THE EFFECT OF IRRIGATION MANAGEMENT ON CROP WATER REQUIREMENT AND CROP WATER PRODUCTIVITY OF TOMATO AND SWEET CORN

IN KIBWEZI, KENYA

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DECLARATION

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

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This thesis has been submitted for examination with our approval as the University Supervisors.

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Signed.. Date 07/04/10

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DEDICATION

To my late guardian and mother
Mrs. Mberia Wambui Gutu
for her insight for taking me to
school to learn
how to read and write.

"You know the worth of water
When the well dries up"

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ABBREVIATIONS AND ACRONYMS

$	Currency (Dollar)
%v/v	Percent volume by volume
%wt/wt	Percent weight by weight
A	Cross sectional area of inner cylinder
ASAL	Arid and semi arid lands
ASDS	Agricultural Sector Development Strategy
atm	Atmospheres
AWC	Available water capacity
CEC	Cation exchange capacity
CWP	Crop water productivity
CWR	Crop water requirement
d	Thickness of soil profile
dh/dx	Hydraulic potential gradient
D_{H2O}	Depth of water per soil depth
DR	Dryrun
dSm^{-1}	Decisremens/m)
dt	Time
DT	Treatment for tomato
D_w	Deep percolation.
E	Evapotranspiration
EC	Electrical Conductivity
emf	Electomagnetic frequency
E_{pan}	Pan evaporation
ET	Actual crop evapotranspiration
ET_a	Actual evaporation
ETcrop	Crop water requirement
ET_m	Maximum or potential evapotranspiration
ETo	Reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FC	Field capacity
GoK	Government of Kenya
I	Irrigation
K	Hydraulic conductivity
k	Intrinsic permeability
K_c	Crop coefficient
KIP	Kibwezi Irrigation Project
kPa	Kilo pascal
K_{pan}	Pan coefficient
K_{sat}	Saturated hydraulic conductivity
ky	Yield response factor
MoA	Ministry of Agriculture
MP&ND	Ministry of Planning and National Development
OC	Organic carbon
P	Precipitation
Pb	Bulky density

PWP	Permanent wilting point
q	Water flux density
R_f	Run off
R_s	Incoming short-wave radiation
R_e	Effective rainfall
RH	Relative humidity.
ST	Treatments for sweet corn
SW1	The first crop of sweet corn
SW2	The second crop of sweet corn
T	Transpiration
TARDA	Tana River Development Authority
ti	Time interval
ton	Tones
TWU	Total crop water use
U	Drainage
UNESCO	United Nations Educational, scientific and cultural organization
USA	United States of America
USDA	United States Department of Agriculture
V	Volume
W	Water content or mass wetness in fraction.
w	Antecedent moisture content
WR	Wetrun
Y	Yield
Δh	Change of water height in one minute
ΔS	Change in soil moisture storage
Δv	Change in volume in aspirator reading
θ	Volumetric soil water content

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ABSTRACT

Research on crop water requirement and productivity is important to reduce agricultural water use in arid and semiarid areas (ASAL), where water is a limited resource. A study was conducted to determine crop water requirement and evaluate crop water productivity of tomato (*Lycopersicon esculentum L. var. M82*) and sweet corn (*Zea mays L. var. Renat*) under drip and sprinkler irrigation systems, respectively, in Kibwezi. The study objectives were (i) to determine crop water requirement (ET_{crop}), (ii) to evaluate yield response to different irrigation water application rates and (iii) to evaluate the effect of different irrigation water application rates on crop water productivity (CWP). Treatments involved reducing the sprinkler irrigation hours for sweet corn and increasing the drip irrigation interval for tomato. The experimental design was a randomized complete block design (RCBD) with six main treatments, replicated thrice for each crop under the respective irrigation system. Crop water requirement (ET_{crop}) values were computed using pan evaporation method. Sweet corn requires most water during the development stage, these stage accounted for 52 and 54 % of the total seasonal ET_{crop} for the first and second crop, respectively. For tomato, ET_{crop} was found to be critical during the development and the mid stage, this being 298 and 269 mm/season which accounts for 73 and 76 % of the total growing seasonal ET_{crop} for the first and second crop, respectively. The highest sweet corn yields of 11.84 and 10.88 t ha^{-1} were obtained from the treatment irrigated for 2.5 and 3 hours, which corresponds to 769 and 882 mm of total irrigation (TI) (irrigation plus effective rainfall) for the first and second crop, respectively. The highest tomato yields of 24.74 and 9.20 t ha^{-1} were obtained from treatment with irrigation interval of 4 days which corresponds to 819 and 732 mm of TI for the first and second crop, respectively. Both the yields of sweet corn and tomato were correlated with TI, at $P \leq 0.05$. The results imply that, 2.5 hours or an average 791 mm of sprinkler irrigation water applied at an interval of three days is adequate for sweet corn production under the prevailing climatic condition, thus saving an average of 41 mm or 5 % of the irrigation water from the 3 hours or an average of 832 mm of TI that is currently applied. On the other hand, 3 hours of drip irrigation can be applied after an interval of 4 days for tomato production without significantly affecting the yields. This corresponds to an average of 776 mm of TI, thus saving an average of 233 mm or 23 % of the irrigation water from the 3 days interval or 1009 mm of TI water that is currently applied. Crop water productivity (CWP) for sweet corn ranged from 1.44 to 2.71 kg m^{-3} for the first crop and from 1.01 to 1.97 kg m^{-3} for the second crop, while for tomato, it ranged from 2.06 to 4.31 kg m^{-3} and from 0.76 to 1.65 kg m^{-3} for the first and second crop, respectively. Sweet corn highest CWP value obtained for the first and second crop was 2.71 kg m^{-3} and 1.97 kg m^{-3} for the treatment irrigated for 2.5 hrs, with average seasonal actual crop evapotranspiration (ET) of 436 and 532 mm, respectively. For tomato the highest CWP value was obtained for treatment with irrigation interval of 4 days, which corresponds to 4.31 kg m^{-3} with ET of 574 mm and 1.65 kg m^{-3} with ET of 558 mm for the first and second crop, respectively. Both the CWP for sweet corn and tomato were correlated with ET, at $P \leq 0.05$. It can be concluded that under the current irrigation practice the two crops are over irrigated. The saved water can be used to increase the hectarage under production, or enable the intensification of the crops already in production. Crop water productivity study is critical in determining the adaptation and productivity of plants in water-limited areas under the present climate.

CHAPTER ONE

INTRODUCTION

1.1 Background information

Land is the most important resource in agricultural production. In Kenya, limited availability of productive land is a major constraint to agricultural production. About 16 % of the country's 587,000 square kilometers land mass is high and medium potential, while 84 % is arid and semi arid lands (ASAL) (Ministry of Agriculture (MoA), 2005). The increasing demand for food due to the rapid population growth estimated at about 3.33 % per annum (Ministry of Planning and National Development (MP&ND), 2006), necessitates that the country's agricultural potential be fully developed to address this challenge. Intensification of agricultural production, in the medium and high potential areas, account for only 66 % (MoA, 2005). Strategies need to be devised to bring the ASAL into productive use by intensification and expansion of the cultivated area through irrigation. Various food and high value crops can be grown in the ASAL for both export and local market. Under irrigation Payero *et al.* (2006) has reported maize grain yields of up to 10.1 t ha^{-1}, while tomato yields of 38.6 t ha^{-1} (Ramalan and Nwokeocha, 2000) have been recorded, compared to maize yield of 7.3 t ha^{-1} and tomato yields of 23.5 t ha^{-1} obtained in the ASAL under rainfed (Anon, 2007).

According to Hussain (2007) the benefits to be derived from irrigation development include; improved crop yields over rain fed agriculture, improved economic security for the farmers through stabilized agricultural produce to the market, greater human carrying capacity and increased opportunities for the introduction of more valuable crops through an assured water supply. Irrigation benefits also vary widely across systems and depend on a range of factors including local conditions, system management, irrigation policy, and broader economic and political factors. Irrigation can also lead to some negative or adverse social, health and environmental impacts (Pereira *et al.*, 2002), such as displacement of families to give way for irrigation, occurrences of water borne diseases, soil erosion and salinity to name but a few.

Kenya has an estimated irrigation potential of 1.3 million hectares (GoK, 2003), of which 540,000 ha can be developed with the available surface water resources, while the rest will require water harvesting and storage. Currently, only 21 % of the irrigation potential has been developed (GoK, 2003). Policies are being designed to develop the country's irrigation potential and to move away from dependence on rain fed agriculture. According to the World Bank (2007), access to water and irrigation is a major determinant of land productivity and the stability of yields. In this regard, the government has prioritized irrigation in its vision 2030 development plan and in the agricultural sector development strategy (ASDS), to rehabilitate existing large-scale irrigation schemes and develop new ones (GoK, 2007; MoA, 2008).

Different crops respond differently to moisture stress due to differences in their characteristics such as leaf area, rooting habit and nutrient requirements (Oktem *et al.*, 2003; Payero *et al.*, 2006; Bhattarai, *et al.*, 2008). Hence outcomes of crop water requirement and crop water productivity of the various crops can be valuable for making tactical in-season irrigation management decisions and for strategic irrigation planning and management. These and many others are some of the considerations relevant to the development of local crop rotation, water resources, project planning and farm irrigation scheduling in irrigation project.

1.2 Problem statement and justification

According to the World Bank (2007), Kenya is classified among the East and Central African countries in actual or potential difficulty of meeting their populations' food need, although it has sufficient irrigation water to produce significant additional food. Therefore appropriate research on irrigated crops, water management, water productivity and other issues need to be carried out so as to increase yields and prevent land degradation (Oster and Wichelns, 2003; Hussain, 2007).

Ensuring food security, increasing small holder real incomes and raising agricultural productivity, is essential for the realization of significant improvement in the standard of living for the Kenyans. In this view, the Ministry of Agriculture's vision points to paradigm shift from the current subsistence agriculture, to agriculture as a business that is profitable and commercially oriented. Irrigation of high value horticultural crops such as tomato, sweet corn and others which can enable achievement of this vision is low as indicated in Table 1. This is due to lack of sufficient information on these enterprises (Ragwa, 2002; MoA, 2005). This therefore necessitates research on crop water requirements, crop water productivity and irrigation efficiency so as to assist farmers and irrigation planners make informed decisions.

Table 1. Main irrigated crops in 2003 in Kenya

Crop	Hactarage
Coffee	14,533
Rice	13,229
Pineapple	5,950
Flowers	3,262
Sugar cane	350
Tea	172

Source: (FAO, 2008)

Ragwa (2002) identified poor water management as one problem facing the existing irrigation schemes. Indeed, wastage of irrigation water is a common occurrence on most individual farms and in irrigation schemes. A typical case of such wastage is shown on Plate 1 at Kibwezi Irrigation Project (KIP) farm which was a common occurrence. Therefore more research on water productivity has to be done to asses the performance of different irrigation systems. Further more, adequate information on the following aspects of irrigation systems needs to be quantified; crop water requirement and crop water productivity at the farm level. Knowledge of the these aspects will lead to, improved designs of future irrigation schemes, expansions of the irrigation projects due to the economical water use and formulation of improved extension packages to farmers.

Plate 1: A ploughed plot being irrigated after planting at KIP farm. Notice the wastage of the pumped irrigation water

These studies will lead to improved water use efficiency which will be in line with the Kenya government policy of optimum utilization of her natural resources (GoK, 2007). Therefore, issues pertaining to the crop water requirement and productivity of the various crops grown through different irrigation systems are paramount areas of research.

1.3 Study objectives

1.3.1 Broad objective

The broad objective of the study was to determine the crop water requirement and evaluate crop water productivity of tomato and sweet corn under drip and sprinkler irrigation systems, respectively, in Kibwezi.

1.3.2 Specific objectives

i. To determine crop water requirement of tomato and sweet corn.

ii. To evaluate yield response of tomato and sweet corn to different irrigation water application rates.

iii. To evaluate the effect of different irrigation water application rates on crop water productivity of tomato and sweet corn.

CHAPTER TWO

LITERATURE REVIEW

2.1 Importance of crop water use data

Crop water use data is mainly used for the improvement of water use economy in irrigation projects. Economic returns from irrigation projects and the proper design and operation of irrigation schemes largely depend on the reliability of available figures on actual water use by crops or evapotranspiration estimates (Rahimikhoob, 2009).

Under rain-fed agriculture, crop water use data can be used to minimize the adverse effects of dry periods by selecting the right crop for the right season in a given environment. Dagg (1965) stated that seasonal crops such as maize can be synchronized to the environment as defined by effective rainfall and soil water storage characteristics.

2.2 Crop water requirements

Dorrenbos and Pruitt (1977) defines crop water requirement (ET_{crop}) as the quantity of water required by a crop over a given period of time for its normal growth under field conditions at a given place. Crop water requirements vary with different crops, prevailing climatic conditions, crop growth stage, soil moisture holding capacity, size of fields, advection, salinity, method of irrigation, extent of root development and cultivation methods.

The primary objective of irrigation is therefore to provide plant with sufficient water to prevent moisture stress that would cause reduction in yield or poor crop growth. The effect of soil water content on evaporation varies with crop rooting characteristics and the meteorological factors determining the level of transpiration. Since any reduction in evapotranspiration may affect crop growth and yields, Rahimikhoob (2009) notes that the timing of irrigation and magnitude of reduction in evapotranspiration are important criteria for determining the irrigation schedule.

The amount and rate of water uptake by plants depends on the ability of the roots to absorb water from the soil with which they are in contact with as well as the ability of the soil to transmit water towards the roots at a rate sufficient to meet transpiration requirements (Hillel, 1980). These in turn depends on soil and plant properties, which are briefly discussed as follows:

1. *Soil properties;* Hydraulic conductivity, diffusivity, water holding capacity, matric suction, soil wetness and to a considerable extent climatic conditions dictate the rate at which the plant is required to transpire and hence the rate at which it must extract water from the soil in order to maintain its own turgidity.

2. *Plant properties;* Rooting depth, rooting density, rate of plant development, leaf area index and stomata behaviour affects the physiological ability of the plant to continue taking in water from the soil at field capacity while maintaining its vital functions even when its own water potential decreases.

2.3 Crop water use theory

The combined losses by evaporation from the soil surface and by transpiration account for the consumptive use of water (actual evapotranspiration), which constitutes the total water lost by evapotranspiration in producing crops (Brady and Weil, 2002). Perry *et al.* (2009) describes evaporation as the direct conversion of water into water vapour when wet leaves or soil are exposed to drier air and radiant heat.

Transpiration is the flow of water vapour from stomata of leaves that causes replacement of liquid water to move from soil to roots, through stems and on to leaves (Perry *et al.*, 2009). Water vapor exits through the same stomata that carbon dioxide enters. The water vapour lost by transpiration in exchange for carbon dioxide is the primary process for plant growth and development. All aerial parts of the plants may loose some water by transpiration, but most water is lost through the leaves. Some water vapour also diffuses out through the epidermal cells of leaves and the cuticle. Other nutrients are "delivered" to the plant from the soil by the water used in transpiration.

Perry *et al.* (2009) defined evapotranspiration (ET) as the sum of direct evaporation (E) from the soil and plant cuticles and transpiration (T) of water through plant systems and into the atmosphere. Evaporation and transpiration are the components of the hydrologic cycle where liquid water does 'disappear' from the local hydrological system in form of vapour to return via precipitation at some other location, and some other time. Thus, because of its generally large magnitude, ET is an important part of the hydrologic cycle, and of water balances. Understanding and evaluating ET are critical elements of water resources management.

