onion crop with a hypothetical growing period of 100 - 140 days in the field are presented in Table 2.

Table 2: The four development and phenological stages of onion and the related kc values

Crop stages	days	kc ranges
Establishment period (from sowing to transplanting)	30-35	0.4-0.6
Vegetative period	25-30	0.7-0.8
Yield formation (bulb enlargement)	50-80	0.95-1.1

Ripening	25-30	0.85-0.9

Source: FAO (2002a)

The crop coefficient (kc) relating reference evapotranspiration (ETo) to water requirements (ETc) for different development stages after transplanting is, for the initial stage 0.4-0.6 (15-20 days), the crop development stage 0.7-0.8 (25-35 days), the mid-season stage 0.95-1.1 (25-45 days), the late-season stage 0.85-0.9 (35-45 days), and at harvest 0.75-0.85 (Table 2).

Soil moisture is an important factor that influences bulb yield. Onions require frequent irrigations. Thus upper soil areas must be kept moist to stimulate root growth and provide adequate water for the plant (Anisuzzaman, 2009). Several investigators reported the sensitivity of onion growth and yield to water stress (Abdullah et al., 2005; Shock et al., 2008; Whalley et al., 2001). Whalley et al. (2001) concluded that water stress can induce a quiescent state in seedlings. He observed that newly germinated onion seedling showed good recovery after exposure to low water potential in the range -1.7 to -2.0 MPa for 35 days. Studies have also shown that the yield of the most onion cultivars decreased when water potential at a depth of 20 cm decreased below -20 kPa (Shock et al., 2004).

Years of field experiments with onion crops show that this plant is differentially sensitive to drought in each stage of its vegetative cycle (FAO, 2002a; Rockstrom and Fox, 2003). That means the impact of dry spell on final yields depends on which developmental stage that is affected (Rockstrom and Fox, 2003). The crop is most sensitive to water deficit during the yield formation period (3), particularly during the period of rapid bulb growth which occurs about 60 days after transplanting. The crop is equally sensitive during transplantation. For a seed crop, the flowering period is very sensitive to water deficit. During the vegetative growth period (1) the crop appears to be relatively less sensitive to water deficits.

If drought occurs at the seedling stage, it increases the rate of foliar emergence, produces a greater number of leaves, accelerates bulb formation by 15 days, and increases the final weight as compared with onions whose seedling stages coincided with periods of sufficient moisture. Emphasis should however not be put on the plant-water relationship at the seedling stage. Since most onions are transplanted, the transplanting stage marks one of the most crucial plant stages that require special attention. The plant-water relationship at this stage influences the final outcome (yield) of the season. Adequate moisture should be available to the crop to prevent water stress which consequently may lead to yield reduction.

When drought occurs at the beginning of the bulb formation, it causes a delay in foliar emergence, a smaller number of leaves, and a decrease in bulb weight (a significant difference as compared with those growing under optimal soil moisture conditions). In other stages of the cycle (post-transplanting, and 50 and 100% of the bulb's weight), the drought does not cause significant damage to the plant's growth. Root growth is reduced and bulb enlargement favoured in a wet soil (Shock et al., 2008)

El-Haris and Abdel-Razek (1997) also found an increase of 16.6% and 20.4% in total yield and water use efficiency of three onion cultivars when the amounts of applied water were increased from 425 and 462 mm to 749 and 687 mm in two seasons' field experiments in central region of Saudi Arabia. Shock et al. (2000) reported increases in total yield, marketable yield and profit of onion with increasing frequency of irrigation (soil water potential measured at 0.2 m depth ranged from –12.5 to –100 kpa). Shock et al. (2008), also, reported increases in total and marketable yields with increasing irrigation threshold.

2.3 Other factors limiting tomato and onion production

2.3.1 Environmental factors

Production of tomato and onion in tropical Africa has been limited by several factors among which are biological factors, water management, and environmental factors that include temperature, relative humidity and rainfall. The major biological production constraints reported in Kenya for tomato (KARI, 2005) include diseases (bacterial wilt, early and late blight, leaf curl, tomato spotted wilt virus, leaf spot and powdery mildew, insect pests and other arthropods (spider mites, thrips, white flies, African bollworm), nematodes, blossom end-rot and poor crop management especially lack of crop rotation practice. Tomatoes thrive best in low-medium rainfall with supplemental irrigation during the off-season. Wet conditions increase disease attacks and affect fruit ripening (Waiganjo, 2006).

Temperature, pre-bulbing plant size, planting time, light intensity, nutrient status and moisture availability have been shown to influence bulb growth and its ultimate size. Kimani et al. (1993) noted that temperature and moisture availability are the most crucial factors affecting onion production. Onion production is generally favoured by the relatively constant day length in the tropics. However, prevailing high temperatures and relative humidity (RH) have strong influence on bulb formation and storability (Brice et al., 1997). High temperatures, characteristic of many areas in eastern Kenya, accelerate bulb maturation, resulting in low yields due to small bulb size and high rates of formation of splits and doubles, which are low quality attributes.

Sombroek et al. (1982) classified the project area (formerly Kibwezi division of Makueni District) into six agro-ecological zones (ACZ). Zone IV and V are the most dominant ones with very high crop failure risks of 75-95 % and 95-100 %, respectively. Grains and pulses are the main cultivated crops; mostly maize (*Zea mays*), millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*), cowpea (*Vigna unguiculata*) and chickpea (*Cicer arietinum*). The natural vegetation is dominated by bushland and shrub and savanna type of vegetation (FAO, 1996). The district is generally low laying, rising from 300 m at lowlands of Mtito Andei to 1100 meters above sea level (m.a.s.l) on Chyullu Hills. The land consists of gently sloping terrain. It slopes south-eastwards towards the coast with a general land slope of 0-2%.

2.4 Water management

Water is the most limiting factor for crop production in the semi-arid tropics (SAT) and its efficient use deserves special attention in efforts to increase the productivity and profitably of agriculture in these areas (Barron and Okwach, 2005). It should, however, be noted that low annual or seasonal rainfall is not necessarily the critical constraint in crop production, but rather the irregular occurrence of rainfall events. Hence, strategies to reduce rural poverty will depend largely on improved water management in agriculture (Eva, 2009) as opposed to relaying on large supply volumes

For both rainfed and irrigated agriculture, the spatial and temporal variation of precipitation is key. The short-term variability of rainfall is a major risk factor. Soil moisture deficits, crop damage and crop disease are all driven by rainfall and associated humidity (Guzman-Plazola et al., 2003). The variability in rainfall intensity and duration makes the performance of agricultural systems in relation to long term climate trends very difficult to anticipate (Hay, 2007).

A number of countries in sub-Saharan Africa already experience considerable water stress as a result of insufficient and unreliable rainfall, changing rainfall patterns or flooding (Hay, 2007).

The impacts of climate change – including predicted increases in extremes – are likely to add to this stress, leading to additional pressure on water availability, accessibility, supply and demand. For Africa, it is estimated that 25% of the population (approximately 200 million people) currently experience water stress, with more countries expected to face high risks in the future (Wilhite, 2007). This may, in turn, lead to increased food and water insecurity for the concerned populace.

As already stated water management for agricultural production, just like the rural agricultural productivity, is a critical component that needs to adapt in the face of both climate and socio-economic pressures in the coming decades (Wilhite, 2007). Changes in water use will be driven by the combined effects of (i) changes in water availability, (ii) changes in water demand for agriculture, as well as from competing sectors including urban development and industrialization, and (iii) changes in water management.

With good management, especially when using drip/spot irrigation, efficiency as high as 80% can be realized as losses through deep percolation are minor.

2.5 Plants selection for the study

Tomato and Onion are among the major vegetables of global importance. They are also among the most important vegetable crops in Kenya. Out of 15 vegetables listed by FAO, onion falls second only to tomato in terms of total annual world production (Pathak, 2000). By the year 2000, the yield of onion in the world averaged at 17.01 t/ha (FAO, 2000b). Tomato is a highly valued crop, possible to grow under differing agro-ecological conditions

According to Mungai et al. (2000), the area under tomato in Kenya averaged 13,680 hectares between 1994 and 1998, most of it in the semi arid low lands. If more efforts are put into promoting the production of tomato, especially under supplemental irrigation, this figure could gone up by upto 50% by 2015. Most farmers will opt for tomatoes as the first choice vegetable, especially in small scale production. Mungai et al. (2000) also observed that this is the likely trend in the ASALs especially where irrigation is permissible. Despite their higher ratings, production of both onion and tomato faces major constrains. For tomato, the major production constraints especially in the ASAL are pests and diseases (MoARD, 2003).

The onion (*Allium cepa* L. var. red Creole) was further chosen for the study because of its availability and preference in the local market. Tomato (*Solanum lycopersicum* var. cal J) was chosen because of its high market demand and long shelf life. Musyoki et al. (2007) reported a shelf life of more than 14 days.

2.6 Selection of irrigation method

The choice of irrigation method depends on a trade-off between water economy on one hand, with energy and capital costs for any specific crop on the other. Key issues to factor in when choosing an irrigation system include, among others, the following: topography; soil characteristics; environmental factors; crop(s); the quality, quantity, and cost of available water. A guideline for interpretation of water quality for irrigation is provided in Appendix 31.

When drip irrigation system was developed, it was to facilitate farming in zones with the following climatic and soil limitations: hot and dry climate; sandy and gravelly underdeveloped and infertile soils; very limited water resources with high salinity (Karlberg et al., 2004). Available climatic data for Kibwezi District (Appendix 1) indicates a place with higher temperatures during the day; rainfall of small total amounts, strong seasonal distribution, with high spatial and temporal variability between seasons and years. The annual rainfall is 550 mm.

The soils are of low fertility and are low in organic matter levels. They are mostly sandy clay to clay (Gachene et al., 2003).

The greatest potential for drip (spot) irrigation is in situations where water is expensive or scant, for marginal soils, and for high-value crops. The selected crops therefore, further necessitated the choice of drip irrigation system. Tomato and onion, in common with most vegetable crops, are susceptible to water deficit. The crops require frequent, light irrigations, which can be applied with drip irrigation system

Precise water application ensures minimum losses. Slow rates of application ensures water percolates immediately downwards and sideways into the soil, reducing evaporation losses. Neither is there any significant runoff or percolation. Drip irrigation is capable of delivering water to the roots of individual crops as often as desired and at relatively low costs and can achieve 90-95% efficiency when compared with other irrigation systems.

2.7 Water Use Efficiency

The term efficiency is used to quantify the relative output obtained from a given input (FAO, 1997; Palacio, 1998). In economic criterion, water use efficiency is the financial return obtained from crop produced per volume of water used (Kadigi et al., 2004)

From the agronomic point of view, water use efficiency is generally defined as crop yield per volume of water (rainfall + irrigation) used to produce that yield (Fan et al., 2005). Simply put, it is the ratio of the amount of crop produced to the volume used by plants throughout evapotranspiration (ETc) process. WUE is therefore a measure of the productivity of water used by the crops.

Water use efficiency has also been reported in terms of crop harvest or marketable yields (Payero et al., 2008; Fan et al., 2005; Dagdelen et al., 2006), given as:

$$WUE = Yields / ETc \quad (2.1)$$

Where;

WUE = water use efficiency (kg/m^3)

Yields = harvested yields (kg)

ETc = total used/consumed water (m^3/season)

2.7.1 Factors affecting water use efficiency

Crop water consumptive uses may show a discrepancy from farm to farm, season to season, and day to day. Since WUE is a fraction of yield (Y) and water applied or need to be applied, factors affecting them (yield and water applied) will affect WUE (Ali and Talukdar, 2008). The factors that influence these changes can be grouped into management and natural factors. Imperative natural factors are; climate, soils and topography.

Management factors can usually be controlled although many are correlated with the natural factors. They include water supply, water quality, planting date, crop variety, fertility, plant spacing, irrigation scheduling, irrigation methods, cultivation and chemical spraying. These factors act to influence the amount of water used by plants, plant growth and subsequent yields (Passioura and Angus, 2010).

2.7.1.1 Climate

Climatic factors include temperature, precipitation, solar radiation, humidity, wind movement, and length of growing season. These elements sway, to a greater degree, the water balance of crop by their effects on the rates of transpiration (Valiantzas, 2006) The higher the solar radiation, the higher the temperature, the higher the evapo-transpiration from plant surfaces will be. Precipitation leads to an increase in available soil water, but it may also lead to an increase in humidity. Higher atmospheric humidity eventually reduces transpiration rates.

Eva (2009) notes that soil moisture deficits, crop damage and crop disease are all driven by rainfall and associated humidity. The inconsistency in rainfall intensity and duration makes the performance of agricultural systems in relation to long term climate trends very difficult to anticipate. For crops like tomato, higher humidity may also lead to favourable conditions for increased disease incidents (Guzman-Plazola et al., 2003). Diseased crops have low vigour and therefore reduced transpiration rates. High wind speed will clearly increase the transpiration rates.