The rate of water loss through ET is determined basically by differences in moisture potential identified as the vapour pressure gradient (Hillel, 1980). This is the difference between the vapour pressure at the leaf or soil surface and that of the atmosphere. It is related to climatic and soil factors, and to plant characteristics. The level of evapotranspiration is thus controlled mainly by meteorological parameters or evaporation demand. It also depends on water availability in the soil and plant characteristics which include extent of ground cover, stage of growth, depth of rooting and length of growing season (Dorrenbos and Pruitt, 1977).

Many observations have shown that the transpiration per unit land area per unit time is largely independent of the nature of the crop, provided that it is supplied with adequate soil water and that the leaf canopy has developed to such an extent as to intercept most of the solar radiation. For this reason, the concept of potential or reference crop evapotranspiration (ET_o) has been introduced.

2.4 Determination of crop evapotranspiration

Crop evapotranspiration (ET_{crop}) refers to evapotranspiration of a disease free crop grown in large fields (one or more hectares) under optimum soil water and fertility conditions and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977).

To determine ET_{crop}, the relation between reference crop evapotranspiration (ET_o) and ET_{crop} has to be studied using data from different location and climates. For the selected crop, its stage of development and prevailing climatic condition is given by the crop coefficient, K_c. Then ET_{crop} is calculated for a given 30 or 10 day period using equation 2.1.

$ET_{crop} = ET_o * K_c$..2.1

Where:

ET_{crop} = crop evapotranspiration (mm/day)

ET_o = reference crop evapotranspiration (mm/day)

K_c = crop coefficient

2.5 Reference crop evapotranspiration

Doorenbos and Pruitt (1977) defined the reference crop evapotranspiration (ET_0) (expressed in mm per day) as the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water. While potential or maximum evapotranspiration (ET_m), refers to conditions when water is adequate for unrestricted growth and development.

ET_0 rates tend to be greatest in areas having the greatest hydrologic water scarcity due to the negative feedback between general water scarcity and climatic aridity, if less water is available, less actual evapotranspiration (ET_a) takes place, humidity is decreased and evaporative demand and ET_0 increase. Conversely, if more water is available, more ET_a takes place, humidity is increased (i.e., aridity is reduced) and evaporative demand decreases.

ET_a is the managed outcome of irrigation of agricultural crops and an unmanaged outcome of rainfall on rainfed crops and natural vegetation. If the water supply is fully adequate to meet the crop water demand, then actual and potential ET will be the same ($ET_a = ET_m$) (Doorenbos and Kassam, 1979).

2.5.1 Methods of estimating reference crop evapotranspiration

A number of methods have evolved to estimate the ET_0 using meteorological parameters. Four main methods are often used, these are; Blaney-criddle, Radiation, Penman and Pan evaporation method. Primarily the choice of method to be used depends on type of climatic data available and on the accuracy required in determining water needs.

2.5.1.1 Penman method

The Penman method is considered using equation 2.2 as given by Doorenbos and Pruitt (1977). Climatic data required are the mean temperature (T), mean relative humidity (%), total wind-run (km/day at 2m height) and mean incoming short-wave radiation (R_s).

$ET_0 = c\ [W.\ Rn + (I - W).\ f(u).\ (ea - ed)]$ 2.2

Where:

(ea - ed) = vapour pressure deficit ie the difference between saturation vapour pressure (ea) at T mean in mbar and actual vapour pressure (ed) in mbar

W = temperature and altitude dependent weighing factor

C = adjustment factor for ration u day/u night, for Rhmax and Rs

F(u) = wind function of $f(u) = 0.27\ (1 + u/100)$ with u in km/day

Rn = total net radiation in mm/day

Compared to the other methods, penman method provides satisfactory results. Simplified version of the equation has been given by Valiantzas (2006).

2.5.1.2 Blaney-Criddle

In Blaney-Criddle method, Reference evaporation (ET_o in mm/day) representing the mean daily value over the period considered is obtained using equation 2.3 as given by Doorenbos and Pruitt (1977).

$$ET_o = c\ [\ P(0.46T + 8)] \qquad 2.3$$

Where:

T = mean daily temperature in °C over the month considered

P = mean daily percentage of annual daytime hours

c = adjustment factor which depend on minimum relative humidity, sunshine hours and daytime wind estimates

Blaney-criddle method is applied to calculate ET_o in areas where only measured daily air temperature and day length data for one month are available. because humid and windy conditions can lead to an under prediction of up to 25 %.

2.5.1.3 Radiation method

The radiation method is applied using equation 2.3 as given by Doorenbos and Pruitt (1977). Climatic data required are mean temperature (T) and mean incoming short-wave radiation (R_s). Estimated values of mean relative humidity (%) and mean daytime wind speed (m/sec at 2 m height) must be available.

$$ET_o = C\ (W * R_s) \qquad 2.4$$

Where:

R_s = measured or calculated mean incoming short-wave radiation in (mm/day)

W = temperature and altitude dependent weighing factor

C = adjustment factor which depend on mean humidity and daytime wind conditions

2.5.1.4 Pan evaporation method

Evaporation pan can provide adequate measure for estimating ET_o, when the pan environment is well described, with the class A pan being the most adaptable because it is widely used and has been used as interim reference for international comparison of evaporation pan (Doorenbos and Kassam, 1979).

Empirical pan coefficients (K_{pan}) to relate pan evaporation (E_{pan}) to ET_o have been applied in the relation shown in equation 2.5 (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979). The inputs for estimating ET_o is pan evaporation, relative humidity (%) and wind speed (m/sec at 2 m height).

$$ET_o = K_{pan} * E_{pan} \qquad (2.5)$$

Where:

ET_o = reference crop evapotranspiration in mm/day from a un screened class A evaporation pan

K_{pan} = pan coefficient

E_{pan} = pan evaporation (mm/day)

Several different types of pans exist; the colour, size, and position of the pan have a significant influence on the measured evaporation results. The pan coefficients are pan specific. In selecting the appropriate pan coefficient the pan type, ground cover, its surrounding, general wind and humidity conditions should be checked.

Some noted disadvantages of this method have been summarized by Allen *et al.* (1998) as follows: i) differences in water surfaces produce significant differences in water loss from an open surface and the crop, ii) storage of the heat within the pan can be appreciable and may cause significant evaporation during the night while most crop transpire only during the daytime, iii) there are also differences in turbulence, temperature, humidity or air immediately above the respective surfaces, iv) heat transfer through the sides of the pan occurs and affects the energy balance. However, despite the foregoing, the pan method is simple and requires only the pan evaporation data. In the absence of rain, the amount of water evaporated during a period in mm corresponds with a decrease in water depth in that period.

In crop evapotranspiration studies, Allen *et al.* (1998) noted that ET_o values obtained by pan evaporation method were reasonably close to those obtained by Lysimeter method. Gundekar *et al.* (2008) while evaluating several approaches concluded that pan evaporation method was best suited for the semi-arid region. Based on these findings and on the consistence of the data available from the study site, this method was used to determine ET_o.

2.5.1.5 FAO Penman–Monteith method

The FAO Penman–Monteith equation is given by equation 2.4 as explained by Allen *et al.*, (1998). Climatic data required are the mean temperature (T), mean relative humidity (%), total wind-run (u), the soil heat flux density (G) and mean incoming short-wave radiation (R_n).

$$ET_o = \frac{K_c\,0.408(R_n - G) + \gamma\,(900/T_{mean} + 273)\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \quad \ldots\ \ldots\ \ldots\ldots\ldots\ldots\ldots\ldots 2.6$$

Where:

ET_o = is crop evapotranspiration under standard condition (mm day^{-1})

R_n = net radiation at the crop surface (MJ $m^{-2}day^{-1}$)

G = the soil heat flux density (MJ m^{-2} day^{-1}) which is relatively small and ignored for day period

T_{mean} = the mean daily air temperature at 2 m height (°C)

u_2 = the wind speed at 2 m height (m s^{-1})

$(e_s - e_a)$ = the vapor pressure deficit (kPa)

Δ = the slope of vapor pressure curve (kPa C^{-1})

γ = the psychrometric constant (kPa C^{-1}) and

K_c = the crop coefficient

The K_c is often between 0.45 and 1.05 and is affected by several factors such as crop type, crop height, albedo (reflectance) of the crop-soil surface, aerodynamic properties, leaf and stomata properties and crop stages Compared to the other methods, FAO Penman–Monteith method provides the most satisfactory results.

2.5.1.6 Other methods

Other methods to calculate ET_0 have been quantitatively described by different researchers. They include Lysimeter, Thornthwaite, Jansen and Haise, Water balance and Bowen ratio-energy balance method among others (Doorenbos and Pruitt, 1977; Fooladmand and Ahmadi, 2009, Irmak *et al.*, 2008).

2.5.2 Crop coefficient

The value of the crop coefficient K_c varies with the development stage of the crop. For most crops the K_c value for the growing period is between 0.85 and 0.9. Information on crop development stages for sweet corn and tomato is given in Table 2. Factors affecting the value of K_c are mainly crop characteristics, crop planting or sowing date, rate of crop development, length of growing season and climatic conditions. Climatic data required for the selection of K_c values are wind speed and humidity.

Table 2. Crop coefficients (K_c) values for the four growing stages for sweet corn and tomato

Crop	Crop development stages					Total growing period
	Initial	Crop development	Mid-season	Late season	At harvest	
Sweet corn	0.3-0.5	0.7-0.85	1.05-1.2	0.8-0.95	0.55-0.6	0.75-0.9
Tomato	0.4-0.5	0.7-0.85	1.05-1.2	0.85-0.95	0.95-1.1	0.8-0.95

Source: (Doorenbos and Kassam, 1979)

2.6 Factors affecting crop water use

Factors affecting crop water use and therefore their growth and yield may be grouped into; soil, plant, climate, cultural and irrigation methods.

2.6.1 Soil

Soil factors include soil water content, texture, structure, depth, salinity, fertility, aeration, temperature and drainage. The water content at field capacity and at permanent wilting point gives some indication of availability of water for absorption by plant roots. The difference in soil water content at field capacity and at permanent wilting point defines the range of plant available water. As the soil dries out, the rate of water transmitted through the soil and supplied to the roots will reduce and consequently the rate of water up-take by the plant will be affected (Brady and Weil, 2002).

Soil texture, organic matter content, structure and depth determines the capacity of the soil to store available moisture for plants and the ease with which the soil water may be reached and absorbed by roots. Brady and Weil (2002) documented that root growth and extension are influenced by texture, structure and depth in addition to soil aeration, temperature, fertility and management.

Salt content of soil can influence soil moisture stress by affecting the osmotic suction of the soil solution. The osmotic suction tends to increase the wilting coefficient thereby reducing the range of available moisture in saline soils (Brady and Weil, 2002).

2.6.2 Plant

The type of plant, its rooting and aerodynamic characteristics and tolerance to drought will affect the crop water use. The root systems vary with respect to volume of the soil it occupies, growth rate and density. All these can affect the plant's response to soil moisture conditions (Bhattarai *et al.*, 2008). The physiological age of the crop may affect water use. Plant height largely determines the roughness and thus the aerodynamic properties of the crop hence affecting the water loss from the crop surface. Plant density or number of plants per unit area of ground in the field will greatly affect the volume of soil available for root ramification. For a given crop, a high plant population would normally require more water in the early stages of crop development than low planting density (Doorenbos and Pruitt, 1977). This is due to quicker development of full ground cover of the high plant population crop. Any factor influencing crop vigour such as the health of the plant, virus infestation or pest attack, may be expected to influence crop water use.

2.6.3 Climate

In a review, Valiantzas (2006) notes that climatic factors such as net radiation, temperature, humidity and wind can greatly influence the water balance of crop by their effects on the rate of transpiration. Rainfall increases soil water availability but also may increase the humidity thereby reducing the transpiration rate. It may also increase disease incidence by changing the crop environment causing a decrease in crop vigour and therefore reduce transpiration rate.

2.6.4 Cultural practices

Cultural practices such as the use of fertilizers has only a slight effect on ET_{crop} unless crop growth was previously adversely affected by low soil nutrition delaying full crop cover. Tillage produces little if any effect on ET_{crop} unless a significant quantity of weed is eliminated. Mulching in agriculture to reduce ET_{crop} is often considered of little net benefit, except for specific purposes such as soil erosion. Vegetative wind breaks may reduce ET_{crop} by about 5% under windy, warm or dry conditions (Doorenbos and Kassam, 1979). The use of anti-transpirants, natural or artificial induces variations in plant foliage properties and soil condition to reduce ET_{crop} (Brady and Weil, 2002).

2.6.5 Methods of irrigation

The ET_{crop} is affected little by the method of irrigation if the system is properly designed, installed and operated (Doorenbos and Pruitt, 1977). Various types of irrigation techniques differ in how the water obtained from the source is distributed in the field. In general, the goal is to supply the entire field uniformly with water, so that each plant has the amount of water it needs. Different irrigation methods apply different rates of water application. Superiority of one method over another may be as a result of too much or too little water being applied. The advantage of one method over another are therefore determined by the adequacy and effectiveness with which crop water requirement can be met.

Four different irrigation methods have been documented namely; surface, sub-surface, sprinkler and localized irrigation (Pereira *et al.*, 2002). However, with advancement in irrigation, other methods such centre pivot sprinkler, subsurface drip and automated irrigation systems have been documented (Kijne *et al.*, 2003; Dukes and Scholberg, 2005).

2.6.5.1 Surface irrigation

In surface irrigation system, water moves over and across the land by simple gravity flow, in order to wet and infiltrate into the soil. Surface irrigation can be subdivided into furrow, border strip and basin irrigation (Pereira *et al.*, 2002). It is called flood irrigation when the irrigation results in flooding or near flooding of the cultivated land. Flood, basin, furrow and border strip methods apply water at intervals to allow the crop to utilize as much as 50 % or more of the available water in the root zone before the next irrigation (Hillel, 1982).

2.6.5.2 Sub-surface irrigation

In Sub-surface irrigation sometimes referred to as seepage irrigation, water table is artificially raised to allow the soil to be moistened from below the plants' root zone. Water is delivered from below and absorbed upwards by the plant roots. A system of pumping stations, canals, weirs and gates allows it to increase or decrease the water level in a network of ditches and thereby control the water table. The system is often combined with drainage (Hillel,1987). Bryla, *et al.*, (2003) has document and used sub-surface drip irrigation system in Faba bean production.

2.6.5.3 Sprinkler irrigation

In this method, water is applied as a spray at a high velocity above the ground surface some what resembling rainfall through sprinkler nozzles or guns. Several sprinkler irrigation systems have been classified by Hillel (1982). Ko and Piccinni (2009) have documented improved form of sprinkler irrigation system called center pivot. Sprinkler irrigation should not normally be used when wind speeds are over 5 m/sec as strong winds result in a poor water distribution pattern (Hillel, 1982).

Sprinkler irrigation system is the most common irrigation system on Kibwezi Irrigation Project (KIP) farm. The method is used to pre-irrigate planting plots and to irrigate crops that do not have a problem of incidences of diseases from wetting of leaves. Hence crops such as maize, brinjals, pigeon pea, chilies and onion are often grown using this method. Based on this, sprinkler irrigation method was chosen for study of sweet corn.

2.6.5.4 Localized irrigation

Localized irrigation system is where water is distributed under low pressure through piped network, in predetermined pattern, and applied in small discharges to each plant or adjacent to it. Drip irrigation, spray or micro-sprinkler, micro-jet and bubbler belong to this category of irrigation method (Frenken, 2005).

Drip irrigation, also known as trickle irrigation, functions as its name suggests. Water is delivered directly through a number of low flow rate outlets (emitters) at or near the root zone of plants, drop by drop. Najafi and Tabatabaei (2007) notes that this method can be the most water-efficient method of irrigation if managed properly since evaporation, deep percolation and runoff are minimized, thereby reduces irrigation water use.