2.7.1.2 Soil factors

The capacity of a particular soil to store available water is influenced by, among other factors, effective depth, aeration, texture, organic matter content, and structure (Al-Qinna and Abu-Awwad, 1998). They determine the water storage and release properties. The rate of water uptake by plants is directly affected by the available moisture content in the soil (Brady and Weil, 2002). Plant available water content is indicated by the different in soil water content at field capacity and at permanent wilting point

These physical and chemical soil characteristics also dictate the rate at which the plant is required to transpire and hence the rate at which it must extract water from the soil to maintain its own turgidity. Energy is involved or required for water to move through the soil, and to be absorbed by the plants roots. In dry soils, the water gets strongly attached to the soil surfaces leading to lower rates of water transmission through the soil and subsequent supply to the plant roots (Wan et al., 2007). Consequently, the rate of water uptake by plants gets lower and lower as the soil dries up, and easier as the soil is wetted. Saline soils with higher osmotic suction also reduce the range of available moisture (Soria et al., 2001).

Soil depth, texture and structure will also influence the crops' rooting characteristics which, to some extent, also affect the rate of uptake (Zhang et al., 2009). Evaporation (lose of water from the soil surface) plays a major role on plants' major growth periods and thus affect yields and water productivity. Soil fertility or N levels also affect the rate of development, especially of the leaves.

2.7.1.3 Cultural practices

Both spatial and temporal management of the crop within the farm play a role in determining crop water productivity. Khan et al. (2005) reports that timeliness of sowing or planting date, evenness of establishment, use of herbicides, plant spacing, crop variety, fertility, irrigation scheduling, cultivation and role of previous crops are some of the considered agronomic factors that may influence the plant water use. Planting time has been shown to have a greater influence on onion growth and subsequent yields (Anisuzzaman, 2009)

Chemical spraying or purposeful use of anti-transpirants will affect crop water use by inducing variations in soil condition and plant foliage properties (Brady and Weil, 2002). Fertilization leads to increased plant vigour, and marginal increase in water use. Unless for extensive weed control, the effects of tillage on crop water use is minimal. Close crop spacing may produce some mulching effect resulting to some diminutive benefits to the crops. Plant density largely affects the volume of soil available for root spreading. A high plant population would necessitate more water in the early stages of crop development than low population.

Irrigation scheduling is a key issue in crop production. Timing of irrigation and magnitude of reduction in ET are important criteria for determining irrigation schedule. Crop water requirement vary with different crops, prevailing climatic conditions, crop stage, size of the field, advection, cultivation method, among other factors. The primary objective of irrigation is therefore to provide plants with sufficient water to prevent moisture stress that could cause reduction in yields or poor growth (Rahimikhoob and Montazar, 2008).

Most vegetable crops are sensitive to water deficit. The crops require frequent, light irrigations (Lema and Herath, 1994) in order to give the highest yield with optimum water use efficiency. Crop water productivity can be enhanced by methods of water application i.e. partial irrigation, deficit irrigation, or drip irrigation (Greenwood et al., 2008). Though these practices might result in lower yields, the water use efficiency would be enhanced.

2.7.1.4 Crop factor

Plant type, rooting system (depth, density), rate of plant development, aerodynamic characteristics (leaf area index, stomach behavior), crop physiological stage and tolerant to drought directly affect the plant's response to the dynamism of soil moisture (Bhattarai et al., 2008). They all affect physiological ability of the plants to continue taking in water from the soil at field capacity while maintaining the vital functions even if its own potential reduces (Richards et al., 2004). When plants are young, the rate of water use is low. The consumptive use increases with plant growth, reaches a peak during some part of the growth period, then tappers off by harvest time. Plant height normally determines the roughness, hence the aerodynamic properties of the crop. This attributes to the proportion of water loss from the crop surface. C_4 plants have higher WUE than C_3 plants (Richards et al., 2004).

2.7.1.5 Methods of Irrigation

Irrigation methods are generally classified according to the manner in which water is applied to the soil. A choice should be made that avoids excess of water in one part of the field and a shortage in another. Surface, overhead, sub-surface, and drip (spot) are the major systems (Pereira et al., 2002). Improvement in technology and innovation in irrigation have made it possible for emergence of other systems (Kijne et al., 2003a; Zotarelli et al., 2005). To help highlight how the irrigation methods affect crops' water, a summary of the methods is provided.

Surface irrigation: Defined by Hillel (1987) as the process of introducing a stream of water at a head field and allowing gravity and hydrostatic pressure to spread the flow over the surface throughout the field, still ranks as a vital method of irrigation, accounting for over 95% of irrigated land worldwide. Flooding, border, level basin, and furrow irrigation are the major surface irrigation systems (Pereira et al., 2002). These surface irrigation systems apply water at intervals to allow the crop to utilize as much as 50% of the available water in the root zone before the next irrigation (Hillel, 1987). The need for large but intermittent charges of water ranks as the major disadvantage, especially in the drier areas.

Sub-surface: The method is possible when there is a high undeviating water table or a relatively impervious soil stratum not too far from the soil surface (Chowdary et al., 2008). Irrigation is achieved by elevating or maintaining the water table at a predetermined depth, 30-75 in most cases, from which moisture can rise by capillary action to the root zone. The method is commonly used for organic soils in order to prevent excessive oxidation or subsidence.

Sub-surface drip irrigation: This involves the placement of permanent drip tape (tickle) below the soil surface, usually at a depth of between 20 and 40 cm (Harris, 2005). Emitters along this tape emit water during irrigation. This system has a number of inherent advantages, including: potential for high uniformity of water application (as high as over 93%), water saving of range of upto 50%, resulting in high water use efficiency compared to traditional systems. Sub-surface drip irrigation also has some limitations associated with its use, especially in the long run. These include: emitter clogging, mechanical damage during farm operations, salt accumulation.

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Sprinkler: The basic components of a sprinkler irrigation system include a water source under pressure, piping system to convey the water, and a system of nozzles to apply the water to the land. In this method, water is applied as a spray at a high velocity above the surface through sprinkle guns or nozzles. Water application almost resembles rainfall. Several classes of sprinkler irrigation exist. The most recent is the center pivot system (Ali, 2010).

Sprinkler irrigation has made it technologically and economically possible to irrigate even too steep or uneven terrains as well as very sandy soils. However, its use is challenged in areas where, or hours of the day when, the wind speed is more than 12 km/h as strong winds result in poor water allotment pattern (Hillel, 1987)., Sprinkler irrigation is known to have problems of incidences of diseases from wetting of leaves. Only crops which do not have this problem like onions, chilies, maize pigeon pea should be grown under sprinkler irrigation.

Drip/spot: The principle of drip/spot is to discharge small amounts of water, under low pressure, to relatively closely spaced emitters in plastic distribution pipes, placed on the soil surface (Frenken, 2005). Water emission can be in the form of small drops, continuous drops, tiny streams, or diminutive sprays. Only a small part of soil is wetted, and the definite rooting volume is usually less than 50% of that of conventionally irrigated soil. The wetted area is kept continuously moist without being saturated (Hillel, 1987). Frenken, (2005) has reported several classes of this type of irrigation.

The use of drip irrigation is very essential on saline soils (Karlberga et al., 2006; Hassanli and Javan, 2005). Because of the high potential maintained in the root zone throughout the growing period, adverse effects on the crop from salinity are insignificant. Water with high salinity levels can therefore be used in drip than in other methods. Suitability of water for irrigation (Appendix 31) greatly depends on the climatic conditions, physical and chemical properties of the soil, the salt tolerance of the crop grown, and the management practices (Osten and Wichelns, 2003). One of the commonly used chemical parameters to evaluate water quality for irrigation is sodium adsorption ratio (SAR). Only water with a minimum SAR of 3.30 is considered as low sodium water hence suitable for irrigation with little harmful impacts (Katerji et al., 2003). At SAR levels of 3.30, therefore, the water is considered of high salinity requiring special irrigation method as drip irrigation.

Precise water application guarantees minimum losses. In drip system, water application is deliberate but recurrent, the volume of water applied is as close to the consumptive use of plants as possible. Slow rates of application ensures water penetrates instantaneously downwards and sideways into the soil, reducing evaporation losses. Neither is there any significant runoff or percolation. The system is also espoused where the aim is to fertigate crops with irrigation water (Pereira et al., 2002).

Drip irrigation system has proven to be the best choice in production of high-value crops and those sensitive to leaves wetting. The greatest potential for drip irrigation is in situations where water is expensive or insufficient, for marginal soils, and for high-value crops. Crops such as tomato, tobacco, melon, brinjals, and other types of vegetables are prone to, and have higher incidents of diseases resulting from wetting of leaves. For example, leaf spot, and blights in tomato; mildews in melon.

Since evaporation, deep percolation, and runoff are diminished, thereby reducing water use, drip irrigation method is arguably the most efficient (Najafi and Tabatabaei, 2007). Efficiency as high as 80% have been reported. The use of frequent but low volume irrigation applications via drip irrigation is superior to the more traditional scheduling of few but large applications (Locascio, 2005)

2.8 Economic consideration

Although it may be possible to show that investment in soil water management generates economic benefits, such as increased food production, other benefits are often difficult to measure as they may be related to improved health and reduced burdens and risk (Rockstrom and Fox, 2003). Integrated soil and water management should be set in a wider context of social and economic resilience where economic benefits are related to the sustainability of the production system.

The high investment cost associated with drip irrigation system for supplemental irrigation (SI) technology has proven to be the most limiting obstacle for the farmer to engage in any investment. Cost ha^{-1} expenditures are expensive for drip irrigation system. Conventional drip systems typically cost Kshs. 375,000-750,000 (US$ 5,000–10,000 at Kshs. 75 exchange rate) per hectare or more in east and southern Africa (Mati, 2007)

Nevertheless, investment to upgrade current farming practices that improve self-sufficiency is a realistic alternative for the resource poor ASAL populace. Initial investment costs can be able to repay over an expected life of the drip systems. The use of drip irrigation for tomatoes and onions (or generally the growing of high value vegetables) has rapidly increased because of both increasing in yield of these crops by using drip irrigation and the high net returns over time (Cetin et al., 2004).

Chapter Three

Materials and Methods

3.1 Study area

The study was conducted in Kyandululu village, Kathyaka sub-location, Kikumbulyu location of the new Kibwezi District. According to the Kibwezi District Development Plan 2008-2012 (GoK, 2008), the district lies approximately at latitude 2°17'11.21''S and longitude 37°49'11.45''E. The District is in agro-climatic zone (ACZ) IV and is classified as semi-arid (Sombroek et al., 1982). The area experiences high temperatures during the day and much lower temperatures at night. Current annual mean temperatures range from 12.4 - 35.5 °C, giving an average of 24.1 °C (Unpublished data from the University of Nairobi Kibwezi meteorological sub-station).

The area has a bimodal rainfall pattern (Appendix 1), characterized by small total amounts, strong seasonal distribution, with high spatial and temporal variability between seasons and years. The long rains are experienced in March/April, while the short rains come in October/November. The short rains are more reliable (GoK, 2008). The annual rainfall is 300 - 550 mm. In 4 out of 10 seasons, enough rainfall is only received for 60 days of the growing period (Gachene et al., 2006). Most river courses remain dry for most parts of the year. Rainfed agriculture is therefore not possible most of the seasons unless supplemented with irrigation.

The area is considered a medium potential zone for millet and ranching and/or livestock keeping systems, though a very low potential zone for most crops, tomato and onion included.

The trials were carried in a women's farm which is located about 1.5 km north of Kisayani market on Kibwezi-Kitui road, some 20 km from Kibwezi town. The total area of the farm is 2 ha.

3.2 History of the farm

The project focused on Ndiwa Women Group (NWOG). Ndiwa is a widow in the local (Kamba) dialect. The group was started in May 2002 and has 110 members with an approximate household number of 580. Twenty members registering with a membership fee of Kshs 22 originally founded NWOG. The number grew over the years to the current 110 members. In May 2002, some volunteers from USA (later to be known as *Watoto wa Dunia*) through the Kenya Voluntary Development Association (K.V.D.A) visited the group. In 2005 the volunteers bought the 2-ha piece of land where this project was conducted. They also facilitated the connection of piped water form Chyullu hills to the farm (Plate 1).

Plate 1: The project site showing the main water source and the orphanage under construction

To sustain the group, the women started several projects on the farm like bricks making, basket making, and planting mango trees. Moreover, they have over the years tried subsistence farming.

growing cereals crops (maize, millet), legumes (beans, cowpea and pigeon pea), fruits (water melon), and vegetable (onion, tomato, kales and spinach) Onion and tomato seem to be the preferred vegetables, though their performance over the years has been dismal despite the availability of piped water.

3.3 Soils of the study site

The soils are well drained, moderately deep to very deep, red to dusky red, friable, sandy to sandy clay (Gachene et al., 2003). They are mainly Chromic Luvisols They are low in organic matter (OM) levels. The low OM content could be due to the low amounts of surface litter coupled with high termite activity and probably high rates of decomposition (encouraged by high temperatures). Most of these soils are compact and have a massive structure with strong surface sealing, which causes much runoff during heavy rains. The soil pH averages 6.89 and 5.98 in water and in $CaCl_2$, respectively. The soils are therefore near neutral

3.4 Field layout

The experimental design was a completely randomized block design (CRBD). The blocks were constructed in a manner that they could allow for placement of drips in a position where they could be used to irrigate properly. The block size was 4.5m x 7m, replicated three times, giving an experimental area with a net size of 94.5m per treatment for crops (Figure 1).

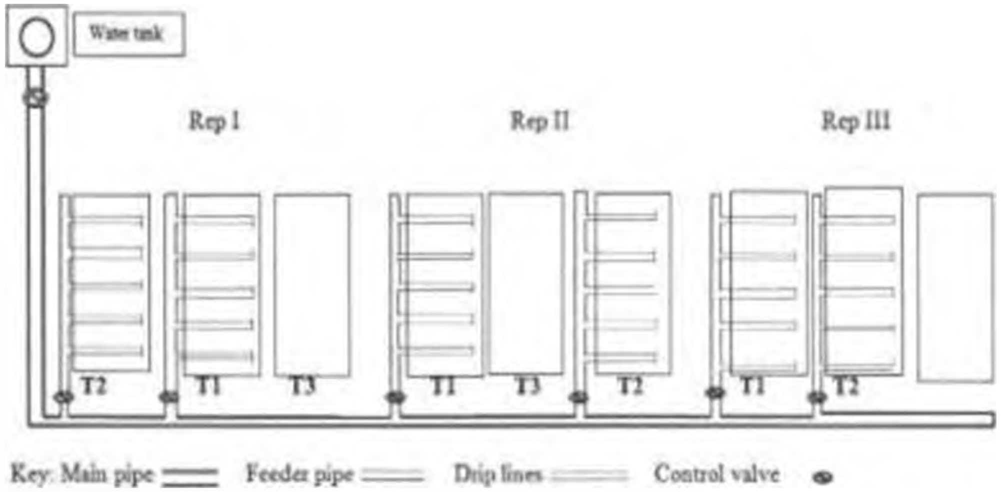

Figure 1: Experimental layout

Three treatments were adopted for both crops: T1, T2 and T3. In treatment T1, the supplemental irrigation was given twice every irrigation day (part in the morning and the remainder in late afternoon); in treatment T2, the deficit moisture was supplemented promptly every irrigation day (irrigated at once in the mornings only); treatment T3 was non-supplemental (100% rainfed). T3, therefore, was the control. Field layout for tomato season 2 remained identical to that of season 1. Onion crop was not included in the second season experiment.

3.5 Irrigation water and application

The water used at the farm originates from Chyullu hills. It is pumped from the source by Mwunyeeti Water Project, a local community-based organization (CBO) that sells water to the community, directly at the water point, or piped to different homes or farms, both for domestic consumption and irrigation. The water was taken and analyzed for chemical characteristics. The results are presented in Appendix 8. Analyses of other parameters based on FAO (1994) guidelines indicate that the water is suitable for maximum crop production

Hygdrogol Integral extruded drip line with emitter spacing of 15 cm and 30 cm were used for onion and tomato plots, respectively. This drip type is capable of delivering upto one litre of water to the plant roots per hour. The irrigation water tank was elevated approximately 1.5m above the ground (Plate 2) to provide enough gravity for water flow. After the set up, ten small containers were positioned under the emitters and water allowed to run for ten minutes to approximate the volume of water outflow. The collected water samples were averaged, and the discharge rates determined. The lines were secured at the end of the beds to ensure precision in delivering water to the desired spots.

Blaney-Criddle method (FAO, 1991) was used to calculate the reference crop evapotranspiration (ETo). The Blaney-Criddle method is simple, using measured data on temperature only. However, this method is not very accurate, and can only provide a rough estimate. The approximation for the ETo is given by the equation:

$ETo = p\,(0.46\,T_{mean} + 8)$, where……………………………………………………………(3.1)

ETo = Reference crop evapotranspiration (mm/day) as an average for a period of 1 month

T_{mean} = mean daily temperature (^{o}C)

p = mean daily percentage of annual daytime hours (given as 0.27 for the $2^{o}S$ latitude).

The climatic data that was used in computing the reference crop evapotranspiration (ETo) estimates was obtained from the University of Nairobi Kibwezi meteorological sub-station. The crop water requirement for tomato seasons 1 and 2 and onion plants are presented in Appendices 2, 3 and 4, respectively.

The water volume allowed to flow into the crops root zone (which was predisposed by how long the drips were allowed to run) depended on the deficit moisture to be supplemented, and fluctuated from time to time depending on rainfall events (Appendices 5, 6 and 7) Based on the literatures reviewed which quoted a range of 4-6 day irrigation interval for vegetables grown in similar AEZ as the research area, the crops were irrigated every 4 days except during periods of rainfall when the application schedule and the supplemental amount were dictated by rainfall events To get the deficit moisture to be supplemented, the difference between the estimated Etc for different crop stages (Appendices 2, 3, and 4) and the received rainfall was calculated for each irrigation day

Plate 2: A section of the drip system showing the water tank

For the late 2009 planting season, both tomato (var cal J) and onion (var red Creole) nurseries were established on September 11, 2009 The nurseries measured 1m wide by 7m long The nurseries were adequately watered early in the morning and evening each day given the hot and dry weather during the month of September The onions were transplanted 50 days later on October 29, 2009 Tomato (season 1) seedlings were transplanted on November 3, 2009. The nursery for tomato season 2 (also measuring 1m x 7m) was established on December 31, 2009 The seedlings were transplanted thirty-five days later, on February 5, 2010

The seedbeds were hand ploughed (Plate 3) and harrowed twice Well decomposed goat and sheep manure was thoroughly mixed with the soil during bed making at the rate of one approximately 10 kg per 45 m-long raised bed (or approximately 12 t/ha) Parallel beds, raised 30 cm above the ground and 0.6 m apart, were formed on each plot The blocks each had 12 beds The plots were then marked, sub-divided, and the drip lines laid as represented on Figure 1 A foot path (0.5 m wide) was left between the blocks The beds were readied atleast four days before transplanting

Plate 3: Land preparation by members of the Ndiwa Women Group

In both seasons 1 and 2, the tomatoes were transplanted with an intra-row spacing of 0.3m (Plate 5) Onion mother bulbs were transplanted on comparable beds, with four rows in each bed (two parallel lines running at the far ends of each bed) The parallel lines had inter and intra row spacing of 0.15m x 0.15m, respectively (Plate 4). During the first week after transplanting, the crops in T1 and T2 were irrigated every two days, except when it rained, in order to establish the newly planted seedlings.

All plots in the three replicates were kept weed-free by manual hand weeding. Upto three weedings were done during the crops' cycle. In both crops, the first weeding was done at 10 day after transplanting (D.A.T). The timing and frequency were dictated by the percentage weed presence in the plots.

Plate 4: A section of the onion crops on a seedbed

Pests and diseases were managed culturally by removing the diseased plants and spraying with appropriate pesticides and fungicides. For tomato, pruning was done by selectively removing the side shoots to limit plant growth. Staking was done on the third week after transplanting with wooden stakes to keep the fruits off ground and reduce fruit rot, this was adopted for both season 1 and 2 crops. Top dressing with chemical fertilizers was done at the fruit setting stage. For onion, top dressing was not done since the qualitative indicators of biophysical performance showed the plants were in good health.

3.7 Plant and soil sampling

For both onion and tomato, plant sampling involved marking 15 randomly selected plants per plot that were monitored, at the specified intervals throughout the growth period, for selected parameters. For tomato, main phenological stages of the crop such as first flowering, first fruiting, and maturity were noted. At each stage, the following plant parameters were recorded: plant height (cm), numbers of branches and numbers of leaves per plant. The above parameters (except numbers of branches per plant) were also monitored on onions at 30, 60 and 90 days after transplanting.

The whole block measuring 4.5 m x 7 m was harvested for both tomato and onion. The respective yields from each plot for both tomato and onion were taken as the weights of marketable yields and adjusted to t/ha when computing the gross margins.

Onions were harvested on the same day for all blocks, when about 75% top fall-over was attained in each plot. A sample of bulbs 15 onion bulbs (5 randomly chosen from each replication) were selected from each treatment for characterization with respect to size (weight, diameter, length) and percentage (%) moisture content. Bulb length was measured, according to the criteria borrowed from Kimani et al. (1993), as the vertical length from the base plate to the neck constriction at a point where curvature changes from convex to concave. Diameter was the longer bulb diameter on a horizontal plane. Mean bulb weight was the average weight (g) of the 15 bulbs in each treatment. The bulbs were later taken to the laboratory for relative (%) moisture (and by extension, the dry matter) content analysis. Bulb yield was total weight of bulbs harvested from a net plot of 94.5 m^2, expressed in t/ha

Plate 5: A section of the tomato crops on a seedbed

For tomato, fresh fruits were harvested piecemeal for the market as they ripened. At every harvesting, tomato fruits from the three treatments were sorted and classified. The classification criteria classifies tomato fruits based on (a) basic fruit sizes determined essentially by weight: beefsteak, cherry, and grape; (b) shapes: oxheart and plum (Roma). The size of a tomato fruit is determined by either its diameter or weight. The weight classes are: 56.6 to 141.5 g, 169.8 to 283 g, and greater than 283 g. The diameter (cm) fruit classifications are: extra small, 4.8-5.4 cm, small, 5.4-5.8, medium, 5.8-6.4, large, 6.4-7.3, extra large, 7.3-8.8, maximum large, >8.8 cm. Based on quality and suitability, the fruit can be classified into (a) first grade (those that are in good quality, full size, vine ripened and free from cracks), and (b) second grade (those that cannot be classified as first grade but display the minimum characteristics).

In this experiment, the harvested fruits were classified according to the USDA (1997) criteria into: culls (non-marketable and/or consumables), US No.2 (medium), US No.1 (large), and fancy (extra large). The different fruit classes were weighed and expressed into t/ha to determine the dominant fruit category for the used variety (cal J). From such cluster, samples of 12 fruits were randomly picked and their diameters measured using Vanier calipers, and then averaged to get the fruit sizes per class. Fruits having a diameter larger than 6.5 cm were categorized as extra-large. Large category had diameters ranging from 5.8 to 6.5 cm; medium class had fruits with 5.0 to 5.8 cm diameter. Any fruit smaller than 5.0 cm but larger than 4.5 cm in diameter were classified as small, though this classification was not considered in the USDA (1997) criterion. Culls included the non-marketable and/or non-consumables: either those that were too small in size or those that had signs of disease, pests or physical damage, no matter the fruit size. Marketable yields were the difference between total yields and the culls.

WUE in this experiment was calculated as fresh marketable fruit (for tomato) or bulb (for onion) weight (kg) obtained per unit volume of total water (irrigation and rainfall water) applied (m^3).

Soil moisture was monitored using gravimetric method. Samples at 0-30 cm depth were randomly collected from the treatment blocks using a 0.05 m auger. These (samplings) were made before irrigation at crucial plant stages: at transplanting, flowering and fruit setting for tomato (samples for onion plots were also taken coinciding with these stages of tomato) and maturity. Monitoring of soil moisture was done at the 0-30 cm depth due to the concentration of active roots mostly at this level and less below this depth range. The chemical and physical characteristics are presented in appendix 9.

3.8 Gross margin analysis

Gross margin analysis and evaluation were computed using the results of this study based on production costs. The production costs were worked out by considering all production inputs (i.e. costs of seeds, pesticides, fungicides, fertilizers, and water) for both tomato and onion growth in the study area. Cost estimates for the production inputs were based on market prices of 2009 and 2010 in the nearby market center and town of Kisayani and Kibwezi, respectively. The gross margin (GM) was computed using farm-gate prices of tomato of Kshs. 20/kg for season 1 and 30/kg for season 2, and Kshs.40/kg for onions, respectively. The cost of irrigation water was averaged at Kshs 0.15/L and represented the actual water price in the study area for farm conditions.

Labour costs were not included in the analysis. The most common approach is to value labour at its opportunity cost, i.e., set the labour cost equivalent to the income foregone during equivalent time spent in alternative production (Rockstrom et al., 2005. If the alternative income for labour is 0 due to unemployment, labour is then valued to 0, the alternative activity for labour is idle and therefore not be attributed an opportunity cost. In this study, the entire labour was provided by the group members (widows), most of whom were advanced in age and had no alternative sources of income. The labour cost was therefore rightfully set at 0 value.

The gross margin for each treatment was computed based on the standard setup by subtracting all the production costs from gross incomes: generated revenue – (input + water costs)

For example assuming:

GM = gross margin per ha; Kshs.

A = crop yield; kg

B = area of crop; ha.