Drip irrigation method is becoming increasingly popular in areas with water scarcity and salt problems, or where poor quality water is to be used for irrigation (Karlberga *et al.*, 2006; Hassanli *et al.*, 2009). Drip irrigation is also adopted where the aim is to fertigate crops with irrigation water (Pereira *et al.*, 2002). In this method, water application is slow but frequent, with the volume of water approaching the consumptive use of the plants. The high water use efficiency achieved with this method can be attributed to improved water conveyance and water distribution to the root zone. Subsurface drip irrigation is being adopted in most areas with the aim of conserving water while maintaining economical production of crops (Duke and Scholberg, 2005).

Drip irrigation system is used to grow high value crops and those crops that are sensitive to wetting of leaves. Wetting of tomato leaves leads to higher incidences of diseases such as leaf spot and blight which reduces yields and increases the cost of production arising from the control of such diseases. The system is used to grow crops such as tomato, melon and asian vegetables. Based on this, drip irrigation method was chosen for the study of tomato production.

2.7 Water management

Irrigation management is the process by which water is controlled and used in the production of food and fiber. To realize improved irrigation performance, both water and other resource must be well managed. Water is a scarce resource but an essential input in agriculture therefore prompting need for careful management. In practice, good irrigation management and scheduling are commonly based on management skills (Fereres *et al.*, 2003).

Irrigation is a combination of physical work and human activity. For success of irrigation, commitment is necessary to control and manage the physical systems. The way water is supplied, conveyed, distributed and finally applied will indicate the level of water management of that particular irrigation scheme (Pereira *et al.*, 2002; Ragwa, 2002). To each of these elements is attached level of efficiency which can be controlled. Poor management of these activities means poor water management.

2.7.1 Automated irrigation

Automated irrigation involves a combination of two or more methods previously discussed, with most of the operation being replaced by automatic gadgets which are controlled by electronic computer (Oster and Wichelns, 2003). Automated irrigation largely arises due to the continuous rise in labour costs in many countries. The need to save water especially where water is expensive and high efficiency is needed makes the system desirable. Automation ensures that precise amounts of water are accurately delivered to crops. This in turn ensures that crops are not damaged by excess water and that soil salinization problems do not occur. This method of irrigation is not yet installed at KIP.

2.8 Irrigation efficiency

The flow of water from source to crop can be separated into conveyance, distribution and field application. Conveyance and distribution networks directly influence field application efficiency in the following ways as described by Oster and Wichelns (2003): First, providing reliable water supply and secondly, providing adequate water supply to the field. Reasons for low irrigation efficiencies include: seepage losses in open channels and leaks in pipelines, wind losses in sprinkler irrigation, unequal and excessive depth of wetting, lack of proper water supply control and finally care taken by the irrigator.

Field application efficiency is the relationship between the quantity of water furnished at the field inlet and the quantity of water needed to maintain the soil moisture at the level required by the crop. Field application efficiency has been defined as the ratio of the average depth of the irrigation water stored in the root zone to the average depth irrigation water applied (Oster and Wichelns, 2003). However, it is pointed out that application efficiency gives no indication of the adequacy and uniformity of irrigation. For small irrigation projects such as KIP which is fully piped, field application efficiency is of major interest since it depends on field practices currently employed at the farm.

2.9 Crop yield response to irrigation water

Water is one of the major constraints to increasing crop production. Crop response to water is complex as it is affected by physical, biological and biochemical processes that are site specific (Payero *et al.*, 2008). Crop response to irrigation depends on the water application regime that includes timing and depth of irrigation.

The marginal response of crop 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). Quantifying crop yield versus water use relationships is important in matching crops and varieties to suitable rainfall regimes. It also offers guidance on timing and level of irrigation for maximizing returns (Ragwa, 2002).

Doorenbos and Kassam (1979) states that when water supply does not meet crop water requirements, actual evapotranspiration (ET_a) will fall below maximum evapotranspiration (ET_m). Under these conditions, water stress will develop in the plant which will adversely affect crop growth and ultimately crop yield. 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.*, 2006).

Yield response to water deficit can vary among varieties of the same crop. In general high yielding varieties are also the most sensitive to water stress. Low yielding ones are less responsive, hence more suitable for rain fed crop production in areas that are prone to drought (Doorenbos and Kassam, 1979). Water stress during vegetative development reduces expansive growth of stems and leaves and results into reduced plant height, lower leaf area index (LAI) and reduced internodes lengths. Kiziloglu *et al.* (2009) observed that increasing water deficit in corn resulted in relatively smaller cob, leaf, stem and reduced total fresh yields.

2.10 Soil water availability

Field capacity and wilting point estimates are necessary for obtaining available water content in soil and therefore how much moisture can be extracted by plant roots. These estimates define the range of plant available water, which is usually equated with the difference in soil water content at field capacity and at wilting point. The available water for plant use is the difference between field capacity (FC) and permanent wilting point (PWP). Hillel (1980) gives the range; it is low at less than 80 mm m^{-1}, moderate at 80-120 mm m^{-1}, high at 120-160 mm m^{-1} and very high at above 160 mm m^{-1}.

The concept of field capacity and wilting point assume static soil water conditions and represent equilibrium value or soil water content. In fact, soil water through continuous redistribution in the soil profile under both saturated and unsaturated conditions is a dynamic process. In a physical sense, no static levels can be assumed. Despite this, the concepts are considered useful criteria for determining the soil water available for plant growth.

2.10.1 Field capacity

Field capacity (FC) is the amount of water remaining in a well drained soil when velocity of downward flow from saturated soil has become minimal. A saturated soil will reach field capacity after two to three days of free drainage, therefore water retained at 10 to 30 mPa tension has generally been used as equivalent to field capacity (Klute, 1986). Field capacity depends on soil texture and structure. Soil structure has the major role of determining field capacity. Water in excess of field capacity value quickly drains away and is not of much value to the crops. This assumption overlooks the fact that soil water is not held so tightly by the soil matrix as such but some of the soil moisture can be used by plants while it remains in contact with the plant roots (Hillel, 1980). In the laboratory, field capacity is determined by the use of pressure plate apparatus, where field capacity is taken to be the water held at a tension of 10 mPa suction (Klute, 1986).

2.10.2 Permanent wilting point

Hillel (1980) describes permanent wilting point (PWP) as the moisture level at which plants wilt and fail to regain their original cell turgidity even when placed in wet soil. At permanent wilting point the ease of release of water to plants is too small to counter-balance the transpiration losses. Below permanent wilting point water is considered unavailable to the growing crops (Doorenbos and Kassam, 1979). Permanent wilting point is dependent on soil profile features and is determined by the amount of water in soil at various depths, and involves any soil depth in which plants roots are growing. PWP varies for different crops depending on the crop characteristics.(Hillel, 1980).

In the laboratory permanent wilting point is determined by use of the pressure plate apparatus. Undisturbed saturated soil samples are subjected to a suction of 1500 mPa and the permanent wilting point is taken as the water held at this pressure (Klute, 1986).

2.11 Soil water balance

Liniger (1991) describes a field soil water balance as an account of all quantities of water added to, subtracted from, and stored within a given volume of soil during a given period of time. Soil water balance is part of the hydrological cycle, and represents the processes by which water enters and leaves the soil profile. Water enters and leaves the root zone via irrigation, rainfall and capillary rise but is also removed directly from the root zone via the deep percolation, runoff, evaporation and water uptake by plant roots which are almost entirely discharged as transpiration. In any given volume of soil, the difference between the amount of water added and amount of water withdrawn during a certain period is equal to the change in water content during the same period.

A water balance model suggested by Liniger (1991) is adapted for the study (equation 2.7a). This original equation was also used by Kironchi (1998) to study soil water balance in the upper Ewaso Ng'iro basin but excluded irrigation as a source of water into the soil profile.

$$P + I - R_f = ET + D_w + \Delta S \quad \text{2.7a}$$

Where:

P = rainfall

I = irrigation

R_f = surface runoff

ΔS = change in soil moisture storage

ET = evapotranspiration

D_w = deep percolation

Modifying the equation for the study, evapotranspiration can be calculated if deep percolation (D_w) and surface runoff (R_f) were assumed to be negligible. This is the case in most parts of the study area (Semi arid climate). Long periods of drought, well drained soils and lack of evidence of erosion, justifies this assumption. Also the amount of irrigation water applied was below field capacity as a result of deficit irrigation. Another assumption is that water interception by plants is taken to be part of evapotranspiration. Evapotranspiration can thus be calculated as;

$ET = (P + I) \pm \Delta S$ 2.7b

Where:

P = rainfall

I = irrigation

ΔS = change in soil moisture storage

Effective rainfall (R_e) is defined as that part of rainfall which is used effectively by the crop after rainfall losses due to surface runoff and deep percolation have been accounted for. Since not all the rainfall is available to the crop, there is a need to estimate the amount of rainfall that is effective. Methods of predicting effective rainfall are given by Doorenbos and Pruitt (1977).

2.12 Crop water productivity

Water productivity with respect to crop production is referred to as crop water productivity (CWP). The CWP is defined by Fan *et al.* (2005) as the amount of crop produced per volume of water used. The unit of CWP is kg m^{-3}. CWP can also be defined in monetary terms, expressed in terms of economic return from crop produced per volume of water, with the unit expressed in equivalent of any currency (e.g. $\$/m^3$) (Kadigi *et al.*, 2004). Before the 1990s, another terminology that had frequently been used to express the concept of CWP was water use efficiency (WUE) (Zoebl, 2006).

The CWP is useful for looking at potential increase in crop yield that may result from increased water availability (Burke *et al.*, 1999). It provides a simple means of assessing whether yield is limited by water supply or other factors (Augus and van Herwaarden, 2001). In deficit irrigation scheduling, CWP is a good indicator for assessing the impact of an irrigation scheduling protocol. CWP reveals the unit increment in yield per unit of water use, from which the impact and worth of additional water supply can be assessed. Quantitative information on CWP is therefore necessary for effective planning of irrigation water management strategies in an area.

There are several definitions and expressions used by the different stakeholders in crop-water issues to quantitatively express CWP. Table 3 summarizes the different stakeholders' definitions and indeed their focus of interest in quantifying water productivity.

Table 3. Examples of definitions of crop water productivity by different stakeholders

Stakeholder	Useful definition	Scale	Target
Plant physiologists	Dry matter/Transpiration	Plant	Productive utilization of light and water resources
Agronomist	Yield/Evapotranspiration	Field	Higher yields t ha^{-1}
Larger scale farmer	Yield/Water supply	Field	Higher yields t ha^{-1}
Irrigation engineer	Yield/Diverted water	Irrigation scheme	Demand management
Water resources planner	\$/Total water depletion from the basin	River basin	Optimal allocation of water resources

Source: Ali and Talukder (2008)

Many scientists (Payero *et al.*, (2008); Fan *et al.*, (2005); Dagdelen *et al.*, (2006)) report CWP in terms of crop harvest or marketable yields given by equation 2.8. This enables the comparison of the effects of different water application regimes on yields enabling the choice of the most efficient one.

$$\mathrm{CWP} = \frac{\mathrm{Yields}}{\mathrm{ET_{crop}}} \ldots\ldots\ldots\ldots 2.8$$

Where:

CWP = crop water productivity (kg/m^3)

Yields = yield harvested in (kg)

ET_{crop} = applied water in (mm/season)

2.12.1 Factors affecting CWP

The factors which affect or influence crop yield (numerator of the productivity equation), and water applied or need to be applied (denominator of the same equation), obviously influence the water productivity. Ali and Talukder (2008) have reviewed these factors. They include the following:

Crop cultivar type: Stomata behavior will determine the CWP of a particular species or cultivar. It is well known that C_4 plants have higher CWP than C_3 plants. Within C_3 plants, reports have shown that genotypes can be selected for higher CWP (Craufurd *et al.*, 1991).

Applied water: In agriculture, many ways of conserving water have been investigated. Techniques such as partial irrigation, deficit irrigation or drip irrigation have shown that CWP can be enhanced (Greenwood *et al.*, 2008). In general, these techniques are a trade-off, a lower yield for a higher CWP. High biomass production supported by high water supply, will not lead to high CWP if defined as the grain production per unit amount of water irrigated. Therefore, the goal is to increase CWP of grain yield by limiting water supply to increase harvest index or harvest ratio.

Remobilization of pre-stored carbon, the variable fraction in grain filling: Delayed whole plant senescence, leading to poorly filled grains and unused carbohydrate in straws is a new problem increasingly recognized in cereals production in recent years (Zhang et al., 1998). Slow grain filling may often be associated with delayed whole plant senescence. Initiation of the whole plant senescence is needed so that stored carbohydrates in stems and leaf sheaths can be remobilized and transferred to developing grains (Zhang and Yang, 2004).

Soil factor: Evaporative loss of water from the soil surface plays a significant role on plant growth during germination and seedling establishment, and also during other growth periods. Soil texture and organic matter content determine the water storage and release properties (Hillel, 1980). Rapid drying of soil does not provide opportunity for osmotic regulation and adjustment and thus affects yield and water productivity. Nutritional status of the young crop, especially nitrogen, can markedly affect the rate of development of leaf area and hence evaporation losses from the soil (Singandhupe *et al.*, 2003). Organic matter in soil interacts with other nutrients and microbial activities (Brady and Weil 2002).

Agronomic factor: Agronomic factors which can affect CWP are timeliness of sowing, evenness of establishment, use of herbicides, and the role of previous crop (Khan *et al.*, 2005). Crop water productivity depends not only on how the crop is managed during its life, but also on how it is fitted into the management of a farm, both in space and time (Raina *et al.*, 1999).

Economic factors: Economic factors may influence the optimum level of CWP. Sometimes large additional costs are involved in increasing CWP, for example, the investment in sprinkler, drip or hose pipe irrigation systems. These systems include the fixed and operational costs of changing the irrigation system. The returns may include water saved plus the increased crop production.

2.12.2. Strategies for enhancement of CWP

The term 'increasing or improving water productivity', implies how we can most effectively improve the outcome or yield of a crop with the water currently in use. The answer lies in three main pathways as documented by Passioura (2006); (i) exchange transpired water for CO_2 more effectively in producing biomass, (ii) capture more water available in the soil and transpire most of the supplied water (minimization of unwanted loss) and (iii) convert most of the biomass into grain or other form of harvestable product .

Many technologies to improve CWP and the management of scarce water resources are available. Kijne *et al.* (2003) provide several strategies for enhancement of CWP by integrating varietal improvement and better resource management at plant level, field level and agro-climatic level.

Examples of the most promising and efficient techniques and practices that can be taken are summarized as follows; (i) increasing the harvest index by use of improved cultivars, and improving drought tolerance and salinity tolerance (plant level), (ii) applying deficit irrigation for optimizing the use of the limited water, improving cultural practices and fertility management (field level) and (iii) water reuse and harvesting for improved farm income in drier environment, spatial analysis for maximum production and minimum ET_0 (agro-ecological level) to mention but a few.