C = total production cost; Kshs.

p = price per kilogram of produce

The calculation can be given as:

$$GM = \{(p^{*}A) - C\} + B \quad \text{.....(3.2)}$$

Just like the yields, all calculations for gross margins were done based on the mean experimental plot area and later adjusted to a unit area of 1 ha.

3.9 Statistical analysis

Statistical analyses were performed using GenStat Discovery Edition 3. Two-way analysis of variance (ANOVA) was done on growth parameters, yield and water use efficiency and growth margins to determine treatment effects on them. Where F-value was significant, means were separated using least significant difference (L.S.D.) at 5% level of probability.

Chapter Four

Results and Discussion

4.1 Effect of supplemental irrigation on growth and development

4.1.1 Effect on Tomato

The response of the growth parameters (plant height, numbers of leaves and of branches per plant) and the interactions among the three treatments were analyzed for the two seasons. In season 2, only data as at flowering stage was included in the analysis for T3 (control plot). No values were available during fruit setting and maturity since the crops had depreciated to below observable standards and were hence disregarded.

For all the three treatments, the above parameters responded positively to the supplemental irrigation, both in seasons 1 and 2 (Tables 3, 4 and 5). Tomato vegetative growth characters declined in the second season (2010) compared to the first season (2009).

4.1.1.1 Number of braches per plant

Average number of branches per plant varied among treatments (Table 3).

Table 3: Analysis of number of branches for tomato seasons 1 and 2 at different growth stages

	Seasons					
Treatments	**Season 1**			**Season 2**		
	Flow^1	FSet	Mat	Flow	FSet	Mat
T1	4.46^c	4.70^c	7.62^c	3.79^b	4.23^c	6.47^c
T2	3.92^b	4.18^b	6.17^b	3.80^b	3.89^b	6.11^b
T3	2.52^a	2.31^a	3.52^a	1.64^a	0.00^a	0.00$_a$

Mean	3.63	3.73	5.77	3.08	2.71	4.20
LSD (T)	0.0920					
cv%	1.5					

[1] Flow-Flowering, FSet- fruit setting, Mat- maturity

[a] Values down the column having common letter(s) are not significantly different at 5% level

It showed a marginal increase between flowering and fruit set stages, but nearly doubled between fruit set and maturity stages in both seasons. This was due to the varied time interval between the stages. The interval between flowering and the first fruit set was averaging 6 days, while that between first fruit set and maturity was 27 days. The longer time interval in the latter stage means more branches. It could also be because of the crops' development characteristics; the plants tend to branch more during the reproductive stages than before.

Season 1 recorded averages that were significantly different ($p < 0.05$) among all the treatments in the three stages (Appendix 13), while in season 2 the average number of branches per plant varied among the treatments but, unlike during season 1, these differences were not statistically significant at flowering stage. At maturity, number of branches per plant was greatest (7.6) in T1 of season 1 while minimum (3.5) was recorded in T3 plots. This was largely due to the fact that supplemental irrigation had the stimulatory effects in branching compared to control at all the stages of plant growth. The results agree with those of Ramalan and Nwokeocha, (2000).

4.1.1.2 Leaves per plant

Significant differences occurred in the average number of leaves per plant at $p \leq 0.05$ (Appendix 14). The average number of leaves per plant were significantly higher for the irrigated plots (T1 and T2), compared to T3 (Table 4).

Table 4: Analysis of number of leaves for tomato seasons 1 and 2 at different growth stages

	Seasons					
Treatments	**Season 1**			**Season 2**		
	Flow[1]	FSet	Mat	Flow	FSet	Mat
T1	9.56^{c}	10.97^{c}	15.46^{c}	9.09^{c}	9.86^{c}	14.07^{c}
T2	8.74^{b}	10.08^{b}	14.52^{b}	8.30^{b}	9.08^{b}	13.22^{b}
T3	7.30^{a}	8.70^{a}	11.58^{a}	4.74^{a}	0.00^{a}	0.00^{a}
Mean	8.53	9.92	13.86	7.38	6.31	9.10
LSD (T)	0.0944					
Cv	0.1					

[1] Flow-Flowering, FSet- fruit setting; Mat- maturity

[a] Values down the column having common letter(s) are not significantly different at 5% level

The leaves increased by constant margin from one stage to the next; with the highest increase in average number occurring between fruit setting stage and maturity in both season 1 and 2. Again the explanation would be similar to that of branches. The highest numbers recorded were from T1, with T3 recording the lowest figures.

During the leaves counting, T1 and T2 treatments were comparatively younger than the T3 treatments and senescence started only in the basal leaves. On the other hand, more dry leaves were observed in T3 plots. Since crops growth and development in T1 and T2 were sustained with supplemental irrigation, while those of T3 were subjected to water stress during periods of little or no rainfall, the marked differences in number of leaves and their general health were justified. As a natural phenomenon, plants tend to shrink and/or shed off their leaves during water stress periods (Robles et al., 2009). Water stress occurring during vegetative stages reduces leaf area development (Ramalan and Nwokeocha, 2000).

4.1.1.3 Plant height

The response of tomato height to different irrigation regimes was more distinct than number of leaves or the average branch number per plant (Table 5). There were significant (Appendix 15) differences among the treatments at all the three stages of measurement, both for season 1 and season 2. Season 2, however, had plants of comparatively lower heights than in season 1.

Table 5: Analysis of plant height for tomato seasons 1 and 2 at different growth stages

	Seasons					
Treatments	**Season 1**			**Season 2**		
	Flow[1]	FSet	Mat	Flow	I Set	Mat
T1	25.98^{c}	40.21^{c}	57.90^{c}	24.68^{c}	36.19^{c}	50.37^{c}
T2	20.98^{b}	34.01^{b}	50.37^{b}	19.93^{b}	30.61^{b}	44.84^{b}
T3	12.98^{a}	21.10^{a}	29.47^{a}	11.68^{a}	0.00^{a}	0.00^{a}
Mean	19.98	31.77	45.92	18.77	22.26	31.74
LSD (T)	0.1855					
Cv	0.5					

[1] Flow-Flowering; I Set- fruit setting; Mat- maturity

[a] Values down the column having common letter(s) are not significantly different at 5% level

These differences were significant at $p \leq 0.05$. The T1 achieved the tallest plants (57.93 and 50.37cm) at maturity, both in first and second season experiments, respectively. As mentioned above, water stress occurring during vegetative stages reduced leaf area development, as well as plant height. This has been observed by several researchers (Recep, 2004; Navarro et al., 2009).

4.1.2 Effect on Onion

4.1.2.1 Plant height

Significant differences ($p < 0.05$) in plant height were apparent from early growth stages (Ds 1) to plant maturity (Ds 3) between the treatments (Table 6).

Table 6: Onion height at different days after transplanting

Treatments	**Days After Transplanting (D.A.T)**			
	Ds 1[1]	Ds 2	Ds 3	Mean
T1	23.67^{c}	29.79^{c}	35.86^{c}	29.77^{c}
T2	18.84^{b}	25.77^{b}	32.91^{b}	25.84^{b}
T3	12.74^{a}	15.31^{a}	20.46^{a}	16.17^{a}
Mean	18.42	23.62	29.75	23.93
LSD (T)	1.617			
cv%	3.1			

[1] Ds 1, Ds 2, Ds 3 represent approximately 30, 60 and 90 DAT respectively when heights and leaves were sampled

[a] Values down a column having common letter(s) do not differ significantly at 5% level

At maturity, the tallest plants (29.77 cm) were recorded in the T1 plots, followed by T2 (25.84 cm). Plant heights were significantly (Appendix 16) low in the T3 (16.17 cm) plots. Improved soil moisture availability for plants under supplemental irrigation plots T1 and T2 contributed to the differences in plant height compared to T3. The differences in plant height between T1 and T2 were not big; however, they still remained significant at 5% level.

4.1.2.2 Numbers of leaves per plant

Leaf numbers among the treatments increased with supplemental irrigation, with marked significant differences at 5% level (Appendix 17) (Table 7).

Table 7: Onion number of leaves at different days after transplanting

	Days After Transplanting (D.A.T)			
Treatments	Ds 1	Ds 2	Ds 3	Mean
T1	5.16^c	5.94^c	8.29^c	6.46^c
T2	4.02^b	4.90^b	6.78^b	5.23^b
T3	3.41^a	4.01^a	4.50^a	3.97^a
Mean	4.20	4.95	6.52	5.22
LSD (T)	0.2877			
cv%	2.9			

[a] Ds 1, Ds 2, Ds 3 represent approximately 30, 60 and 90 DAT respectively when heights and leaves were sampled

[*] Values down a column having common letter(s) do not differ significantly at 5% leve

Leaf numbers per plant gradually increased from 30 to 90 DAT. In irrigated plots, T1 and T2, the leaf numbers increased by an average of 18.45% between 30 (Ds 1) and 60 (Ds 2) DAT. The increase was more outstanding between the 60th and 90th DAT; accounting for a 39% increase. This was attributed to the vigorous plant growth after full establishment. In T3, there was a considerable increase of 17.84% from 30 to 60 DAT, and at final counting (90 DAT) it showed declining trend to 12.5%.

During final harvest, the highest number of leaves per plant (8.2) was counted in T1 plots followed by T2 (6.8) while the number was least in T3 (4.5). Furthermore, throughout the entire season, the T1 and T2 onions always had leaves that were comparatively younger than those in T3 plots. Senescence started early in the basal leaves of T3 than T2 and T1 plots, in that order. This could have been caused by uneven distribution of rainfall during the growing season, which greatly affected T3 plots. This observation agrees with the earlier findings of Abdulla et al. (2005) and Shock et al. (2008).

4.2 Yield response to supplemental irrigation

4.2.1 Tomato yields

Tomato exhibited a trend of some harvest on the first week, increased in the middle and declined towards the last week of harvest. The harvesting period lasted 27 days. The results indicated that supplemental irrigation had a remarkable effect on increasing crop yield based on the fruit yield analysis in both seasons.

Tomato yields were increased significantly (Appendix 18) with supplemental irrigation (T1 and T2) compared with control (T3) in the first season (Table 8).

Table 8: Tomato fruits expressed in marketable and total yields for season 1 and season 2

Parameters	**Fruit yield**					
	Marketable (kg)		**Total/mean area (kg)**		**Yield (t/ha)**	
Treatments	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
T1	35.27^{c}	18.50^{b}	39.44^{c}	21.39^{b}	11.20^{c}	5.74^{b}
T2	31.96^{b}	19.17^{b}	37.44^{b}	22.68^{b}	10.15^{b}	6.09^{b}
T3	19.71^{a}	0.00^{a}	24.98^{a}	0.00^{a}	6.26^{a}	0.00^{a}

Mean	28.98	12.56	33.95	14.69	9.20	3.94
LSD (T)	2.666		2.010		0.855	
cv%	2.0		2.2		2.3	

[a] Values down a column having common letter(s) do not differ significantly at 5% level

Significant differences ($p < 0.05$) were also observed between T1 and T2 of season 1, but the differences were not significant between T1 and T2 in the second season.

When compared to T3, T1 and T2 respectively represented a 78.91% and 62.14% increase in yield. Other researchers (Cetin and Demet, 2008; Zotarelli et al., 2009) have also reported high increases in tomato yield resulting from supplemental irrigation.

While irrigated tomatoes (T1and T2) produced good yields, response to irrigation varied slightly from one treatment to the next depending upon the mode of irrigation during the growing season. T1 crops responded to irrigation 9.38% better than T2, implying that spreading irrigation water can be beneficial to crops. These findings seemed to agree to those of Mathieu et al. (2007) who reported that withholding drip irrigation for a short period increased tomato marketable yield by 8–15%, fruit number by 12–14% while reducing amount of irrigation water by 20%.

The yields obtained from irrigated plots T1 and T2 in season 2 were much lower, representing a 44.59% decrease, compared to the corresponding yields in season 1. T3 results for season 2 were unavailable for analysis since the crops had withered before fruit setting stage. This underscores the importance of supplemental irrigation in sustaining crop growth and yields, especially in the ASALs where rainfall is inadequate and highly variable.

The decrease in tomato yield in season 2 (2010) compared to season 1 (2009) was attributed to several factors, but mainly to the contribution of the crop of previous season (1). First, tomato was planted in the same field for two consecutive seasons, and showed that repeated planting of the same crop would decrease yield (Lenssen et al., 2007). For this reason alone, the yield of tomato in 2010 were lower than 2009. Some disease presence was noted during the cropping season 1. Repeated planting in 2010 promoted favorable condition to the appearance of these diseases, particularly bacterial wilt (*Ralstonia solanacearum*) at the beginning of the crop season 2. Frequent applications of fungicide were used to prevent disease spread but warm and wet conditions hampered disease suppression

The contrasting performance of T3 in season 1 as compared to season 2 was mainly due to weather. Insufficient rains during the crucial phase of tomato development lead to the total crop failure in season 2. While the total in-season rainfall for season 2 (Appendix 1) was more than the average in-season for season 1, the rainfall was much lower and unevenly distributed in 2010 than in 2009 during the crucial tomato growth stage. For season 1, rainfall in mid November to part of early December was substantial, which was critical because at this time the season 1 crop was at its reproductive stages and was also reaching its peak crop water demand. Peak performance for season 2 occurred during the month of February when there was very little rain.

4.2.1.1 Tomato fruit classification

Only three classes (culls, medium and large) were included in the analysis (Table 9). Only a few fruits had sizes that could be classified as extra large, not enough to form part of the overall analysis. Total large, medium, and culls fruits followed the same yield pattern both for season 1 and season 2. Tomato fruit classes were least affected by irrigation treatments (Appendices 19, 20, 21). Nonetheless, medium category appeared to have dominated the total yield in both seasons. Sampling at the local market also revealed that medium sizes dominate the market. This was particularly identical to the variety that was grown (cal J) which mostly have fruits that are of medium class.

Table 9: Analysis of tomato fruit classification for season 1 and season 2 based on the USDA criteria of 1997

Parameters	**Fruit classification (kg)**					
	Large		**Medium**		**Culls**	
Treatments	Season1	Season2	Season1	Season2	Season1	Season2
T1	17.13^{b}	8.02^{b}	18.14^{b}	10.48^{b}	4.17^{a}	2.89^{b}
T2	12.94^{a}	8.06^{b}	19.02^{b}	11.11^{b}	5.47^{a}	3.83^{b}
T3	10.35^{a}	0.00^{a}	9.36^{a}	0.00^{a}	5.27^{a}	0.00^{a}
Mean	13.47	5.36	15.51	7.20	4.97	2.24
LSD Treat. (T)	2.670		1.729		1.504	
cv%	10.3		9.0		17.5	

[a] Values down the column having common letter(s) do not differ significantly at 5% level

[1] NS-not significant at 5% level of probability

4.2.2 Onion yields

Total bulb yield (t/ha) for the three treatments ranged from 1.55 to 4.0 t/ha (Table 10). The results clearly show that supplemental irrigation had an impact on yield compared to rainfed agriculture. However, yields obtained from T1 and T2, the irrigated plots, did not show any statistical differences between them (Appendices 22).

Table 10: A summary of onion bulb yields

	Bulb yields	
Treatments	Total(kg)	t/ha
T1	12.61^{b}	4.00^{b}
T2	11.81^{b}	3.76^{b}
T3	4.98^{a}	1.58^{a}
Mean	9.81	3.11
LSD	1.691	0.5358
cv%	1.3	1.2

[a] Values down the column having common letter(s) do not differ significantly at 5% level
[1] percentage moisture content

The improvement of total yield response to amounts of water applied could be attributed to the enhancing effects of water to crop's biological functions and growth in addition to the improving effects of water on nutrients availability. The high irrigation frequency might also be regarded as an additional factor that contributed positively to higher yields in irrigated treatments (T1 and T2) than control (T3), by maintaining high water content in the effective onion rooting depth. These results were comparable with those of Shock et al. (2008) who reported increases in total (t/ha) yields with increasing irrigation thresholds.

Nonetheless, the performance of all the treatments was below average when compared to the world's averages which stood at 8-18 t/ha (FAO, 2000); with control (T3) having the lowest yield. But this is not a new phenomenon. Low yields are a common occurrence in onion production in most areas. Diverse yields have been reported by several researchers working in similar ACZ. According to FAO (2000) statistics, the average yield of onion in Tanzania was about 2.9 t/ha. Mutungu et al. (2003) reported yield ranges of 4.2 -11.6 t/ha. Musyoki et al. (2007) reported a 10-15 t ha^{-1} yield range, and Kimani et al. (1993) reported yield range of 4.2-32.1 t/ha for Red Creole variety

The variations in onion yield in this experiment could be as a result of other key growth aspects since their influence was not factored. Onion production is generally favoured by the relatively constant day length in the tropics (FAO, 2002a). However, prevailing weather conditions have strong influence on bulb formation. Temperature, pre-bulbing plant size, light intensity, nutrient status and moisture availability are among the factors influencing bulb growth and its ultimate size. Kimani et al. (1993) further categorized temperature and soil moisture availability as the most crucial factors

High temperatures, which are a characteristic of many areas in eastern Kenya, accelerate bulb maturation, resulting in low yields due to small bulb size and high rates of formation of splits and doubles, which are low quality attributes (Brice et al., 1997). Most rapid bulb's growth rate and earliest onset of a decline in leaf occur at temperatures of 25 and 30^{0}C. Lower temperatures give successively less rapid bulbing and maturity. Temperature during the growth season in the study area averaged at 24.2^{0}C, which were considerably high.

The impact of dry spell on final yields depend on which tomato developmental stage that is affected. The onion yield formation period (3), occurred from mid December upto mid January when the average rainfall was very low and unevenly distributed; 4.38 mm and 0.47 mm in December and January respectively. This negatively affected the T3 crops. The crop is most sensitive to water deficit during the yield formation period 3 (Table 2), particularly during the period of rapid bulb growth which occurs about 60 days after transplanting (Rockstrom and Fox, 2003). When drought occurs at the beginning of the bulb formation, it causes a delay in foliar emergence, a smaller number of leaves, and a decrease in bulb weight (a significant difference when T1 and T2 plots were compared with the T3 plot). Root growth is reduced and bulb enlargement is favoured in a wet soil.

4.2.2.1 Bulbs characteristics

Bulb characters including average weight, length, diameter and moisture content responded positively and significantly to the amounts of soil moisture in all the treatments (Table 11). Significant and positive relationship between marketable yield with bulb size (diameter) and bulb weight could be detected.

Table 11: A summary of onion bulb characteristics

Treatments	**Bulb characteristics**			
	Length	Diameter	Weight	%MC[1]
T1	7.56^{b}	5.74^{b}	32.20^{c}	77.79^{c}
T2	7.24^{b}	5.63^{b}	28.80^{b}	73.09^{b}
T3	4.84^{a}	3.69^{a}	17.00^{a}	62.67^{a}
Mean	6.55	5.02	26.00	71.19
LSD	1.466	0 2407	8 06	1.717
cv%	5.1	3.0	3.6	1.9

[a] Values down the column having common letter(s) do not differ significantly at 5% level
[1] percentage moisture content

Bulb size (diameter) is a component which directly influences bulb yield. Average bulb weight and bulb size were also significantly and positively associated with each other; larger-sized bulbs weigh more than smaller ones, concurring with the findings of Mulungu et al. (2003).

The influence of supplemental irrigation (SI) on average bulb weight over control was observed. Further, significance differences were observed among bulbs in T1, T2 and T3 (Appendix 25). The heaviest bulbs (32.2g) were obtained in T1 compared to the mean weight of the lightest bulbs (17.0g). This was attributed to the fact that as the soil dried the rate of absorption by roots fell short of transpiration rate by the plant, thus creating internal water deficit which affected photosynthesis and resulted in reduced leaf area, cell size and intercellular volume which reduced bulb moisture accumulation.

The largest bulbs (diameter) were realized in treatment T1 and T2, which were significantly different from that obtained from T3 plots. There was only a 0.1 cm difference between the maximum bulb diameter (5.70 cm) obtained in T1 and that obtained in T2 (5.60 cm). The differences were not significant (Appendix 24) The maximum bulb diameters (5.70 cm) compared closely to that reported by Kimani et al. (1993) (5.38 cm) for Red Creole onions Average bulb weight and bulb size were significantly and positively associated with each other, agreeing with the findings of Mulungu et al. (2003).

The dry matter content of the onion bulbs ranged from 22-37%. Plants on the supplemented plots (T1 and T2) had relatively higher water content (73.09 and 77.79%) compared to T3 (62.67%) The reported differences in moisture contents in T1 and T2 were significant at $p \leq 0.05$ level (Appendix 26). These results are in agreement with those reported by Al-Harbi, (2002) who found significant and continuous declines in relative water contents with increasing water stress duration.

The maximum bulb lengths (7.6 cm) and (7.2 cm) were produced from the irrigated plots, T1 and T2. However, the two lengths were not statistically different at $p \leq 0.05$ level (Appendix 23). T3 (control) plots produced the shortest bulbs (4.8 cm). There were marked differences between the bulb lengths of the control (T3) versus the irrigated plots (T1 and T2). This, again, could be as a result of moisture differences during the growth period.

4.2.3 Comparing the research results and the previous yields

In one of the farmers' group, Ndiwa Women Group (NWOG), crop yields obtained were way much below the farm's potential. This was despite the availability of piped water. In reality, they were near total loss every season. When the results of this trial were compared with previous results obtained by the Ndiwa Women group on the same farm (Table 12), there were marked differences in yields.

Table 12: Sample of farm yields from a previous harvest as reported by NWOG

Plant	Planting date	Days to 1st harvesting	Yield (kg)	Area (ha.)	Yield (t/ha)
Tomatoes	19/12/2008	8 weeks	111	2.995×10^{-2}	3.71
Onions	18/1/2009	9 weeks	79.3	3.5073×10^{-2}	1.70

The yield results obtained from the rainfed (control) for this research were comparable with those previously obtained by the women group. T3 results for onion were 1.58 t/ha against 1.70 t/ha from the previous farming; while T1 and T2 results showed a 57.5% and 51.5% increase, respectively, compared to the previous yields. Supplemented tomato plots in season 1 (T1 and T2) were averaging 66.8 and 63.4 %, respectively, higher than the previously obtained yields. The sampled yield data from the previous seasons have clearly highlighted the marginal performance in the farm.

One of the possible reasons for such a recurrence loss was because almost all the 110 group members were old and illiterate. With lack of sufficient knowledge among the target group on sustainable water use and management, it was not surprising that the yields were always below optimum. Poor management (misuse) of the available water resource and/or cropping system by the women resulted in periodic low yields. The results of this research are an indication that supplemental irrigation alone can be a major factor in ensuring yield in the ASALs though it, too, has to be well managed to be sustainable.

4.4 Water Use Efficiency

4.4.1 Tomato WUE

The WUE for tomato for T1 and T2 (the irrigated plots) varied significantly from that of T3 treatments in season 1 results, though the differences between T1 and T2 were not significant (Appendix 27). In the second season, T1 had a slightly higher WUE compared to T2 but, again, the differences were not significant at 5% level (Table 13). Judged on this basis alone, it can be concluded that the mode of irrigation had no bearing on the seasons' outcomes. Farmers are therefore at liberty to choose between T1 and T2 depending on the mode that would most convenient at the prevailing circumstance.

T3 for season 2 was not evaluated due to complete crop failure, clearly proving that supplemental irrigation is a major contributor to crop productivity, especially in the water scarce regions like Kibwezi District.

Table 13: Water use efficiency for tomato seasons 1 and 2

Parameters	**Water Use Efficiency (kg/m^3)**	
Treatments	Season 1	Season 2
T1	27.04^{b}	14.49^{b}
T2	25.38^{b}	13.98^{b}
T3	31.92^{a}	0.00^{a}
Mean	28.11	9.49
LSD (1)	1.999	
cv%	6.6	

* Values down a column having common letter(s) do not differ significantly at 1% level

Contrary to other observations that were made (Rockstrom and Fox, 2003), irrigated treatments T1 and T2 had significantly lower WUE compared to T3. These results sharply contrast to the general trends reported by several researchers who found increases in WUE with increase in total water (Cetin and Demet, 2008; Zotarelli et al., 2009). This may be due to the dismal increase in yield following the supplemental, seasonal water application. For instance, a negative relationship between irrigation applied with WUE does not mean that irrigation is detrimental to the crops (Imtiyaz et al., 2000; Fairweather et al., 2004). In this case the relationship was negative because the total seasonal irrigation achieved other roles; meaning that supplemental irrigation was, among other benefits, requisite in sustaining plant growth but not necessarily sustaining yield in the exact proportion it was applied.

A reduction in plant growth and yield can result at higher irrigation levels (Imtiyaz et al., 2000). Howell (2006), though not specifically referring to tomato, reported that irrigation water use efficiency (IWUE) differ considerably among the treatments and generally showed an increase with a decline in irrigation. Similar opinions were also shared by Fairweather et al. (2004) who observed that when irrigation application is below optimum there is generally a positive response in yield for each unit of irrigation water applied. Beyond the optimum point there is, on well drained soils, no further increase in yield for each extra input of irrigation water. Moreover, studies have shown that supplementing irrigation water when rainwater was lacking during the plant establishment and reproductive stages increased WUE compared to irrigation water throughout the whole season (Kijne et al., 2003b).

WUE is not a function of amount of supplied water alone; it can be improved by timely planting, matching nutrition to yield potential and sound rotational and varietal management. Howell (2001) categorized ways for improving irrigation efficiency at a field level into four options: agronomic, engineering, management and institutional. Management is an important aspect and as well as being listed explicitly is also intrinsic in the other three options. Proper savings in water can therefore, be expected through improved management, which results from enhanced understanding of the system. Consequently, increases in WUE will require simultaneous improvements in each of the options.