CHAPTER THREE

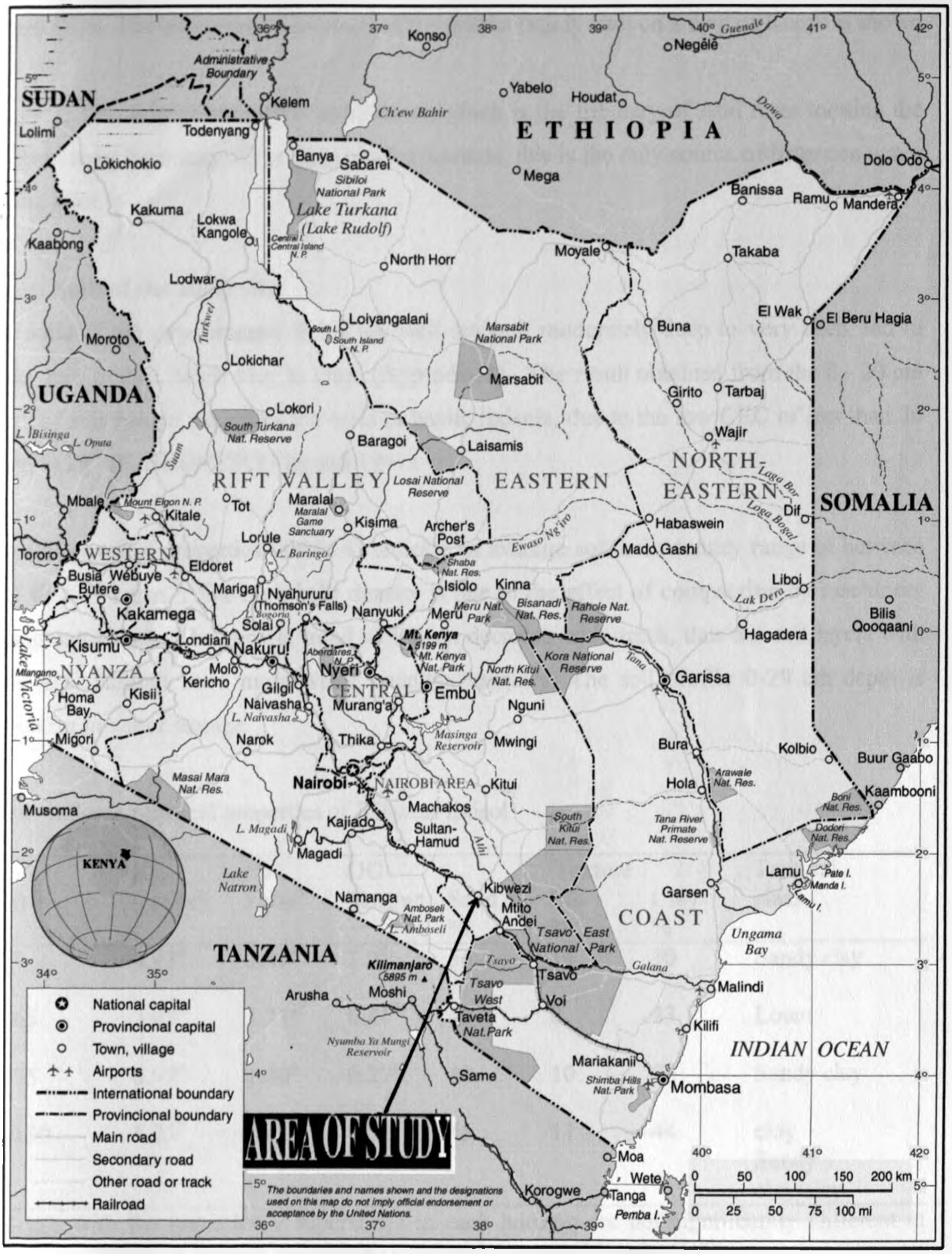
MATERIALS AND METHODS

3.1 Area of study

Kibwezi District in Eastern province of Kenya, receives an average annual rainfall of 500 mm in the lowlands in the south and 1200 mm in the highlands in the north. The rainfall is characterized by small total amounts, strong seasonal and bimodal distribution, with high temporal and spatial variability between seasons and years. Annual mean temperatures, range from 19 to 26 °C (Jaetzold and Schmidt, 1983). The District is classified into six agro-climatic zones (ACZ) (Sombroek *et al.*, 1982). The dominant ones are ACZs IV and V (Appendix 3) where risks of crop failure are high. The land consists of gently slopping terrain ranging in altitude from 700-900 meters above sea level. It slopes south-eastwards towards the coast with the general land slope being 0 – 2 % and is dissected by several dry water courses.

The natural vegetation consists of dense woodlands and savanna. Wood layer is dominated by: *Acacia spp., Albizia anthalmiritica, Commiphora africana, Melia volkensii, Cassia abreviata, Sterculia steriocarpa, Adonsonia digitata and Tamarindus indica.* Shrub and the herb layer consist of: *Grevia bicolor, Solanum incanum, Ocimum basilicum, Combretum exalatum, Premna holstii, A. mellifera, A. Senegal, Grewia spp.* and *Abutilon maritum.* Perennial grasses include: *Cenchrus ciliaris, Chloris roxburghiana, Panicum maximum, Eragrostis superba, Digitaria milanjiana, Rotbellia exaltata.* and *Enteropogon macrostachyus*. Other important grasses are: *Heteropagon contortus, Aristide kenensis, Digitana macroblephara, Oropetium cafense,* and *Erogrotis aethiopice* Ekirapa and Muya (1991). The Kamba agropastoralists are the main inhabitants. Their mainstream economic activity is raising livestock and cultivating grains and pulses.

The study was conducted at the University of Nairobi Dryland Field Station, Kibwezi Irrigation Project (KIP) farm, situated in Kibwezi District. The farm is located about 16 km south east of Kibwezi town and about 7 km south of Kasayani market on Kibwezi - Kitui road. The farm lies at latitude 2°17'00"S and longitude 38°01'36"E. The farm is characterized by rainfall regimes and vegetation similar to those found in the rest of the district. The farm is mainly dry and mostly lies in ACZ V., described as very low potential maize zone and medium potential livestock and millet zone.



Source: Ministry of Planning and National Development (2006)

Figure1. The approximate location of the area of study on the map of Kenya

The total area of land on the farm is 4800 ha, however the current irrigated area under use covers 52 ha. The approximate location of the district (study site) on a map of Kenya is shown on f Figure 1. The only existing river is Kibwezi, which is the tributary of Athi river forming the southern most boundary of the farm. At the moment, this is the only source of irrigation water for the farm.

3.2 Soils of the study site

The soils of the experimental fields are well drained, moderately deep to very deep, red to dusky red, friable, sandy clay to clay, (Appendix 1). The result obtained from the 0 - 20 cm depth of soil further describes the soils as haplic lixisols, due to the low CEC of less than 24 cmol(+) kg^{-1} (FAO/UNESCO legend 1991).

The soil physical properties (Table 4) indicate an average soil bulk density range of between 1.31 to 1.49 kg m^{-3}. The high bulk density is due to the effect of compaction by machinery during cultivation. The general trend of Pb is a decrease with depth, thus the soil layers with more clay content have more water retention capacity. The soil profile 0-29 cm depth is important in water storage.

Table 4. Some physical properties of Kibwezi lixisol

Depth (cm)	K_{sat} (cm/hr)	Pb kg/m^3	OC %wt/wt		Texture		Textural class
				Sand %	Silt %	Clay %	
0-29	4.93^{a}	1.49^{a}	1.2^{d}	56	14	30	Sandy clay
29-65	2.83^{b}	1.31^{ab}	0.41^{d}	49	8	43	Loam
65-95	0.97^{c}	1.40^{a}	0.27^{cd}	40	10	50	Sandy clay
95-130	1.25^{c}	1.42^{a}	0.31^{b}	45	11	44	clay Sandy clay/clay

(Means with the same letter superscript in each horizon are not significantly Different at $p<0.05$ according to Duncan's multiple range test). Source: Mwaura (1995)

The carbon content of the soil is low ranging between 0.27 to 1.2 %, this could be due to the low amount of litter released on the surface coupled with high termite activity and probably high rates of decomposition. The mean saturated hydraulic conductivity (K_{sat}) value ranges between 0.27 to 4.93 cm/hr, the high permeability of upper soil layers results from relatively high soil intake rates. Lower saturated hydraulic conductivity of the lower layers hinders fast downwards water flow thus enhancing lateral spread.

The soil chemical properties (Table 5) showed a pH range of 7.0 to 7.1 in water and 6.8 to 6.8 in CaCl in the 0-29 and 29-65 cm soils depth, respectively. The soils are therefore neutral and will favour both base exchange and high microbial activity making most nutrients available to plants. The cation exchange capacity (CEC) values of the soil profile are medium raging from 17.5 to 20.8 cmol (+) kg^{-1} soil. The CEC of the top soil is lower than that of the underlying horizons probably due to the low organic matter on the surface. The top soil and subsoil exchangeable cations (Ca^{2+}, Mg^{2+} and K^+) are high, and well balanced for plant uptake (Msanya *et al.,* 1996). However supplementary fertilization is essential depending on specific crop demand.

Table 5. Some chemical properties of Kibwezi lixisol

Depth (cm)	pH		Exchangeable bases cmol (+) kg^{-1} Soil				Total bases cmol(+) kg^{-1} Soil	CEC cmol(+) kg^{-1} Soil	Percent Bs
	H_2o 1:2.5v/v	CaCl 1:2.5v/v	Ca^{2+}	Mg^{2+}	K^+	Na^+			
0-29	7	6.8	12.35	4.3	1.5	1	19.1	17.5	100+
29-65	7.1	6.8	13.75	4.5	2	1	21.25	20.8	100+
65-95	7.4	7	12.25	4.9	2.2	0.5	19.8	20.5	99
95-130	7.3	6.9	11.5	3.3	2.2	0.5	17.45	18.4	95

Source: Mwaura (1995)

3.3 Irrigation water quality

The results of the analyzed samples of water from the Kibwezi River showed the chemical characteristics shown in Table 6. According to Richards (1954), water with a minimum SAR of 3.30 is classified as low sodium water hence can be used for irrigation with little development of harmful levels of exchangeable sodium in the soil.

Analysis of the other parameters shown on Table 6 based on the FAO (1985) guidelines (Appendix 2), indicate that the irrigation water is suitable for maximum crop production. However, suitability of water for irrigation greatly depends on the climatic conditions, physical and chemical properties of the soil, the salt tolerance of the crop grown and the management practices. Hence, because of the high carbonate ion (HCO_3^-) level good management must be observed in order to ensure sustainability in a manner that does not degrade the quality of soil. Sustainability involves maintaining the productive resources required for irrigation, so that future generations may have the opportunity to use those resources as we do (Oster and Wichelns, 2003).

Table 6. Chemical characteristics of irrigation water from Kibwezi river

pH	8.36
EC (dSm^{-1})	0.60
Na^+ (cmol(+) kg^{-1})	0.17
K^+ (cmol(+) kg^{-1})	0.45
Ca^{2+} (cmol(+) kg^{-1})	1.5
Mg^{2+}(cmol(+) kg^{-1})	1.9
CO_3^{2-} (cmol(+) kg^{-1})	0.4
HCO_3^- (cmol(+) kg^{-1})	15.1
Cl^- (cmol(+) kg^{-1})	1.8
SO_4^{2-}(cmol(+) kg^{-1})	0.46
SAR_{Adj}	0.341

Source: (Adapted from, Mwaura 1995).

3.4 Selection of crop and irrigation method

Basing on soil data, altitude and the possibility of irrigating high value cash crop in this region, the two crops; tomato (*Lycopersicon esculentum L* var. M82) and sweet corn (*Zea mays L* var. renat) were selected for the study. The optimal temperature range for these two crops are 18-25 °C and 24-30 °C for tomato and sweet corn, respectively. Hence comparison of these temperatures with the Agro-climatic zones indicates that these crops could be grown successfully on this farm and the surrounding region as long as water is not a limiting factor. The tomato variety chosen was the most appropriate for the market due to its longer shelf life.

Several options for choice of an irrigation method are available. Though, sprinkler irrigation being appropriate for sweet corn production due to low costs and specific crop water demand, it is not appropriate for tomato production. Doorenbos and Kassam (1979) note that under sprinkler irrigation the occurrence of fungal disease and possibly bacterial canker may become a major problem. Further, under sprinkler, fruit set may be reduced with an increase in fruit rotting. In the case of poor quality water, leaf burn will occur with sprinkler irrigation. Due to crop specific demand, for high soil water content achieved without leaf wetting, trickle or drip irrigation has been adopted for tomato production. Surface irrigation by furrows can also be practiced where cost of installation of drip irrigation is a hindrance.

3.5 Experimental set up

Two crops namely tomato and sweet corn were differently grown in a randomized complete block design (RCBD) of three blocks. Tomato was grown under drip irrigation while sweet corn was grown under sprinkler irrigation system. Limited irrigation (different application rates) served as the treatments.

In a randomized block design, blocking was done to reduce variability among the blocks, such that variability was only due to treatments in a given block (Steel and Torrie, 1981). Each treatment appears in equal number of times in each block and each block contained all the treatments. Thus variability between the three blocks did not affect differences between treatment means. Each replicate (block) had the six different levels of water application (treatments) thus each experiment consisted of 18 plots. The plot sizes were 8 x 12.5 m for tomato and 6 x 5 m for sweet corn. For sweet corn yield harvest, the guard rows were left out and yield computed from the 6 x 4.9 m plot. For both crops the experiments were repeated on two occasions.

The land was disc ploughed, and then disc harrowed twice before each crop was grown. Marking of plots was done immediately and randomization of the six treatments for plot allocation in each replicate done using the random number tables (Steel and Torrie, 1981). Figure 2 and Figure 3 shows the field layout and treatments administered.

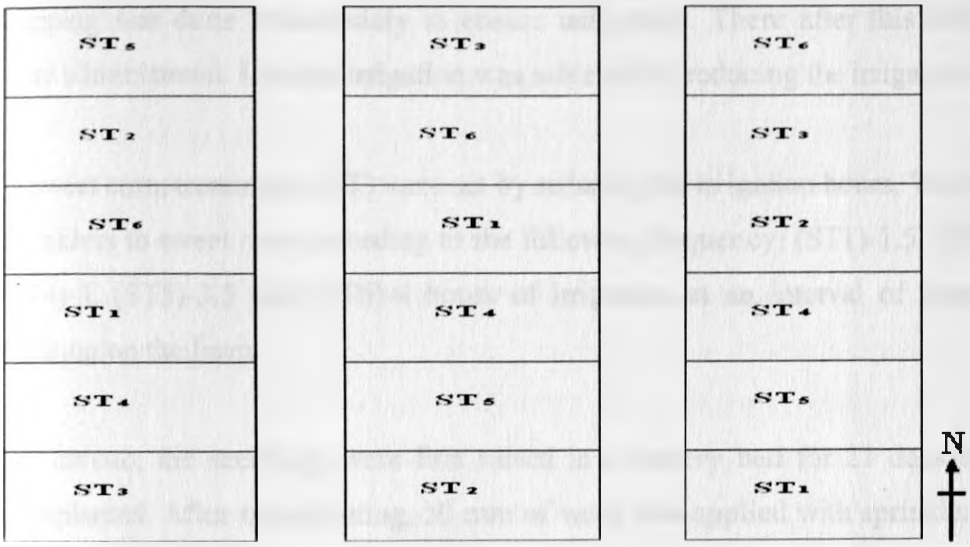


Figure 2: Field layout for sweet corn treatments (ST) grown under sprinkler irrigation.