Improving the efficiency and effectiveness of water use can result from better managing a number of factors, including water availability, fertility, pests and diseases, crop or pasture variety, planting date, soil water conditions at planting, plant density and row spacing. This means that improving water use efficiency requires an understanding of the whole system and should not focus solely on the application of water (Fairweather et al., 2004).

4.4.2. Onion WUE

Though T1 had the highest (9.0 kg m^{-1}) WUE among the three treatments in the season (Table 14), the WUE in T1 and T2 were not significantly different (Appendix 28). The WUE for the T3, however, significantly differed with that of the irrigated treatments, T1 and T2.

The findings compare well to those reported by other researchers (Al-Harbi, 2002; Rabinowitch and Currah, 2002) who reported increases in WUE with increased water used.

Table 14: Water use efficiency for onion crop

Treatments	**Water use efficiency (kg/mm^3)**
T1	9.07^b
T2	8.50^b
T3	6.37^a
Mean	7.98
LSD	1.348
cv%	7.5

[a] Values down a column having common letter(s) do not differ significantly at 5% level.

4.5 Gross margins analysis

Economic analysis and evaluation were computed by using the results of this study based on production costs (Tables 15, 16 and 17). The production costs were computed by considering all production inputs (i.e costs of seeds, pesticides, fertilizers, manures, transportation) for tomato and onion growths in the study area. Since water costs varied from treatment to treatment, it was separately computed based on local standards for each treatment and finally added to the input costs.

Table 15: Types and costs (Kshs.) of farm inputs used for season 1 tomato production

Inputs	Quantity		Unit cost	Total	Estimated cost per mean area 9.45×10^{-3} ha.	Estimated cost per ha.
Seed	50g (2 sachets)		400	800.00	266.70	28,222.20
Manures	120 kg		2	240.00	80.00	8,465.60
Pesticide/	*twigathoate*		960	960.00	320.00	33,862.40
funngicide	*milraz*	750g	1000	1000.00	333.30	35,269.80
	confidor	50ml	550	550.00	183.30	19,396.80
Fertilizers	20 kg CAN		43	860.00	286.70	30,338.60
Others	Transport			150.00	50.00	7,751.90
Total					**1,520.00**	**163,307.3**

Table 16: Types and cost (Kshs.) of farm inputs used for season 2 tomato production

Inputs	Quantity		Unit cost	Total	Estimated cost per mean area 9.45×10^{-3} ha.	Estimated cost per ha.
Seed	50g (2 sachets)		410	820.00	273.30	28,920.60
Manures	120 kg		2	240.00	80.00	8,465.60
Pesticide/	*Bestox*	500g	700	1400.00	466.70	49,386.20
funngicide	*milraz*	500g	1000	1000.00	333.30	35,269.80
	Cuflro caf	500g	600	600.00	200.00	21,164.00
Fertilizers	25kg CAN		42	1050.00	350.00	37,037.00
Others	Transport			150.00	50.00	7,751.90
Total					**1,753.30**	**185,534.4**

Table 17: Types and cost (Kshs.) of farm inputs used for onion production

Inputs	Quantity	Unit cost	Total	Average Estimated Cost per mean area 9.45×10^{-1} ha.	Estimated cost per ha.
Seed	50g (2 sachets)	250	500	166.70	17,640.20
Manures	120 kg	2	240	80.00	8,465.60
Pesticide	*Confidor* 50ml	550	550	183.30	19,396.80
Others	Transport		150	50.00	7,751.90
Total				**480.00**	**53,254.5**

4.5.1 Tomato gross margins

According to the calculation and evaluation (Table 18), the maximum net income (gross margin) was obtained from T1 of the first season as Kshs. 58,481.10 ha^{-1}. The treatment T2 resulted in a net income of Kshs 37,433 ha^{-1}, and it was ranked second among the treatments. T3, which relied on rainfall, resulted in a huge loss (Kshs. 38,164.4) to the farmers.

In monetary terms, the difference in profits obtained between T1 and T2 was substantial (over Kshs. 21,000). However, these margins were not statistically different at $P \le 0.05$ (Appendix 29). It is eminent that there were significant differences in terms of net income between the control treatment, T3, and the irrigated treatments T1 and T2.

Table 18: Gross margin (Kshs.) for tomato produced from the site for season 1

Average	Estimated amount per mean area 9.45×10^{-1} ha.			Estimated amount per ha.		
	T_1	T_2	T_3	T_1	T_2	T_3
Total Output	2,366.60	2,246.20	1,498.80	250,433.9	237,693.1	158,603.2
Total Marketed tomato	2,116.20	1,917.80	1,182.60	223,936.5	202,941.8	125,142.9

Total inputs cost	1,520.00	1,520.00	1,520.00	163,307.3	163,307.3	163,307.3
Total water costs	20.30	20.80	0.00	2,148.10	2,201.10	0.00
Gross margin	**575.90^c**	**377.00^b**	**-337.4^a**	**58,481.1^b**	**37,433.4^b**	**-38,164.4^a**
LSD (T)	55.58			18,831.6		
cv%	7.9%			12.6%		

[a] Different letters in a row denote significant differences between treatments at $P \leq 0.05$.

The net incomes for the treatments were, however, considerably lower. This is because the treatments produced lower marketable yields and also due to price differences. The selling prices appear low for season 1 because the crops were harvested and sold when supply was high. Season 2, which was harvested at low peak, achieved a much better price. Though tomato is a fresh product and can easily be damaged, transport losses and storage losses were greatly minimized due to ready market for the produce from the local market center.

Price fluctuation is not a new trend. Given that the cultivation of tomatoes is mostly carried out during dry season, demand and market prices reach their peaks, and the probability of finding a buyer for the whole stock increases (Rockstrom et al., 2005). During rainy season, tomatoes generally flood the market, and the producers should not expect to be able to sell the whole produce nor to obtain a good price.

Production in season 2 followed the same trend as observed in season 1; where T1 and T2 had marketable yields, although the production still resulted in a loss to farmers since the revenue obtained were much less compared to the cost of production inputs used. There was no output for T3 season 2, resulting to a total loss to investment equivalent to the exact cost of inputs used in T3 plots (Table 19). The economic losses (negative gross margins) in season 2 was as a result of the reduction in the marketable yields (in T1 and T2), and total yield failure (in T3). Supplemented plots (T1 and T2) had marketable yields, but the revenue generated could not sufficiently compensate for the cost of production; resulting into partial losses. In T3, lack of marketable yields resulted to a total loss to production. Factors contributing to the yield reductions have been enumerated under chapter 4.2.1.

Table 19: Gross margin (Kshs.) for tomato produced from the site for season 2

Average	**Estimated amount per mean area 9.45×10^{-3} ha.**			**Estimated amount per ha.**		
	T_1	T_2	T_3	T_1	T_2	T_3
Total Output	1,797.00	1,904.80	0.00	190,158.7	201,566.1	0.00
Total Marketed tomato	1,554.30	1,610.60	0.00	164,476.2	170,433.8	0.00
Total inputs cost	1,753.30	1,753.30	1,753.30	185,534.4	185,534.4	185,534.4
Total water costs	11.40	12.60	0.00	1,206.30	1,371.10	0.00
Gross margin	**-210.40^{b}**	**-155.30^{b}**	**-1,753^{a}**	**-22,264^{b}**	**-16,472^{b}**	**-185,534^{a}**
LSD (T)	166.74			17,643		
cv%	7.9%			12.6%		

[a] Different letters in a row denote significant differences between treatments at $P < 0.05$

Losses in T2 (Kshs. 16,472) were slightly lower than in T1 (Kshs. 22,264); a fact attributed to slight differences in the quantities of marketable tomatoes between the treatments, but the differences between them still did not reach the $p < 0.05$ significant level. The loss in revenue in the irrigated treatments T1 (14.6%) and T2 (10.2%) was as a consequence of yield reduction (previously explained in this document under WUE).

Water costs were variable and represented 1.35 and 0.68 % of the total production costs for season 1 and season 2, respectively. This implies that production in season 2 was more expensive in terms of inputs, since the crops' vigour was lower than the previous season, and therefore water costing constituted a small margin of the total cost.

4.5.2 Onions gross margin

The irrigated treatments T1 and T2 provided a 48.93 and 45.61 % (equivalent to 52,872 and 46,301 Kshs.ha^{-1}) profit to the farmers (Table 20). The current farming practices could, at best, give a 24.75 % loss to investment.

Water cost represented 3.65 % and 3.71 % of the total production costs in T1 and T2 in that order. The profits realized from T1 and T2 were not statistically different (Appendix 30), but they differed with that obtained from T3. It therefore means the extra costs of water incurred in T1 and T2 were totally necessary; they basically contributed to increasing productivity, hence the high gross margin.

Table 20: Gross margins (Kshs.) for onion crop

Average	**Estimated amount per mean area 9.45×10^{-3} ha.**			**Estimated amount per ha.**		
	T_1	T_2	T_3	T_1	T_2	T_3
Total Output	1,062.70	976.00	412.80	112,455.0	103,280.4	43,682.5
Total Marketed onion	1,021.10	959.30	403.40	108,052.9	101,513.2	42,687.8
Total inputs cost	480.00	480.00	480.00	53,254.5	53,254.5	53,254.5
Total water costs	18.20	18.50	0.00	1,926.90	1,957.70	0.00
Gross margin	**522.90b**	**460.80b**	**-76.60a**	**52,872b**	**46,301b**	**-10,567a**

LSD (T)	92.7	9,527.9
cv%	7.7	7.4

Different letters in a row indicate significant differences between treatments at P 0.05.

4.5.3 Onion vs. Tomato

It is worth noting that a comparison between onion and tomato profitability is made here, albeit with caution since the field layout did not give provision for such comparison on a direct linkage. The simple analysis provided here primarily compares the two crops as independent farm enterprises between which a farmer has to make a decision based on perceived risks and benefits associated with them.

Since onions were only produced in one season (season 1 for tomato), results of season 2 were not used to analyze the differences. To better do this, production costs, profit margins and losses from control plots were compared. When water costs were compared against the total production costs, it accounted for an average of 1.35 % in tomato, as compared to 3.68 % in onion. The susceptibility of tomatoes to several pests and diseases make it a more sensitive crop. It means tomato production as an enterprise is capital intensive than onion; more is spent on variable inputs like pesticides and fungicides and, under commercialized production, fertilizers.

Despite the production constrains, tomato gross margins per hectare were still considerably high; giving an average return of 26.12 % (T1) and 18.45 % (T2) against 48.93 % (T1) and 45.61 % (T2) for onion, respectively. Predictably, losses associated with the production of the two crops follow the same trend. When the current rainfed agriculture was practiced (T3) with full investment on other variable costs, losses of upto 30.50 % in tomato and 24.75 % in onion were observed. This, in part, explains why tomato is a common home gardening crop in the ASALs and among the small-scale farmers; full scale production has high risk associated with it and resource poor farmers are unwilling to venture into production

Chapter Five

Conclusion and Recommendations

5.1 Conclusion

The results of this study confirmed that supplemental irrigation (SI) can considerably improve growth and yields, and generate meaningful economic benefits compared to the currently practiced rainfed agriculture. The low yields, negative gross margins and WUE realized among the treatments, especially in tomato season 2, were because of the crops' poor health resulting from the agronomic practices than from the failures of supplemental irrigation system. The trials' results also demonstrated that the twice-a-day supplemental irrigation mode at 4-day interval (T1) was comparatively effective in enhancing yields than supplementing at once-very-day (T2), in both tomato and onion trials.

Since the field layout did not give provision for the comparison of onion and tomato profitability on a direct linkage, a simple analysis was done that compared the two crops as independent farm enterprises; between which a farmer has to make a decision based on perceived risks and benefits associated with them. The two crops had one thing in common, the yield increase with supplemental irrigation alone was sufficient to compensate for the investment of input and capital in the system. But farmers must consider their production cost before using on a commercial scale. When the gross margin analysis was carried out for the supplemental irrigation system (SI) and compared to the current rainfed agriculture, it could contentedly be adduced from the results that potentially higher benefit in terms of yield increases can be obtained through the combination of supplemental irrigation and other appropriate agronomic practices specific to the crops grown.

As far as productivity on an agricultural system is concerned, WUE seems to be the major criterion of evaluation. From the present investigation and other reviewed work, marketable yields and water use efficiency of tomato and onions can be increased significantly by supplemental irrigation. Tomato results agreed with this trend, albeit with some divergence on the WUE findings. It should be appreciated that the biggest challenge faced when trying to determine the efficiency of a single irrigation or an irrigation season, at field, farm or plot scales, is accurately measuring all the components of the water balance required to calculate this efficiency. Thus a deviation of tomato WUE from the popular findings should not be interpreted to mean a system failure. Therefore, while more emphasis is laid on WUE, it should also be apparent that good management practices are essential to ensure the greatest returns from irrigation. The grower must plant recommended varieties and plant populations, provide the proper control of weeds, diseases and insects, and maintain proper fertility levels.

5.2 Recommendations

- Since the current rainfed production system would most definitely result into an economic loss to the farmers, and especially after proving the potentials of SI, it would be wiser to encourage farmers to invest in supplemental irrigation as a means to cushion against losses. What are needed are efforts towards enhancing farmers' willingness to act with self-interest towards its adoption.
- It would be more prudent if vigorous rural extension services were initiated to encourage culture change among small-scale farmers so that they can shift to growing high value crops like tomato and onions, as opposed to traditionally grown low-yielding crops like maize. Supplemental irrigation, in general, requires that the crop be of high value in order to pay for the extra investment

- Supplemental irrigation looks promising as good alternative to rainfed agriculture in the district. However, it is also important to recommend further investigations and/or demonstration on response of tomato, onion and other high-value crops to supplemental irrigation, with more emphasis on low-cost drip system, in different regions before recommending these practices for use. This will increase awareness and acceptability
- Access to water has remained a problem owing to the insufficient and/or unreliable rainfall. Therefore, to improve and sustain agriculture in the ASALs through supplemental irrigation, parallel efforts on soil and water conservation are needed, particularly to enhance water harvesting and/or storage during the storms when runoffs become a menace.
- The government should provide loans or incentives to resource-poor farmers/farming groups to enable them acquire the needed infrastructures and/or farming inputs.

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Appendix

Appendix 1: The climatic data at the University of Nairobi Kibwezi meteorological sub-station from October 2009 to April 2010

Month	Monthly rainfall		Monthly Temperature (°C)			Monthly RH (%)[1]	
	Total (mm)	Mean (mm)	Mean max.	Mean min.	Monthly mean	Max.	Min.
Oct.	31.62	1.02	30.2	20.1	25.1	76.0	41.8
Nov.	67.8	2.26	29.6	21.2	25.4	78.0	41.6
Dec.	137.02	4.42	29.3	21.4	25.4	78.1	46.0
Jan.	8.68	0.28	27.9	20.8	24.4	82.7	44.7
Feb.	22.8	0.81	30.3	19.4	24.9	77.2	41.9
March	251.5	8.11	30.7	20.1	25.4	73.6	38.6
April	77.8	2.59	29.8	18.3	24.1	76.7	39.2

[1]-relative humidity (%)

Appendix 2: Crop water requirement for onions planted on 29/10/2009

Dates	Growing days	Stage of devpt.	Crop coefficient	ET_o(mm/day)	ET_c(mm/day)	ETc(mm/season)
29/10-13/11/2009	15	Initial stage	0.6	5.26	3.16	47.40
13/11-9/12/2009	26	Crop devpt.	0.8	5.26	4.21	109.46
9/12/2009-6/1/2010	28	Mid season	1.1	5.26	5.79	162.12
6/1-13/12/2010	15	Late season	0.9	5.26	4.74	71.10
Total						**390.08**

Appendix 3: Crop water requirements for tomato (season 1) planted on 3/11/2009

Dates	Growing days	Stage of devpt.	Crop coefficient	ET_o(mm/day)	ET_c(mm/day)	ET_c(mm/season)
3/11-18/12/2009	45	Crop devpt.	0.85	5.26	4.471	201.2
18/12/09-9/1/2010	22	Mid stage	1.2	5.26	6.312	138.86
9/1-20/1/2010	15	Late stage	0.95	5.26	4.997	74.95
Total	**82**					**415.01**

Appendix 4: Crop water requirements for tomato (season 2) planted on 5/2/2010

Dates	Growing days	Stage of devpt.	Crop coefficient	ET_o(mm/day)	ET_c(mm/day)	ET_c(mm/season)
5/2-22/3/2010	45	Crop dev.	0.85	5.26	4.471	201.20
22/3-13/4/2010	22	Mid stage	1.2	5.26	6.312	138.82
13/4-24/4/2010	11	Late stage	0.95	5.26	5.00	55.00
Total	**78**					**394.97**

Appendix 5: Comparing the seasonal water requirement (ETc), total rainfall (R) and the supplemented amounts (SI) for onion growth

Crop stage	Total crops water need (ETc)	Total rainfall (R)	Amounts supplemented in irrigation (SI)	
		(mm per crop season)		
			T1	T2
Initial stage	47.40	28.70	25.28	25.28
Crop development	109.46	108.00	21.05	19.34
Mid season	162.12	95.00	71.54	69.74
Late season	71.10	3.10	64.22	70.38
Total	**390.08**	**234.8**	**182.09**	**184.74**

Appendix 6: Comparing the seasonal water requirement (ETc), total rainfall (R) and the supplemented amounts (SI) for season 1 tomato growth

Crop stage	Total crops water need (ETc)	Total rainfall (R)	Amounts supplemented in irrigation (SI)	
		(mm per crop season)		
			T1	T2
Crop development	201.20	139.90	60.61	62.58
Mid stage	138.86	64.80	71.55	73.04
Late stage	74.95	1.60	70.60	72.12
Total	**415.01**	**206.30**	**202.76**	**207.74**

Appendix 7: Comparing the seasonal water requirement (ETc), total rainfall (R) and the supplemented amounts (SI) for season 2 tomato growth

Crop stage	Total crops water need (ETc)	Total rainfall (R)	Amounts supplemented in irrigation (SI)	
		(mm per crop season)		
			T1	T2
Crop development	201.20	202.90	63.05	65.05
Mid stage	138.82	115.30	18.93	25.02
Late stage	55.00	10.70	32.17	36.05
Total	**394.97**	**328.9**	**114.15**	**126.12**

Appendix 8: Chemical characteristics of irrigation water from Chyulu hills

pH	8.02
EC(μS/cm)	0.26
SAR	3.03

OH^- meq/L	Trace
CO_3 meq/L	Trace
HCO_3 meq/L	3.15
Cl^- meq/l	0.25
Na^+ meq/L	2.10
Ca^+ meq/L	0.16
Mg^+ meq/L	0.80
K^+ meq/L	0.68

Appendix 9: Some chemical and physical characteristics of soils at the study site

pH	
(H_2O)	6.89
($CaCl_2$)	5.98
N (%)	0.20
P (%)	10.0
K^+ meq/L	10.13
Organic carbon (OC) (%)	0.86
Texture	
Sand (%)	47
Silt (%)	11
Clay (%)	42
Bulk density (kg/m^3)	1.41
Field capacity (FC, %$_m$)	68.93
Wilting point (PWP, %$_m$)	1.69
Ksat (cm/hr)	3.88

Appendix 10: Calculated total irrigation (TI) and evapotranspiration (ET) values for the three treatment of tomato (season 1)

Treatment	T1	T2	T3
Effective rainfall, R(mm)	234.80	234.80	234.80
No. of irrigation days	22	22	0
Irrigation, I (mm)	202.76	207.74	0
TI (R+I) (mm)	437.56	442.54	234.80
ET (mm)	415.01	415.01	415.01
Δ S	22.55	27.53	-180.21

Appendix 11: Calculated total irrigation (TI) and evapotranspiration (ET) values for the three treatment of onion

Treatment	T1	T2	T3
Effective rainfall, R(mm)	234.80	234.80	234.80
No. of irrigation days	22	22	0
Irrigation, I (mm)	182.09	184.74	0
TI (R+I) (mm)	416.89	419.54	234.80
ET (mm)	390.08	390.08	390.08
Δ S	26.81	29.46	-155.28

Appendix 12: Calculated total irrigation (TI) and evapotranspiration (ET) values for the three treatment of tomato (season 2)

Treatment	T1	T2	T3
Effective rainfall, R(mm)	328.90	328.90	328.90
No. of irrigation days	20	20	0
Irrigation, I (mm)	114.15	126.12	0
TI (R+I) (mm)	443.05	455.05	328.90
ET (mm)	394.97	394.97	394.97
Δ S	48.08	60.08	66.07

Appendix 13: Analysis of variance table for Tomato number of Branches/plant

```
Source of variation      d.f.      s.s.       m.s.     v.r.     F pr.
Rep stratum                 2    0.12774    0.06387   12.40
Rep.Season stratum
Season                      1   14.94682   14.94682 2902.29   <.001
Residual                    2    0.01030    0.00515    0.23
Rep.Season.Time stratum
Time                        2   34.69685   17.34842  775.41   <.001
Season.Time                 2    2.34570    1.17285   52.43   <.001
Residual                    8    0.17899    0.02237    1.25
Rep.Season.Time.Treatment stratum
Treatment                   2  131.66669   65.83335 3679.74   <.001
Season.Treatment            2   10.30643    5.15322  288.04   <.001
Time.Treatment              4   17.92593    4.48148  250.49   <.001
Season.Time.Treatment       4    3.31097    0.82774   46.27   <.001
Residual                   24    0.42938    0.01789
Total                      53  215.94579
Stratum standard errors and coefficients of variation *****
Stratum                    d.f.           s.e.          cv%
```

```
Rep                              2          0.0596          1.5
Rep.Season                       [illegible]          0.0239          0.6
Rep.Season.Time                  8          0.0864          2.2
Rep.Season.Time.Treatment       24          0.1338          3.5
Least significant differences of means (5% level) ***
Table                    Season          Time   Treatment       Season
                                                                  Time

rep.                          27            18          18            9
l.s.d.                    0.0840        0.1150      0.0920       0.1365
d.f.                           2             8          24         9.45
Except when comparing means with the same level(s) of
Season                                                          0.1626
d.f.                                                                 8
```

Appendix 14: Analysis of variance table for Tomato number of Leaves/plant

```
Source of variation      d.f.         s.s.         m.s.      v.r.  F pr.
Rep stratum                 2      0.00218      0.00109      0.45
Rep.Season stratum
Season                      1    136.00907    136.00907  56496.08 <.001
Residual                    2      0.00481      0.00241      0.13
Rep.Season.Time stratum
Time                        2    142.23681     71.11841   3694.28  <.001
Season.Time                 2     30.47071     15.23536    791.41  <.001
Residual                    8      0.15401      0.01925      1.02
Rep.Season.Time.Treatment stratum
Treatment                   2    395.17551    197.58776  10500.68 <.001
Season.Treatment            2    133.03601     66.51801   3535.06  <.001
Time.Treatment              4     63.32304     15.83076    841.32  <.001
Season.Time.Treatment       4     34.53976      8.63494    458.90  <.001
Residual                   24      0.45160      0.01882
Total                      53    935.40353
Stratum standard errors and coefficients of variation *****
Stratum                        d.f.           s.e.           cv%
Rep                               2         0.0078           0.1
Rep.Season                        2         0.0164           0.2
Rep.Season.Time                   8         0.0801           0.9
Rep.Season.Time.Treatment        24         0.1372           1.5
Least significant differences of means (5% level) ***
Table                    Season          Time   Treatment       Season
                                                                  Time

rep.                          27            18          18            9
l.s.d.                    0.0575        0.1067      0.0944       0.1248
d.f.                           2             8          24         8.89
Except when comparing means with the same level(s) of
Season                                                          0.1508
d.f.                                                                 8
```

Appendix 15: Analysis of variance table for Tomato plant Height

```
Source of variation      d.f.         s.s.         m.s.      v.r.  F pr.
Rep stratum                 2   6.249E-01    3.124E-01     10.30
Rep.Season stratum
Season                      1   9.300E+02    9.300E+02  30654.22 <.001
Residual                    2   6.068E-02    3.034E-02      0.34
Rep.Season.Time stratum
Time                        2   3.458E+03    1.729E+03  19186.20 <.001
Season.Time                 2   3.880E+02    1.940E+02   2152.49  <.001
Residual                    8   7.209E-01    9.011E-02      1.24
Rep.Season.Time.Treatment stratum
Treatment                   2   7.098E+03    3.549E+03  48797.06 <.001
Season.Treatment            2   5.476E+02    2.738E+02   3764.72  <.001
Time.Treatment              4   1.317E+03    3.291E+02   4525.83  <.001
```

```
Season.Time.Treatment      4  2.844E+02  7.111E+01  977.81  <.001
Residual                  24  1.745E+00  7.273E-02
Total                     53  1.403E+04
Stratum standard errors and coefficients of variation *****
Stratum                     d.f.          s.e.          cv%
Rep                            2        0.1318          0.5
Rep.Season                     2        0.0581          0.2
Rep.Season.Time                8        0.1733          0.6
Rep.Season.Time.Treatment   24          0.2697          0.9
Least significant differences of means (5% level) ***
Table                Season          Time   Treatment      Season
                                                            Time
rep.                     27            18          18           9
l.s.d.               0.2040        0.2307      0.1855      0.2790
d.f.                      2             8          24        9.81
Except when comparing means with the same level(s) of
Season                                                    0.3263
d.f.                                                           8
```