Treatments:

ST1	36.2 mm or 1½hrs irrigation/day	ST4	48.4 mm or 3hrs irrigation/day
ST2	37.5 mm or 2hrs irrigation/day	ST5	49.2 mm or 3½hrs irrigation/day
ST3	47.0 mm or 2½hrs irrigation/day	ST6	50.8 mm or 4hrs irrigation/day

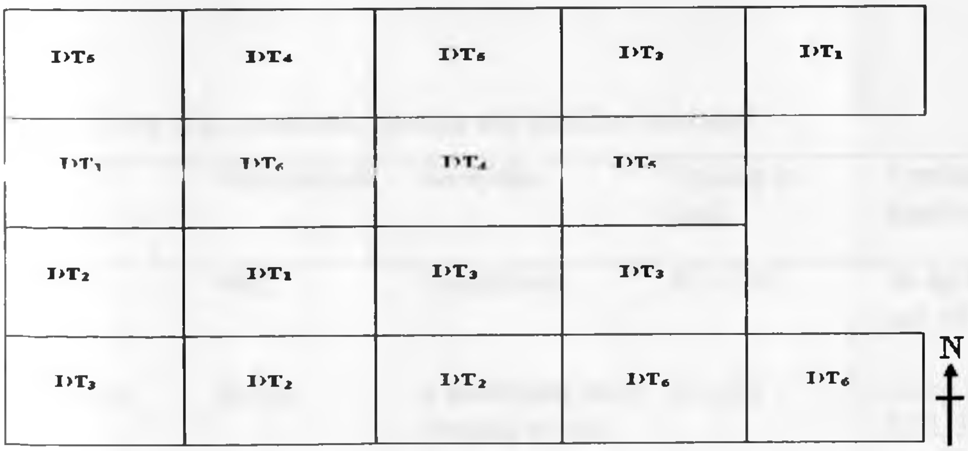


Figure 3: Field layout for tomato treatments (DT) grown under drip irrigation

Treatments:

DT1	42.4 mm or 3hrs irrigation after1day	DT4	42.4 mm or 3hrs irrigation after 4 days
DT2	42.4 mm or 3hrs irrigation after 2days	DT5	42.4 mm or 3hrs irrigation after 5 days
DT3	42.4 mm or 3hrs irrigation after 3days	DT6	42.4 mm or 3hrs irrigation after 6 days

After planting sweet corn, 50 mm of water was applied for one hour per day uniformly in all the plots for two weeks (14 days) until uniform emergence and establishment was obtained. Gapping was done immediately to ensure uniformity. There after this different treatments were administered. Limited irrigation was achieved by reducing the irrigation hours.

In sweet corn, treatments (ST) were set by reducing the irrigation hours. Water was applied by sprinklers to sweet corn according to the following frequency; (ST1)-1.5, (ST2)-2, (ST3)-2.5, (ST4)-3, (ST5)-3.5 and (ST6)-4 hours of irrigation, at an interval of three days as is the tradition on the farm.

For tomato, the seedlings were first raised in a nursery bed for 21 days before they were transplanted. After transplanting, 50 mm of water was applied with sprinkler irrigation to the young plants every day for one hour for period of ten days until they had uniformly established. After this the drips were installed and the treatments put into place. For tomato limited irrigation was applied by increasing the interval between irrigations.

In tomato, treatments (DT) involved increasing the interval between irrigation. Drip irrigation intervals corresponding to (DT1)-1, (DT2)-2, (DT3)-3, (DT4)-4, (DT5)-5 and (DT6)-6 days was set. The crop variety, seed/seedling rate, spacing and fertilizer rate used are shown in Table 7.

Table 7. Crop type, seed rate, spacing and fertilizer rate used

Crop	Variety/type	Seed rate	Spacing in (cm)	Fertilizer rate at planting time (kg/ha)
Tomato	M82	1 seed/hole	30 x 130	30 kg KCl., 73.6 kg N and 10 kg H_3PO_4
Sweet corn	Renat	2 seeds/hole later thinned to one	15 x 80	65 kg D.A.P, 100 kg KCl, 37.5 kg C.A.N and 23 kg N

Infestation of the crops by pests and diseases was checked by the use of appropriate pesticides and fungicides. All plots in the three replicates (blocks) were kept free of weeds and normal agronomic practices such as gapping and thinning of sweet corn and tomato done.

3.6 Irrigation water application

The sprinkler system used in this study for sweet corn production can be described as a line source irrigation system. Six sprinklers at a spacing of 12 meters were used; these were the NAAN 233 type and were operated at a pressure of 20 kPa. Two kinds of sprinkler heights were used the single riser and the double riser (Plate 2). The former was used to irrigate young crops, while the latter was used when plants grew more than 1 meter tall up to harvest.

Flow in the irrigation main line was controlled by means of blind end caps. Irrigation depth was taken as the average depth of water collected in the 28 catch cans with average circular opening diameter of 8.50 cm and height of 15.25 cm, placed on the ground between the two sprinklers. A total of 16 cans were placed on the wind ward side to collect maximum amount of water, while 12 cans were placed on the opposite side in a pattern shown in Figure 4. The precipitation collected in the catch cans for the test duration was measured with graduated measuring cylinder of 250 ml capacity with accuracy of 2 ml. The average amount of water in mm for each treatment was calculated.

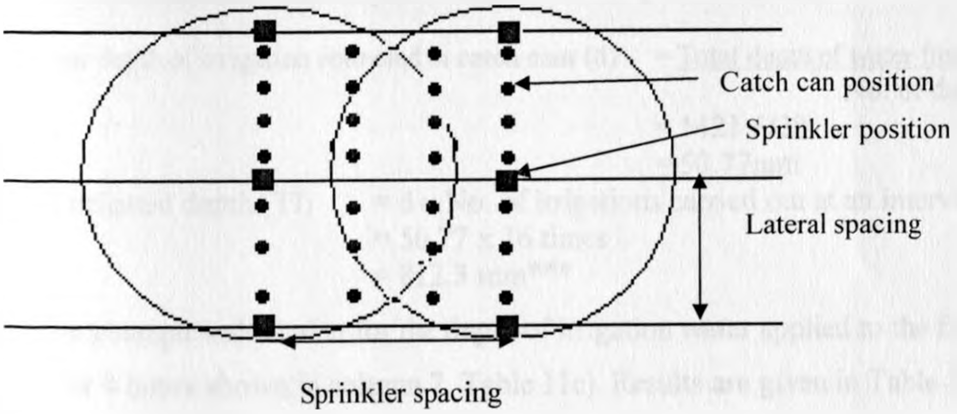


Figure 4: Pattern of the catch can layout on the sprinklers

The drip type used in this study for the production of tomato was the NAAN PAZ-13, typhoon drippers, with discharge of one liter per hour. The drip holes spacing on the tube were 30 cm. Tying the drip lines with strings ensured that water flowed only in the desired plots.

Gikonyo (1992) found out that, on a fluvisol which had an initial soil matrix suction of 22 kPa and on which an emitter of 2 l/hr had been used the emitted water had attained a depth of 25 cm in one hour, while forming a radius of 25 cm on the surface. In 2 hours a depth of 55 cm had been attained while the surface radius was 28 cm. Therefore, on Kibwezi lixisol, on which the soil consisted of alternating layers of sand clay, loam and sandy clay the one liter per hour emitters used could have supplied water to the mentioned water depth within the three hours they were operated hence justifying the mentioned soil water depth.

3.6.1 Calculation of total irrigation (TI) for sprinkler irrigation

The average values for total irrigation TI for sweet corn from the 28 catch cans were calculated as shown below:

Open area of each catch can = $3.14 \times (8.5)^2/4 = 56.75\text{cm}^2$

Depth of irrigation collected in one catch can (di) = $\dfrac{\text{Volume collected in catch cans(ml)} \times 10}{\text{Open area of catch cans (cm}^2\text{)}}$

di = $209^* \times 10/56.75$

= 36.83^{**} mm

(* is the volume (ml) of water collected in one catch cans for 4 hours)

(** is the calculated water depth (mm) in one of the 28 catch can)

Average depth of irrigation collected in catch cans (d) = $\dfrac{\text{Total depth of water from all 28 the cans}}{\text{No. of data}}$

= 1421.5/28

= 50.77mm

Total irrigated depth (TI) = d x No. of irrigations carried out at an interval of 3 days

= 50.77 x 16 times

= 812.3 mm***

(*** is a sample calculation for the depth of irrigation water applied to the first crop of sweet corn for 4 hours shown in column 7, Table 11c). Results are given in Table 11c and 11d).

3.6.2 Calculation of irrigation (I) for drip irrigation

The values for irrigation (I) for tomato were calculated as shown below:

Wetted diameter of the drip = 30 cm

Discharge of the emitter =1 liter per hour = 1000 ml

Area of the wetted area = $\pi r^2 = 3.14 \times (15)^2 = 707.1\ \text{cm}^2$

Depth of irrigation for 3 hrs = 3 hrs x 1000 ml x 10/707.1

= 42.4 mm

The total irrigation depth (I) (mm) was obtained by multiplying the depth of irrigation with the number of irrigation days. Results are shown in Table 12a and 12b.

3.7 Instrumentation of experimental site

3.7.1 Calibration and installation of tensiometers

Before use, the tensiometers were filled with distilled water and tested for any leakage using a hand operated pump. The tensiometers were then dipped into a bucket of clean water ensuring that the cups were adequately covered with water and the dial reading noted after five minutes. The reading was adjusted to read zero.

Two tensiometers per plot at a spacing of 15 cm from the plant and at a depth of 20 and 39 cm were installed by first making a hole of desired depth. The hole was made by use of a T-bar auger supplied with the tensiometer (of external diameter slightly larger than the tensiometer tube). While ensuring that the ceramic cup is wet and not touched by hand, the tensiometer was then dipped into the hole made slightly deeper by about 2 cm, which was back filled to ensure some good hydraulic contact between the soil and the ceramic cup. The hole was then back filled holding the tensiometer upright with some soil pressing to ensure the instrument was firm and in good contact with the soil. A few drops of soil moisture blue fluid (Algaecide) were put into the tensiometer to curb any possible growth of algae and fungus on the ceramic cup. The jet of the tensiometer was then filled with distilled water and any accumulated air released by use of the hand operated hand pump. The tensiometer was then ready for data recording. Regular inspection of the tensiometers was maintained throughout the data collection period.

3.8 Soil moisture monitoring and determination of infiltration

Soil moisture was measured before each irrigation event using soil tensiometers inserted next to the irrigated crop in each plot (Plate 3). Readings of the changes in soil water suction (tension) of the profile was determined in the 0-20 and 20-39 cm depth for each crop treatment over the two irrigation period. Monitoring of soil moisture depletion was done at these depths due to compaction of the sub-soil and lack of roots at depth below this range. Moisture retention curve was used to convert the measured tensions into volumetric soil moisture contents. The depth of water (ΔS) (mm) was obtained by calculation using equation 2.9.

$D_{H2O} = \theta * d$ 2.9

Where:

D_{H2O} = depth of water (mm)

θ = volumetric water content (in fraction)

d = thickness of soil profile (mm)

The double-cylinder infiltrometer with an initial falling head and after 10 minutes a constant head was used to determine infiltration rate. The procedure outlined by Klute (1986) was used. Infiltration rate was calculated from the rate of change of water level from infiltrometer during the falling head and from the rate of fall of water level reservoir during constant head using equations 2.10a (for 10 minutes) and 2.10 (for 10 to 120 minutes), respectively.

Infiltration rate = $\Delta h / \Delta ti$ (cm/hr)..2.10a

Where:

Δh = change of water height in one minute (cm)

ti = time interval in hours

Infiltration rate = $\Delta v / A\ \Delta ti$ (cm/hr)..2.10b

Where:

Δv = change in volume in aspirator reading (cm^3)

A = cross sectional area of inner cylinder (cm^2)

ti = time interval in hours

3.9 Collection of climatic data

During the study period climatic data was collected. Rainfall and Pan evaporation data was collected from Kibwezi meteorological observatory station situated on the study site while, data on mean air temperature was collected from meteorological station on the adjacent goat project farm. The data collected was used in the computation of evaporation estimates by use of pan evaporation methods described earlier (Doorenbos and Pruitt, 1977). Since the rain was received when the crops had achieved full ground cover, it can safely be assumed that intercepted light rainfall is close to 100 % effective (Doorenbos and Kassam, 1979).

Plate 2. Two types of sprinklers used for irrigating sweet corn; a- single riser and b - double riser.

Plate 3. Placement of tensiometer in sweet corn rows. Note the T-bar auger for making the holes.

3.10 Crop development and phenological stages

In order to obtain the crop coefficients (K_c) planting and harvesting dates were noted so as to determine the length of the growing season. Phenological changes of the crops such as flowering and drying of leaves for tomato and tasselling and silking in sweet corn were noted.

The crops development at different stages during the growing season was determined visually using the four stage approach as described by Doorenbos and Pruitt (1977). These stages are described in Table 8. Using this information, the approximate lengths of the crop developmental stages for both tomato and sweet corn was determined.

Table 8. The four stages in crop development

Stage	Characteristics
Initial stage	germination and early growth when the soil surface is not or is handily covered by the crop
Crop development stage	from the end of the initial stage to attainment of effective full ground cover
Mid season stage	from the attainment of effective full ground cover to time of start of maturity as indicated by discolouring or falling of leaves as in tomato
Late season stage	from the end of mid-season stage until full maturity or harvest

Source: Doorenbos and Pruitt (1977)

3.11 Crop yields

For sweet corn, the middle rows in each plot were harvested, leaving the guard rows. Ideally an area of 6 x 4.9 m was harvested. The yields in each plot were then determined and adjusted to kg ha^{-1}. It is important to note that sweet corn is harvested at the milk stage, hence the yield are for the marketable fresh ear cob.

In determination of tomato yields, the whole plot measuring 12.5 x 8 m was harvested. The yields were determined by weighing on a scale. The yield in each plot was then adjusted to kg ha^{-1}. Hence the yields for both sweet corn and tomato are taken as the weight of marketable yield. At each level of irrigation water application, crop yields (kg ha^{-1}) were analyzed using analysis of variance for randomized completely block design.

3.12 Statistical analysis of data

Statistical analyses on data were performed using Genstat version 5, release 3.2 computer programme (Lawe Agricultural Trust, 2007). Analysis of variance (ANOVA) was done on yield to determine treatment effects on yields, ET and CWP. Where the *F* value was significant, means comparison was performed using Least Significant Difference (LSD) (Steel and Torrie, 1981) at a *P* value of 0.05. Simple correlation analysis (Draper and smith, 1981) was used to determine the amount of associations between Yield, CWP and. ET.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Climate of the study area

The study area has rainfall that is characterized by small total amounts, strong seasonal and bimodal distribution, with high temporal and spatial variability between seasons and years. The mean annual rainfall is about 650 mm (Sombroek *et al.*, 1982). During the study period, rain was received in November-January and in March-April, with a total of 321 mm being received during the seven months of study period. Mean daily maximum temperatures ranged from 34.8 to 39.6 °C, while minimum temperatures ranged from 15.4 to 19.4 °C, respectively. The highest value was recorded in January, while the lowest value was experienced in April. The total open pan evaporation from October to April when the experiment was carried out was about 1066 mm. Figure 5 shows the mean daily weather data from Kibwezi meteorological observatory station situated on the study site and from meteorological station on the adjacent goat project farm.

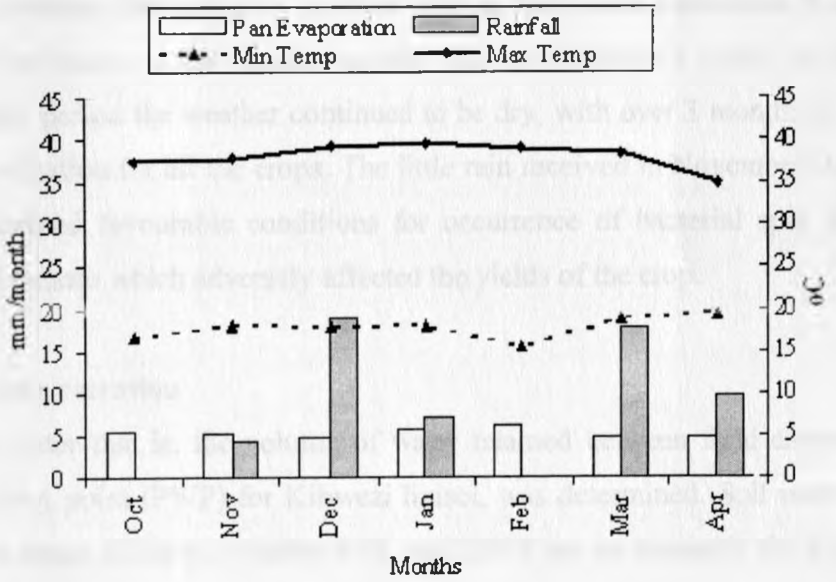


Figure 5: Some climatic data for KIP for October 1998 and April 1999, the study period

Climatic conditions with reduced evaporative demand will reduce both beneficial transpiration and non-beneficial evaporative consumption of water. A reduced evaporative demand from the atmosphere is usually associated with low wind, low solar radiation, lower temperature and low vapor pressure deficit in the atmosphere (i.e., high relative humidity). When the reduced evaporative demand is associated predominantly with low radiation and temperature, it is important to account for possible impacts on the biology of the crop.