Appendix 16: Analysis of variance table for Onion plant Height

```
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
Rep stratum                 2      10.106       5.053     0.33
Rep.Time stratum
Time                        2     578.473     289.237    18.67  0.009
Residual                    4      61.967      15.492     6.25
Rep.Time.Treatment stratum
Treatment                   2     881.510     440.755   177.76  <.001
Time.Treatment              4      34.316       8.579     3.46  0.042
Residual                   12      29.754       2.479
Total                      26    1596.126
Stratum standard errors and coefficients of variation
Stratum                     d.f.          s.e.          cv%
Rep                            2         0.749          3.1
Rep.Time                       4         2.272          9.5
Rep.Time.Treatment            12         1.575          6.6
Least significant differences of means (5% level)
Table                  Time   Treatment        Time
                                          Treatment
rep.                      9           9           3
l.s.d.                5.151       1.617       5.081
d.f.                      4          12        6.74
Except when comparing means with the same level(s) of
Time                                          2.801
d.f.                                             12
```

Appendix 17: Analysis of variance table for Onion number of Leaves/plant

```
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
Rep stratum                 2     0.41662     0.20831     1.85
Rep.Time stratum
Time                        2    25.33876    12.66938   112.26  <.001
Residual                    4     0.45142     0.11286     1.44
Rep.Time.Treatment stratum
Treatment                   2    27.90180    13.95090   177.79  <.001
Time.Treatment              4     4.27618     1.06904    13.62  <.001
Residual                   12     0.94162     0.07847
Total                      26    59.32640
Stratum standard errors and coefficients of variation *****
Stratum                     d.f.          s.e.          cv%
Rep                            2        0.1521          2.9
Rep.Time                       4        0.1940          3.7
Rep.Time.Treatment            12        0.2801          5.4
```

```
Least significant differences of means (5% level) ***
Table                    Time   Treatment        Time
                                            Treatment
rep.                        9           9           3
l.s.d.                 0.4397      0.2877      0.5255
d.f.                        4          12       13.90
Except when comparing means with the same level(s) of
Time                                           0.4983
d.f.                                               12
```

Appendix 18: Analysis of variance table for tomato fruit Yield (t/ha)

```
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
Rep stratum                 2      0.2707      0.1353     0.52
Rep.Season stratum
Season                      1    124.4516    124.4516   481.43  0.002
Residual                    2      0.5170      0.2585     0.63
Rep.Season.Treatment stratum
Treatment                   2    106.9766     53.4883   129.74  <.001
Season.Treatment            2      3.7180      1.8590     4.51  0.049
Residual                    8      3.2983      0.4123
Total                      17    239.2323
Stratum standard errors and coefficients of variation *****
Stratum                    d.f.            s.e.          cv%
Rep                           2           0.150          2.3
Rep.Season                    2           0.294          4.5
Rep.Season.Treatment          8           0.442          9.8
Least significant differences of means (5% level) ***
Table                  Season   Treatment      Season
                                            Treatment
rep.                        9           6           3
l.s.d.                  1.031       0.855       1.095
d.f.                        2           8        9.91
Except when comparing means with the same level(s) of
Season                                          1.209
d.f.                                                8
```

Appendix 19: Analysis of variance table for Large tomato fruits

```
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
Rep stratum                 2      11.325       5.662     2.25
Rep.Season stratum
Season                      1     296.137     296.137   117.88  0.008
Residual                    2       5.024       2.512     0.62
Rep.Season.Treatment stratum
Treatment                   2     174.971      87.485    21.76  <.001
Season.Treatment            2      24.653      12.327     3.07  0.103
Residual                    8      32.165       4.021
Total                      17     544.275
Stratum standard errors and coefficients of variation *****
Stratum                    d.f.            s.e.          cv%
Rep                           2           0.971         10.3
Rep.Season                    2           0.915          9.7
Rep.Season.Treatment          8           2.005         21.3
Least significant differences of means (5% level) ***
Table                  Season   Treatment      Season
                                            Treatment
rep.                        9           6           3
l.s.d.                  3.215       2.670       3.416
d.f.                        2           8        9.91
Except when comparing means with the same level(s) of
Season                                          3.775
d.f.                                                8
```

Appendix 20: Analysis of variance table for Medium tomato fruits

```
Source of variation      d.f.         s.s.          m.s.     v.r.  F pr.
Rep stratum                 2       12.562         6.281     3.96
Rep.Season stratum
Season                      1      310.752       310.752   196.11  0.005
Residual                    2        3.169         1.585     0.94
Rep.Season.Treatment stratum
Treatment                   2      402.236       201.118   119.30  <.001
Season.Treatment            2        2.545         1.272     0.75  0.501
Residual                    8       13.486         1.686
Total                      17      744.750
Stratum standard errors and coefficients of variation *****
Stratum                        d.f.          s.e.          cv%
Rep                               2         1.021          9.0
Rep.Season                        2         0.727          6.4
Rep.Season.Treatment              8         1.298         11.4
Least significant differences of means (5% level) ***
Table                    Season    Treatment        Season
                                                 Treatment
rep.                          9            6             3
l.s.d.                    2.553        1.729         2.367
d.f.                          2            8          9.18
Except when comparing means with the same level(s) of
Season                                               2.445
d.f.                                                     8
```

Appendix 21: Analysis of variance table for Culls tomato fruits

```
Source of variation      d.f.         s.s.          m.s.     v.r.  F pr.
Rep stratum                 2        4.764         2.382    33.53
Rep.Season stratum
Season                      1       33.565        33.565   472.49  0.002
Residual                    2        0.142         0.071     0.06
Rep.Season.Treatment stratum
Treatment                   2       12.272         6.136     4.81  0.042
Season.Treatment            2       14.599         7.299     5.72  0.029
Residual                    8       10.203         1.275
Total                      17       75.545
Stratum standard errors and coefficients of variation *****
Stratum                        d.f.          s.e.          cv%
Rep                               2         0.630         17.5
Rep.Season                        2         0.154          4.3
Rep.Season.Treatment ,            8         1.129         31.3
Least significant differences of means (5% level) ***
Table                    Season    Treatment        Season
                                                 Treatment
rep.                          9            6             3
l.s.d.                    0.541        1.504         1.745
d.f.                          2            8          8.43
Except when comparing means with the same level(s) of
Season                                2.126
d.f.                                  8
```

Appendix 22: Analysis of variance table for Onions Yield (t/ha)

```
Source of variation      d.f.         s.s.          m.s.     v.r.  F pr.
Rep stratum                 2      0.00862       0.00431     0.08
Rep.*Units* stratum
Treatment                   2     10.68416       5.34208    95.63  <.001
Residual                    4      0.22344       0.05586
Total                       8     10.91622
Stratum standard errors and coefficients of variation
Stratum                        d.f.          s.e.          cv%
```

```
Rep                               2          0.0379          1.2
Rep.*Units*                       4          0.2363          7.6
Least significant differences of means (5% level)
Table             Treatment
rep.                      3
d.f.                      4
l.s.d.               0.5358
```

Appendix 23: Analysis of variance table for Onion bulb Length

```
Source of variation     d.f.        s.s.        m.s.    v.r.  F pr.
Rep stratum                2      0.6625      0.3312    0.79
Rep.*Units* stratum
Treatment                  2     13.2608      6.6304   15.85  0.013
Residual                   4      1.6729      0.4182
Total                      8     15.5962
Stratum standard errors and coefficients of variation
Stratum                      d.f.           s.e.          cv%
Rep                             2          0.332          5.1
Rep.*Units*                     4          0.647          9.9
Least significant differences of means (5% level)
Table             Treatment
rep.                      3
d.f.                      4
l.s.d.                1.466
```

Appendix 24: Analysis of variance table for Onion bulb Diameter

```
Source of variation     d.f.        s.s.        m.s.    v.r.  F pr.
Rep stratum                2     0.13202     0.06601    5.85
Rep.*Units* stratum
Treatment                  2     7.96382     3.98191  353.08  <.001
Residual                   4     0.04511     0.01128
Total                      8     8.14096
Stratum standard errors and coefficients of variation
Stratum                      d.f.           s.e.          cv%
Rep                             2         0.1483          3.0
Rep.*Units*                     4         0.1062          2.1
Least significant differences of means (5% level)
Table             Treatment
rep.                      3
d.f.                      4
l.s.d.               0.2407
```

Appendix 25: Analysis of variance table for Onion bulbs' Weight

```
Source of variation     d.f.        s.s.        m.s.    v.r.  F pr.
Rep stratum                2        5.30        2.65    0.21
Rep.*Units* stratum
Treatment                  2      384.00      192.00   15.18  0.014
Residual                   4       50.61       12.65
Total                      8      439.91
Stratum standard errors and coefficients of variation
Stratum                      d.f.           s.e.          cv%
Rep                             2           0.94          3.6
Rep.*Units*                     4           3.56         13.7
Least significant differences of means (5% level)
Table             Treatment
rep.                      3
d.f.                      4
l.s.d.                 8.06
```

Appendix 26: Analysis of variance table for Onion bulbs' % Moisture content

```
Source of variation      d.f.         s.s.         m.s.     v.r.  F pr.
Rep stratum                 2      10.6094       5.3047     9.25
Rep.*Units* stratum
Treatment                   2     359.2808     179.6404   313.13  <.001
Residual                    4       2.2948       0.5737
Total                       8     372.1850
Stratum standard errors and coefficients of variation
Stratum                       d.f.           s.e.          cv%
Rep                              2          1.330          1.9
Rep.*Units*                      4          0.757          1.1
Least significant differences of means (5% level)
Table               Treatment
rep.                        3
d.f.                        4
l.s.d.                  1.717
```

Appendix 27: Analysis of variance table for tomato WUE

```
Source of variation      d.f.         s.s.         m.s.     v.r.  F pr.
Treatment                   2       76.247       38.123    24.52  0.006
Season                      1     1561.101     1561.101  1004.18  <.001
Rep                         2        2.778        1.388     0.89  0.478
Treatment.Season            2      398.468      199.234   128.16  <.001
Treatment.Rep               4       11.907        2.977     1.91  0.272
Season.Rep                  2        4.638        2.319     1.49  0.328
Residual                    4        6.218        1.555
Total                      17     2061.355

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

Stratum                       d.f.           s.e.          cv%
Rep                              2          1.247          6.6
Rep.Season                       2          1.018          9.7
Rep.Season.Treatment             8          1.990         19.0
Least significant differences of means (5% level) ***
Table               Treatment      Season          Rep   Treatment
                                                            Season
rep.                        6           9            6           3
d.f.                        4           4            4           4
l.s.d.                  1.999       1.632        1.999       2.826
Table               Treatment      Season
                          Rep         Rep
rep.                        2           3
d.f.                        4           4
l.s.d.                  3.462       2.826
```

Appendix 28: Analysis of variance table for Onions WUE

```
Source of variation      d.f.         s.s.         m.s.     v.r.  F pr.
Rep stratum                 2       0.1773       0.0886     0.25
Rep.*Units* stratum
Treatment                   2      12.2059       6.1029    17.26  0.011
Residual                    4       1.4141       0.3535
Total                       8      13.7932
Stratum standard errors and coefficients of variation
Stratum                       d.f.           s.e.          cv%
Rep                              2          0.172          2.2
Rep.*Units*                      4          0.595          7.5
Least significant differences of means (5% level)
Table               Treatment
rep.                        3
```

```
d.f.                         4
l.s.d                    1.348
```

Appendix 29: Appendix 28: Analysis of variance table for Onions WUE

```
Source of variation      d.f.         s.s.         m.s.     v.r.  F pr.
Rep stratum                 2  2.070E+07  1.035E+07     0.89
Rep.Season stratum
Season                      1  4.921E+09  4.921E+09   423.31  0.002
Residual                    2  2.325E+07  1.163E+07     0.52
Rep.Season.Treatment stratum
Treatment                   2  6.298E+09  3.149E+09   140.76  <.001
Season.Treatment            2  7.429E+08  3.714E+08    16.60  0.001
Residual                    8  1.790E+08  2.237E+07
Total                      17  1.219E+10
Stratum standard errors and coefficients of variation *****
Stratum                    d.f          s.e.        cv%
Rep                          2        1313.5       12.6
Rep.Season                   2        1968.5       18.9
Rep.Season.Treatment         8        4729.8       45.4
Least significant differences of means (5% level) ***
Table                  Season   Treatment      Season
                                            Treatment
rep.                        9           6           3
l.s.d.                 4915.6      6297.2      7886.2
d.f.                        2           8       10.00
Except when comparing means with the same level(s) of
Season                                         8905.5
d.f.                                                8
```

Appendix 30: Analysis of variance table for onion Gross margin (GM/ha)

```
Source of variation      d.f.         s.s.         m.s.     v.r.  F pr.
Rep stratum                 2      750484.      375242.     0.08
Rep.*Units* stratum
Treatment                   2  600148740.   300074370.    66.08  <.001
Residual                    4   18165052.     4541263.
Total                       8  619064276.
Stratum standard errors and coefficients of variation *****
Stratum                    d.f.         s.e.        cv%
Rep                          2         353.7        4.0
Rep.*Units*                  4        2131.0       24.1
Least significant differences of means (5% level) ***
Table              Treatment
rep.                       3
d.f.                       4
l.s.d.                4830.8
```