Total water requirement after transplanting of tomato crop grown in the field for 90 to 120 days, are 400 to 600 mm while, for sweet corn grown for 75 to 110 days it is 500 to 800 mm (Doorenbos and Kassam, (1979). These demands can not be met through rainfall as shown in Figure 5, hence a need for irrigation to meet the crop water requirement. Crops like maize, for example, require warm climatic conditions to grow vigorously and productively, with optimum temperature requirement being more than 10 °C for germination, on the other hand cool temperature causes problem for ripening. Doorenbos and Kassam, (1979) states that, tomato require cool climate, with optimum night temperature range of between 10 and 20 °C, they are also particularly sensitive to high relative humidity and strong winds. In addition, minimum threshold of solar radiation is needed for photosynthesis.

Despite temperature limitations for tomato in the ASAL where temperatures are higher than the optimum, varieties that can grow in these regions have been introduced. Cal J, M82 and Money maker are some of the tomato varieties that are commonly grown in these regions. During the study period the weather continued to be dry, with over 3 months of water deficit necessitating irrigation for all the crops. The little rain received in November–January and in March-April created favourable conditions for occurrence of bacterial spot disease in the second crop of tomato which adversely affected the yields of the crop.

4.2 Soil water retention

The available water that is, the volume of water retained between field capacity (FC) and permanent wilting point (PWP) for Kibwezi lixisol, was determined. Soil water retention in the 0-1500 kPa range of the two depths 0-20, and 20-39 cm are shown in the Figure 6. Water retention in the 0-110 kPa range of the two depths 0-20 and 20-39 cm soil depicts a general increase in water retained down the profile. This is as a result of decreasing bulky density (pb) and hence micro-porosity with depth. Moisture at field capacity is held in the macro-pores hence soils with high sand content require less energy to remove the moisture (Gikonyo, 1992).

Factors which could have a bearing on the soil water retention include organic carbon content through its influence on pore size distribution, soil surface area and also silt content.

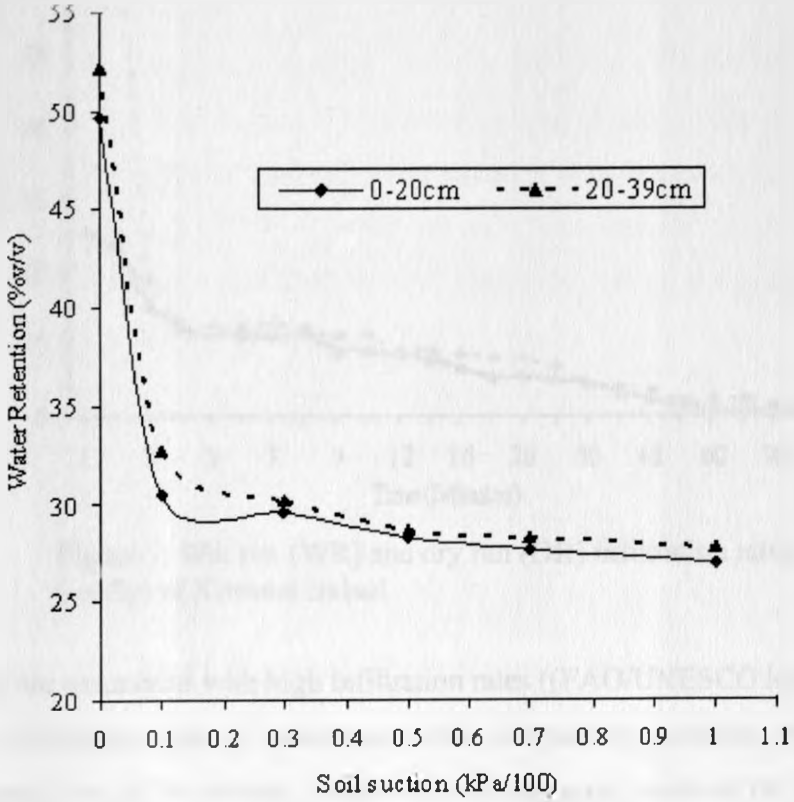


Figure 6: Soil water retention of the two horizon of Kibwezi lixisol

The high water retention capacity makes the soil well suited for irrigation since with good management high irrigation efficiency can be realized as water losses through deep percolation are minimal. The retained water acts like a reservoir and is available to the crops use for a longer period of time hence minimizing the need for frequent irrigation.

4.3 Infiltration rates

Infiltration rates during the dry season (dryrun, (DR) and during the wet season (wetrun, (WR)) of the Kibwezi lixisol varied markedly in the first 3 minutes. Infiltration rate after 1, 2 and 3 minutes for dry run were higher than that of the wet run, after which the infiltration became uniform and consistently low as shown in Figure 7.

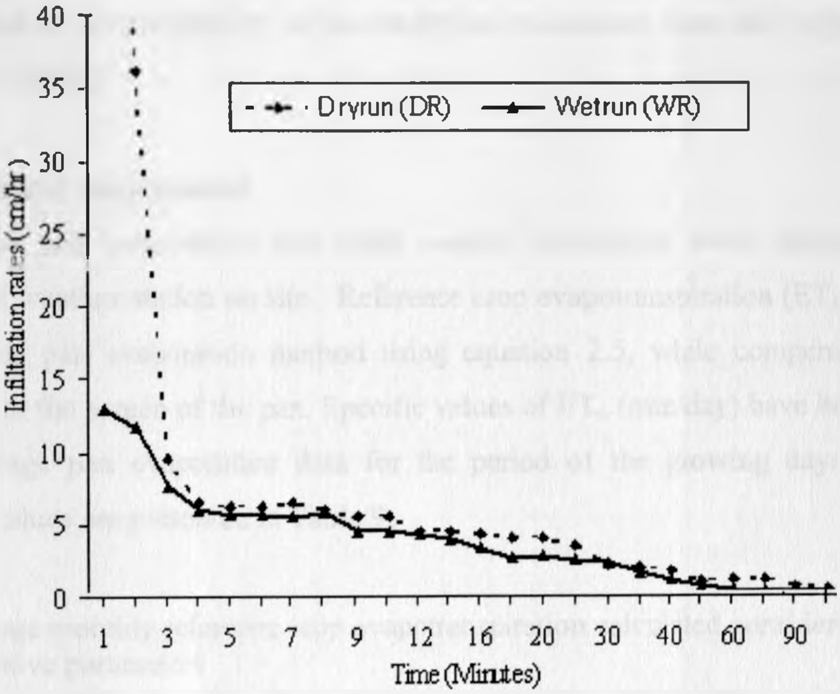


Figure 7: Wet run (WR) and dry run (DR) infiltration rates (cm/hr) of Kibwezi lixisol

Though, lixisols are associated with high infiltration rates ((FAO/UNESCO legend, 1991), the observed low infiltration rate is associated with compaction resulting from effects of machinery imposed on soil by wheels, tracks and soil engaging tools on the cultivated land. This compaction resulted in increased bulk density (Table 4), impeding the flow of water as the numbers of macro pores are reduced. The low infiltration rate could also have been caused by fewer biotic channels in the upper profile, as biotic activity had been discouraged due to negligible litter accumulation which could have led to limited food supplies.

The initial high water infiltration rates makes the soil well suited for irrigation since with good management high irrigation efficiency can be realized as water losses through runoff are minimized. During the study period and especially with drip irrigation incidences of runoff and water stagnation were not observed. With sprinkler irrigation, runoff and water stagnation was not observed in plots being irrigated for 3. 2 ½, 2 and 1 ½ hours, unlike those irrigated for 3 ½ and 4 hours. This is due to prolonged irrigation which could not cope with the rate of infiltration.

The observation points out to the most suitable irrigation system and the optimal irrigation schedule subject to the profitability of the enterprise in question, since drip irrigation system is expensive to install.

4.4 Crop water requirement

The values for pan evaporation and other weather parameters were obtained from the meteorological weather station on site. Reference crop evapotranspiration (ET_o) values were computed using pan evaporation method using equation 2.5, while compensating for the reduction due to the screen of the pan. Specific values of ET_o (mm/day) have been calculated from the average pan evaporation data for the period of the growing days in question. Monthly ET_o values are presented in Table 9.

Table 9: Average monthly reference crop evapotranspiration calculated considering indicative parameters

Months Parameters	October	November	December	January	February	March	April
Wind	Light	Light	Light	Light	Light	Light	Light
RH mean	low	low	low	low	low	low	low
K_p	0.7	0.7	0.7	0.7	0.7	0.7	0.7
E_{pan}	5.4	5.3	4.7	5.7	6.1	4.6	4.7
*ET_o mm/day	3.6	2.3	3.6	3.8	4.8	2.7	2.9

* The 10% Reduction due to screen has been factored. (Doorenbos and Pruitt 1977)

Crop water requirement (ET_{crop}) values for each vegetative stage for the two crops, tomato and sweet corn were calculated for the entire crop growing season using equation 2.1. The crop coefficients (K_c) values used for computation of ET_{crop} during the different stages of crop growth are those given by Doorenbos and Kassam (1979) in Table 2. Results are presented in Tables 10a to 10d.

From Table 10a and 10b, it is evident that sweet corn requires most water during the development stage, with the seasonal ET_{crop} being 148 and 137 mm/season for the first and second crop, respectively. These stages accounted for 52 and 54 % of the total seasonal ET_{crop} of 284 and 255 mm/season for the first and second crop, respectively. These results concur with those reported by Dagdelen *et al,* (2006) who obtained average seasonal water use values ranging from 174 to 558 mm/season in a corn crop. Water at the development stage is critical, for it is the period when the crop is developing effective ground cover and flowering. Deficit irrigation at this stage leads to reduction in biomass, yield and harvest index (Farre and Faci, 2009).

Table 10a. Crop water requirement of the first crop of sweet corn (SW1) planted on 3/12/98

Date	Growing days	Stage of dev.	Crop coeff. (K_c)	ET_o (mm/day)	ET_{crop} (mm/day)	ET_{crop} (mm/season)
3/12-18/12/98	15	Initial	0.5	3.4	1.7	25.5
18/12/98-27/1/99	40	Dev.	0.9	4.1	3.7	147.6
27/1-16/2/99	20	Mid.	1.2	4.6	5.5	110.4
	0	Late	-	-	-	-
Total	75					283.5

Table 10b. Crop water requirement of the second crop of sweet corn (SW2) planted on 19/1/99

Date	Growing days	Stage of dev.	Crop coeff. (K_c)	ET_o (mm/day)	ET_{crop} (mm/day)	ET_{crop} (mm/season)
29/1-13/2/99	15	Initial	0.5	4.8	2.4	36.0
13/2-25/3/99	40	Dev.	0.9	3.8	3.4	136.8
25/3-13/4/99	19	Mid.	1.2	3.6	4.3	82.1
	0	Late				
Total	74					254.9

From Table 10c and 10d, the ET_{crop} for tomato was found to be highest during the development and the mid stage; 298 mm/season and 269 mm/season for first and second crop, respectively. These stages accounted for 73 and 76 % of the total seasonal ET_{crop} of 409 and 352 mm/season for first and second crop, respectively.

During these stages the crop is attaining effective full ground cover, flowering, developing fruits and attaining maturity. Water deficit at this stage adversely affects the quality and yields of crop (Doorenbos and Kassam, 1979). From the results it is noted that, accurate estimates of ET_{crop} on a daily and seasonal basis is essential for making tactical in-season irrigation management decisions and for strategic irrigation planning and management.

Table 10c. Crop water requirement of the first crop of tomato (TM1) planted on 3/10/98

Date	Growing days	Stage of dev.	Crop coeff. (K_c)	ET_o (mm/day)	ET_{crop} (mm/day)	ET_{crop} (mm/season)
3/10-24/10/98	21	Initial	0.5	3.9	2.0	41.0
24/10-14/12/98	51	Dev.	0.8	3.8	3.0	155.0
14/12/98-13/1/99	30	Mid.	1.25	3.8	4.8	142.5
13/1-2/2/99	20	Late	0.8	4.4	3.5	70.4
Total	122					408.9

Table 10d. Crop water requirement of the second crop of tomato (TM2) planted on 9/1/99

Date	Growing days	Stage of dev.	Crop coeff. (K_c)	ET_o (mm/day)	ET_{crop} (mm/day)	ET_{crop} (mm/season)
9/1-30/1/99	21	Initial	0.5	4.3	2.2	45.2
30/1-21/3/99	50	Dev.	0.8	4.2	3.4	168.0
21/3-13/4/99	23	Mid.	1.25	3.5	4.4	100.6
13/4-26/4/99	13	Late	0.8	3.7	3.0	38.5
Total	107					352.3

4.5 Crop response to water

4.5.1 Sweet corn yields response to water

The response of the yields of sweet corn to application of different amounts of water after every three days is shown in Figure 8. The yields increased with reduction in period of application of irrigation water up to a point where water limitations affected the yields. The low yields at the end of the curves indicate that excessive irrigation water negatively affected the yields.

Average total irrigation (TI) (irrigation plus effective rainfall) water applied to crops ranged between 596 and 829 mm for the first crop, while 761 to 913 mm of water was applied to the second crop. Sweet corn, fresh ear yield varied from 10.88 to 4.93 t ha^{-1} and from 11.84 to 4.02 t ha^{-1} for the first and second crop, respectively. The highest sweet corn yields of 11.84 and 10.88 t ha^{-1} were obtained from the treatment irrigated for 2.5 and 3 hours which corresponds to 769 and 882 mm of TI for the first and second crop, respectively. Statistically, no significant differences ($P \le 0.05$) existed in yields, between treatments receiving irrigation water for 4, 3 ½, 3 and 2 ½ hours for both first and second crop. Sweet corn yields were highly correlated with irrigation water supplied (TI) at P≤ 0.05 for the first and second crop, respectively.

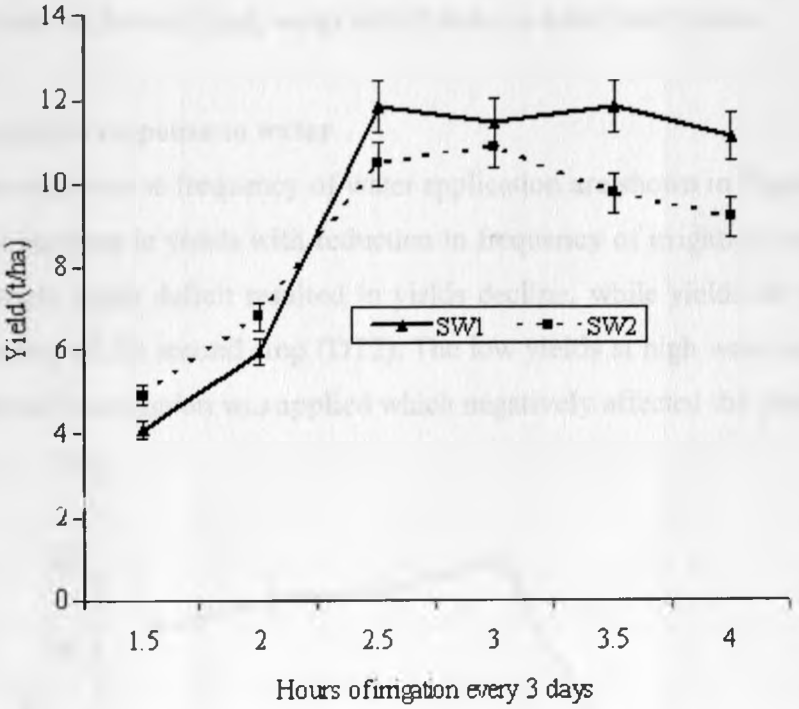


Figure 8: Effect of different irrigation regimes on the yield of sweet corn

The results imply that 2.5 hours or an average of 791 mm of total irrigation water applied at an interval of three days is adequate for sweet corn production under the prevailing climatic condition, thus saving an average of 41 mm or 5 % of the total irrigation water from the 3 hours or an average of 832 mm of TI that is currently applied.

In a similar investigation, Oktem *et al.* (2003), while working to determine appropriate irrigation frequencies and water-yield relationship for sweet corn, in a semi-arid region, applied irrigation water corresponding to 2, 4, 6 and 8 day irrigation frequency. Irrigation water applied to crops ranged between 610 and 876 mm in 1998, while 612- 889 mm of water was applied in 1999. Fresh ear yield, based on irrigation frequencies, was found to be statistically significant (P≤ 0.01) in both years. The highest fresh ear yields were 13.66 and 13.19 t ha^{-1} for the 2-day irrigation frequency while, minimum fresh ear yields were found to be 8.55 and 7.29 t ha^{-1} with the 8-day irrigation frequency in 1998 and 1999, respectively.

Yields were reduced with deficit irrigation in both years. They concluded that a 2-day irrigation frequency, with 100 % evaporation water application by a drip system was optimal for sweet corn grown in semi-arid regions similar to that of Turkey where the work was done. In conclusion it can be deduced that, water deficit reduces total fresh yields.

4.5.2 Tomato yields response to water

Yields of tomato response to frequency of water application are shown in Figure 9. The figure shows a general increase in yields with reduction in frequency of irrigation water application up to a point where water deficit resulted in yields decline, while yields for the first (DT1) was higher than that of the second crop (DT2). The low yields at high water application rates indicate that excessive irrigation was applied which negatively affected the yields.

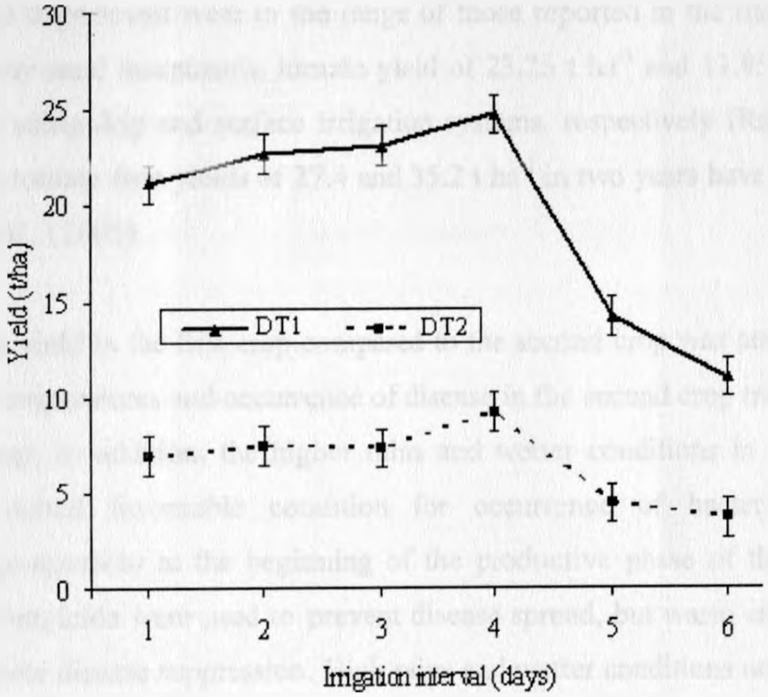


Figure 9: Effect of different irrigation regimes on yield of tomato

The TI water applied to crops ranged between 2684 to 607 mm for the first crop, while 2724 to 562 mm of water was applied to the second crop. Tomato yield varied from 24.74 to 11.02 t ha^{-1} and 7.47 to 3.63 t ha^{-1} for the first and second crop, respectively. The highest tomato yields of 24.74 and 9.20 t ha^{-1} were obtained from treatment with irrigation interval of 4 days which corresponds to 819 and 731 mm of TI for the first and second crop, respectively. Statistically, no significant differences ($P \leq 0.05$) existed in yields, between treatment being irrigated at intervals of 1, 2, 3 and 4 days for both the first and second crop. Yields of tomato were found to be weakly correlated with applied irrigation water (TI), at $P \leq 0.05$ for the first and second crop, respectively.

The results imply that under the prevailing climatic condition, 3 hours of drip irrigation can be applied after an interval of 4 days for tomato production without significantly affecting the yields. This corresponds to an average of 776 mm of TI, thus saving an average of 233 mm or 23 % of the irrigation water from the 3 days interval or 1009 mm of TI water that is currently applied.

Except in second crop when unfavorable conditions hampered plant growth, tomato yield obtained in these experiment were in the range of those reported in the literature for ASAL climate. On loamy sand inceptosols, tomato yield of 23.25 t ha^{-1} and 11.95 t ha^{-1} have been reported, grown using drip and surface irrigation systems, respectively (Raina *et al.*, 1999), while maximum tomato fruit yields of 27.4 and 35.2 t ha^{-1} in two years have been reported by Singandhupe *et al.*, (2003).

The high tomato yield in the first crop compared to the second crop was attributed to several factors. Higher temperatures and occurrence of disease in the second crop treatment increased stress on the crop. In addition, the higher rains and wetter conditions in the treatment for second crop created favourable condition for occurrence of bacterial spot disease *(Xanthomonas campestris)* at the beginning of the productive phase of the crop. Frequent applications of fungicide were used to prevent disease spread, but warm and wet conditions hampered complete disease suppression. High rains and wetter conditions occurred during the vegetative phase of the first crop resulting in low disease pressure.

Much higher yield of tomato (134.8 t ha^{-1}) has been reported in cooler climates (Cetin *et al.*, 2008) because the number of days with temperatures above 28 °C adversely affects fruit production. In the study area, average temperature ranged between 34.8 and 39.2 °C during the study period hence explaining the observed low tomato yields.

4.6 Soil water balance

Soil matrix suction was converted to volumetric water content (θ %) by extrapolation using moisture retention curve in Figure 6. Change in moisture storage (ΔS) obtained as the depth of water (D_{H2O}) per crop rooting depth (mm) was obtained by calculation using equation 2.9. Summarized calculated values for change in moisture storage (ΔS) for both sweet corn and tomato receiving different treatments are shown in Tables 11a and 11b and Table 12a and 12b for sweet corn and tomato, respectively.

4.6.1 Calculation of ET for sweet corn

The values for effective rainfall, R_e and change in moisture storage, ΔS have been obtained from Figure 5 and Table 11a and 11b, respectively. Value of R_e is added on depth of irrigation to get total irrigation, (TI). Reference evapotranspiration, ET_0 is also added to get total water input into the system. From these, ΔS is subtracted to get the crop evapotranspiration ET, as shown by equation 2.7b. The calculated ET values for sweet corn have been summarized in Table 11c and 11d for the first and second crop, respectively. Table 11c and 11d shows both values of ET and ΔS increasing with increasing duration of irrigation.

Ideally, at the beginning of the growing season, the amount of water supplied per irrigation application, also called the irrigation depth, was small and supplied frequently. This is due to the low evapotranspiration of the young plants and their shallow root depth. Hence the ET for the sweet corn when young (<14 days) was assumed to be the same as the ET_0.

Table 11a: Monthly change in moisture storage (mm) in the 0-39 cm soil profile for the six treatments of the first crop of sweet corn

Date	Treatments					
	ST1	ST2	ST3	ST4	ST5	ST6
December 1998	93.8	104.5	113.2	117.2	117.5	122.4
January 1999	187.5	187.8	188.3	192.5	202.4	218.2
February 1999	93.6	93.6	94.1	94.4	91.0	108.8
ΔS (mm)	374.9	386.0	395.6	404.0	410.9	449.4

Table 11b. Monthly change in moisture storage (mm) in the 0-39 cm soil profile for the six treatments of the second crop of sweet corn

Date	Treatments					
	ST1	ST2	ST3	ST4	ST5	ST6
February 1999	122.5	122.1	123.8	127.1	123.6	140.2
March 1999	142.1	144.6	146.5	151.1	146.5	165.5
April 1999	93.4	98.3	93.9	93.9	95.2	104.8
ΔS (mm)	358.0	365.0	364.1	372.1	365.4	410.5

Table 11c. Calculated ET values (mm) for the six treatments of the first crop of sweet corn

Irrigation interval	1.5 hrs	2 hrs	2.5 hrs	3 hrs	3.5 hrs	4 hrs
Effective rainfall (R) (mm)	17.0	17.0	17.0	17	17.0	17.0
No. of irrigation days	16	16	16	16	16	16
Irrigation (I) (mm)	578.9	600.1	751.9	775.1	787.9	812.3
TI (I+R) (mm)	595.9	617.1	768.9	792.1	804.9	829.3
ET_0 for 14 days (mm)	63.0	63.0	63.0	63.0	63.0	63.0
ΔS (mm)	374.9	386.0	395.6	414.0	410.9	449.4
ET (mm)	284.0	294.1	436.3	441.1	457.0	442.9

Table 11d. Calculated ET values (mm) for the six treatments of the second crop of sweet corn

Irrigation interval	1.5 hrs	2 hrs	2.5 hrs	3 hrs	3.5 hrs	4 hrs
Effective rainfall (R) (mm)	112.0	112.0	112.0	112.0	112.0	112.0
No. of irrigation days	15	15	15	15	15	15
Irrigation (I) (mm)	542.7	562.6	704.9	726.0	738.7	761.5
TI (I+R) (mm)	654.7	674.6	816.9	838.0	850.7	873.5
ET_0 for 14days (mm)	82.8	82.8	82.8	82.8	82.8	82.8
ΔS (mm)	251.5	270.1	367.8	328.3	319.0	371.2
ET (mm)	486.0	487.3	531.9	592.5	614.5	585.1

4.6.2 Calculation of ET for tomato

The values for effective rainfall, R_e and change in moisture storage, ΔS have been obtained from Figure 5 and Table 12a and 12b, respectively. A similar approach to that used on sweet corn was followed. The ET for the young tomato plants in the nursery and in the early stages of growth (31 days) was assumed to be the same as ET_0. The ET values for tomato are summarized in Table 12c and 12d for the first and second crop, respectively. Table 12c and 12d shows both values of ET and ΔS decreasing with increasing irrigation interval.

Table 12a. Monthly change in moisture storage (mm) in the 0-39 cm soil profile of the six treatments of the first crop of tomato

	Treatments					
Date	DT1	DT2	DT3	DT4	DT5	DT6
November-98	617.6	237.2	156.3	117.2	47.1	77.2
December-98	843.5	336.5	230.3	181.6	98.9	82.5
January-99	799.7	271.2	155.4	103.4	75.2	70.5
ΔS (mm)	2260.8	844.9	542.0	402.2	221.2	230.2

Table 12b. Monthly change in moisture storage (mm) in the 0-39 cm soil profile of the six treatments of the second crop of tomato

	Treatments					
Date	DT1	DT2	DT3	DT4	DT5	DT6
February 1999	654.8	239.6	140.7	94.0	70.4	76.9
March 1999	844.0	268.8	211.8	133.9	130.2	108.8
April 1999	831.5	285.9	161.3	117.9	94.1	70.4
ΔS (mm)	2330.3	794.2	513.8	345.7	294.7	256.1

Table 12c. Calculated ET values for the six treatments of the first crop of tomato

Irrigation interval	1 day	2 days	3 days	4 days	5 days	6 days
Effective rainfall (R) (mm)	183.0	183.0	183.0	183.0	183.0	183.0
No. of irrigation days	59	30	19	15	10	10
Irrigation (I) (mm)	2501.6	1272.0	805.6	636.0	424.0	424.0
TI (I+R) (mm)	2684.6	1455.0	988.6	819.0	607.0	607.0
ET_o for 31 days (mm)	157.4	157.4	157.4	157.4	157.4	157.4
ΔS (mm)	2260.8	844.9	542.0	402.2	221.2	230.2
ET (mm)	581.2	767.5	604.0	574.2	543.2	534.2

Table 12d. Calculated ET values for the six treatments of the second crop of tomato

Irrigation interval	1 day	2 days	3 days	4 days	5 days	6 days
Effective rainfall (R) (mm)	138.0	138.0	138.0	138.0	138.0	138.0
No. of irrigation days	61	30	21	14	12	10
Irrigation (I) (mm)	2586.4	1272.0	890.4	593.6	508.8	424.0
TI (I+R) (mm)	2724.4	1410.0	1028.4	731.6	646.8	562.0
ET_o for31 days (mm)	172.2	172.2	172.2	172.2	172.2	172.2
ΔS (mm)	2330.3	794.2	513.7	345.7	294.7	256.1
ET (mm)	566.4	788.0	686.9	558.1	524.4	478.1

4.7 Crop water productivity

4.7.1 Sweet corn CWP response to ET

Crop water productivity (CWP) for sweet corn was determined using equation 2.8. The results are shown in Figure10. There was an increase in CWP with increase in duration of irrigation up to a maximum point before falling, while the CWP for first crop (SW1) was higher than that of the second crop (SW2).

Average seasonal actual crop evapotranspiration (ET) for sweet corn ranged from 284 to 457 mm and 486 to 614 mm for the first and second crop, respectively. The CWP ranged from 1.44 to 2.71 kg m^{-3} for first and 1.01 to 1.97 kg m^{-3} for the second crop. The highest CWP value obtained was 2.71 and 1.97 kg m^{-3} for the treatment irrigated for 2.5 hrs, with ET of 436 and 532 mm for the first and second crop, respectively. The CWP was highly correlated with ET. at $P< 0.05$ for the first and second crop. This indicates that the observed variation in CWR is as a result of the variation in ET. The results further suggest that the treatment irrigated for 2.5 hrs is the most suitable for the farm. The high CWP value indicates that water is well utilized.

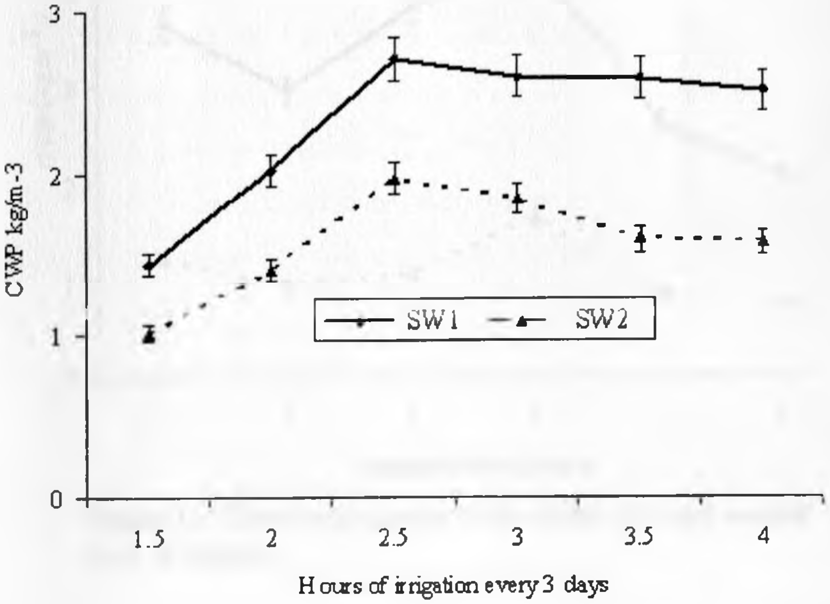


Figure 10: Crop water productivity of the first and second crop of sweet corn

In a similar experiment by Dagdelen *et al.* (2006), in which maize received 70, 50, 30 and 0 % times the water depletion on the same day, the average seasonal water use values ranged from 174 to 558 mm. They noted that water deficit significantly affected crop yields, the average maize yields varied from 2.88 to 11.34 t ha^{-1} while, the average CWP ranged from 1.65 to 2.15 kg m^{-3}. In another study by Ko and Piccinni (2009) it was noted that, maize grain yields increased as irrigation increased, from 50%, 75% and 100% crop evapotranspiration. The greatest CWP of 1.6 kg m^{-3} was achieved at 456 mm of water input, while yields plateaued at less than 600 mm. O'Neill *et al.* (2008), while comparing performance of maize under three irrigation systems obtained grain yield of 10.5 t ha^{-1} and CWP of 1.4 kg m^{-3}. In a review by Sander and Wim (2004), CWP for maize ranged between 1.1 to 2.7 kg m^{-3}. Therefore the findings obtained in this study are in agreement with those reported in literature.

4.7.2 Tomato CWP response to ET

There was a general increase in CWP with an increase in limited irrigation up to a maximum point before falling, while CWP for the first (DT1) was higher than that of the second crop (DT2) as indicated in Figure 11.

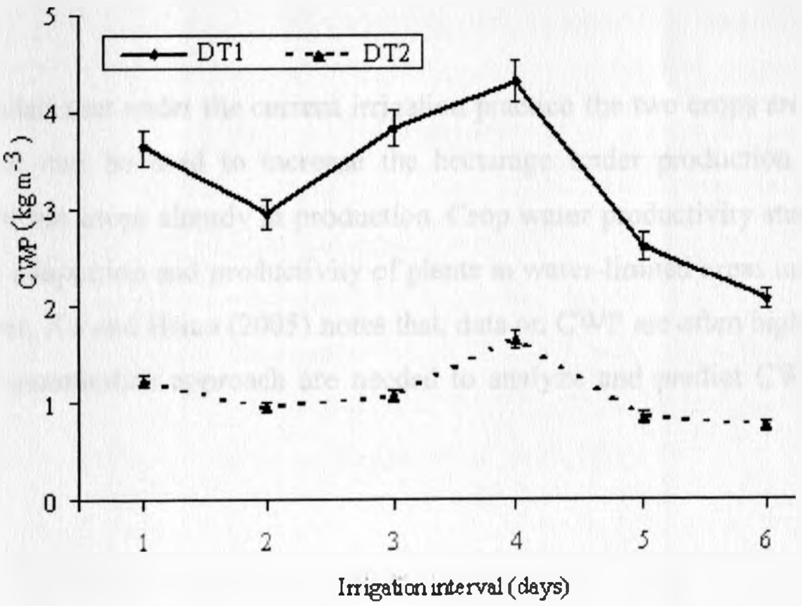


Figure 11: Crop water productivity of the first and second crop of tomato

Average seasonal actual crop evapotranspiration (ET) for tomato ranged from 534 to 768 mm and 478 to 788 mm for the first and second crop, respectively. The CWP ranged from 2.06 to 4.31 kg m^{-3} for the first and 0.76 to 1.65 kg m^{-3} for the second crop. The highest CWP value obtained was 4.31 and 1.65 kg m^{-3} for the treatment irrigated for 3 hrs, at an interval of 4 days with ET of 574 and 558 mm for the first and second crop, respectively. The CWP was weakly correlated with ET at $P \leq 0.05$ for the first and second crop. These results further illustrates that drip irrigated tomato for 3 hrs at an interval of 4 days is the most suitable irrigation schedule for the farm. The high CWP value indicates that water is well utilized.

In a study by Ramalan and Nwokeocha (2000) in which tomato received water in three irrigation schedules: 5-day interval, irrigation at 30 and 60 kPa soil moisture suction, yields of 38.01, 19.97 and 14.75 t ha^{-1} corresponding to ET of 685, 424 and 404 mm, respectively were obtained. Crop water productivity ranged between 5.55, 4.71 and 3.65 kg m^{-3} for the respective irrigation schedules. They concluded that the yield reduction and therefore CWP was associated with increased soil moisture tension, which when allowed to continue resulted in loss in turgidity, cessation of growth, yield reduction, and eventual death of the plant. Higher CWP values for tomato of 13.15 kg m^{-3} have been reported by Najafi and Tabatabaei (2007). The findings obtained in this study are therefore in agreement with those reported in literature.

It can be concluded that under the current irrigation practice the two crops are over irrigated. The water saved can be used to increase the hectarage under production, or enable the intensification of the crops already in production. Crop water productivity study is critical in determining the adaptation and productivity of plants in water-limited areas under the present climate. However, Xu and Hsiao (2005) notes that, data on CWP are often highly variable and a unifying and quantitative approach are needed to analyze and predict CWP for different environments.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

- During the study period rain was received in November- December and in March-April, with a total of 321 mm being received during the seven months study period. Mean daily maximum temperatures ranged from 34.83 to 39.6 °C, while minimum temperatures ranged from 15.4 to 19.4 °C. The little rain received in November–January and in March-April created favourable conditions for occurrence of bacterial spot disease in the second crop of tomato which adversely affected the yields of the crop.

- From the study on seasonal crop water requirement ET_{crop}, sweet corn required most water during the development stage, with the seasonal ET_{crop} averaging 143 mm/season. This stage accounted for 53 % of the total seasonal ET_{crop} of 270 mm/season. For tomato, ET_{crop} was found to be highest during the development and the mid stage, averaging 284 mm/season, these stages accounted for 79 % of the average total seasonal ET_{crop} of 381 mm/season. Water deficit at this stage adversely affects the quality and yields of the crop.

- The current irrigation practices of an irrigation interval of 3 days for tomato under drip irrigation and 3 hrs of sprinkler irrigation of sweet corn irrespective of the growing season resulted in over irrigation. Both crops require shorter irrigation intervals or less water for optimum crop production. Sweet corn yielded an average of 11.15 t ha^{-1} with 5 % less water while, tomato yielded an average of 16.97 t ha^{-1} with 23 % less water from the current practice. The water saved can be used to increase the hectarage under production, or enable the intensification of the crops already in production.

- The average CWP for both crops of sweet corn, ranged from 1.23 to 2.34 kg m^{-3}. The highest CWP value obtained was 2.34 kg m^{-3} for treatment irrigated for 2.5 hrs at an interval of 3 days, with ET of 517 mm. The average tomato CWP ranged from 1.41 to 2.98 kg m^{-3}. The highest average CWP value obtained was 2.98 kg m^{-3} for treatment with irrigation interval of 4 days, with ET of 534 mm. The high CWP value indicates that water is well utilized.

5.2. Recommendations

- On KIP farm and in the surrounding area, various high value crops are grown for both export and local market. Some of the crops grown include; water melon, onion, banana, chilies, okra, brinjals and asian vegetables to name but a few. Hence, this study recommends that the CWP for these and other crops be investigated. These studies should aim at increasing their water productivity.

- In addition there are potential problems which can easily arise when farmers venture into irrigation without seriously considering some technical aspects such as those of soil salinity and raising water table. Such problems make land totally unproductive. This study therefore recommends that research work to be done specifically on the water characteristics in relation to its suitability for irrigation use, the soil characteristics and its suitability for irrigation, appropriate irrigation methods and long term effects of irrigation water on soil quality.

- By changing from rainfed agriculture to irrigated agriculture the farmer's annual operating expenditure on the farm is bound to increase. The study therefore recommends that a detailed study on the economics of water use and technical aspects of running different irrigation systems be undertaken. With this information farmers and irrigation planners can make wise decisions on the appropriate irrigation system to adopt and choose or recommend the most profitable crops to be grown.

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APPENDICES

Appendix 1: Representative soil profile description of Kibwezi soils under cultivation

General site information	
Soil classification	
FAO/UNESCO (1991):	Haplic lixisol
Geological formation:	Basement system rocks
Local petrography:	Gneisses
Physiography:	Upland
Macro relief, Slope:	Flat to very gently undulating, 1-2% Linear, regular
Micro relief:	None
Land use/ vegetation:	Cultivated under irrigation
Erosion:	Nil
General ground water Level:	Deep
Surface sealing/ Crusting/Cracking:	Slight to moderate sealing
Drainage class:	Well drained
Effective soil depth:	>130 cm

Soil profile description

AP	0 – 29 cm	Dark reddish brown (5YR 3/4) moist; sandy clay loam; moderate fine to medium subangular blocky; friable moist, sticky and plastic wet; Many very fine , fine and common medium to coarse pores; few fine roots; gradual, smooth transition to:
Bt1	29 - 65 cm	Dark reddish brown (2 5YR 3/6) moist ; sandy clay; moderate fine to medium subangular blocky; friable moist, slightly sticky and plastic wet Many fine , fine and common; medium to coarse pores ; no detectable cutans; few fine roots ; gradual. smooth transition to:
Bt2	61 – 95 cm	Red (10YR 4/8) moist; sandy clay; moderate fine to medium subangular blocky; friable moist, sticky and plastic wet; Many very fine and common medium to coarse pores; broken thick cutans possibly of clay with Iron oxides and hydroxides; few fine roots; diffuse smooth transition to:
Bt3	95 – 130 cm	Red (10YR 4/8) moist; sandy clay; moderate very fine to fine subangular blocky; friable moist , slightly sticky and plastic wet; many very fine, fine and common medium to coarse pores; patchy, thin cutans possibly of clay with Iron oxides and hydroxides; few fine roots
Remarks		Fine sandy grains in all horizons Charcoal pieces were observed throughout the profile The top soil was slightly compacted by machinery There were crop residues buried on the top horizon.

Source: Mwaura (1995)

Appendix 2: Guidelines for interpreting water quality for irrigation

Problems	Degrees of problems		
	No problem	Increasing problem	Severe problem
Salinity			
(Affects crop water availability) Ecw (dsm^{-1}0	<0.75	0.75-3.0	>3.0
Permeability (of water into the soil) Ecw (dsm^{-1})			
Adj.SAR	>0.5	0.5-0.2	<0.2
Montmorillonite			
Illite-vermiculite	<6.0	6.0-9.0	>9.0
Kaolinite-sesquioxide	<8.0	8.0-16.0	>16.0
	<16.0	16.0-24*	>24.0
Specific ion toxicity			
(affects sensitive plants)			
sodium (adj.SAR)*	<3.0	3.0-9.0	>9.0
Chloride (meql)*	<0.75	0.75-2.0	>2.0
Miscellaneous effects			
(affects susceptible plants)			
NO$^-$ –NO-N or NH-N (cmol(+) kg^{-1})	<0.5	5.0-30.0	>30.0
HCO$^-$ (cmol(+) kg^{-1}) [overhead sprinkling]	<1.5	1.5-8.5	>8.5
pH		Normal range of [6.5 - 8.4]	

Source: (FAO, 1985)

NB

*1 Lower limit, intermediate range and upper limit are used when Ecw < 0.4 dsm^{-1}; Ecw = 0.4 to 1.6 dsm^{-1} and Ecw > 1.6 dsm^{-1}

*2 Most tree crops and woody ornamental are sensitive to Na$^+$ and Cl^{-1}

When sprinkler irrigation is used on sensitive crops, Na$^+$ or Cl$^-$ in excess of 3.0 cmol(+) kg^{-1}) under certain conditions has resulted in excessive leaf absorption and crop damage.

Appendix 3: Agro-climatic zones of Makueni District, Kenya

Zone	r/EO*	Classification	Annual average rainfall (mm	Annual average potential evapo-transpiration (mm)	(Vegetation (altitude not exceeding 3,000m)	Potential for plant growth (assuming soil condition is unlimiting	Risk of crop failure
I	>80	Humid	1100-2700	1200-2000	Moist forest	Very high	Extremely low (0-1%)
II	65-80	Sub-humid	1000-1600	1300-2100	Moist and dry forest	High	Very low (1-5%)
III	50-65	Semi-humid	800-1400	1450-2200	Dry forest and moist woodland	High to medium	Fairly low (5-10%)
IV	40-50	Semi-humid to semi-arid	600-1100	1550-2200	Dry woodland and bush land	Medium	Low (10-25%)
V	25-40	Semi-arid	450-900	1650-2300	Bush land	Medium to low	High (25-75%)
VI	15-25	Arid	300-500	1900-2400	Bush land and shrub	Law	Very high (75-95%)
VII	<15	Very arid	150-300	2100-2500	Desert scrub	Very low	Extremely high (95-100%)

*r is annual average rainfall in mm; EO is potential annual average evaporation in mm
Source: Sombroek and Braun (1980)

Appendix 4: Length of growing days as calculated from planting and harvesting dates for the two growing periods of the sweet corn and tomato

Crop	Date of planting	Date of harvesting	Length of growing days
First crop of sweet corn	3/12/98	15/2/99	74
Second crop of sweet corn	19/1/99	13/4/99	75
First crop of tomato	3/10/98	2/2/99	122
Second crop of tomato	9/1/99	26/4/99	107

Appendix 5a: Amount of water (mm) in 0-39 cm soil profile for the six treatments at each sampling date for the first crop of sweet corn

Date	Treatments					
	ST1	ST2	ST3	ST4	ST5	ST6
18/12/98	33.15	33.15	32.96	33.15	24.49	23.48
22/12/98	33.15	33.15	33.15	33.15	33.15	23.48
26/12/98	27.77	23.60	23.44	23.48	23.48	23.48
30/12/98	28.28	27.61	27.61	23.44	23.44	23.40
3/1/99	26.01	26.05	24.96	23.48	23.44	23.48
7/1/99	27.69	26.05	26.09	23.56	23.48	23.40
11/1/99	28.08	24.10	23.44	23.48	23.48	23.36
15/1/99	27.61	24.06	23.44	23.44	23.48	23.44
19/1/99	27.57	24.96	23.67	23.56	23.44	23.44
23/1/99	27.61	24.84	23.48	23.56	23.48	23.44
27/1/99	26.01	24.10	23.67	23.44	23.52	23.52
31/1/99	27.61	26.05	23.56	23.71	23.52	23.44
4/2/99	27.61	26.01	23.67	23.56	23.48	23.44
8/2/99	26.01	12.87	23.56	23.44	23.36	23.40
12/2/99	27.61	24.06	23.44	23.52	23.40	23.36
15/2/99	27.61	26.05	23.71	23.60	23.40	23.36
ΔS	449.40	406.73	403.85	395.54	386.02	374.91

Appendix 5b: Amount of water (mm) in 0-39 cm soil profile for the six treatments at each sampling date for the second crop of sweet corn

Date	Treatments					
	ST1	ST2	ST3	ST4	ST5	ST6
13/2/99	29.84	28.67	33.35	29.84	28.08	28.67
17/2/99	27.57	23.67	23.48	23.56	23.56	23.52
21/2/99	27.61	23.60	23.44	23.44	23.52	23.48
25/2/99	27.57	23.60	23.44	23.56	23.52	23.44
29/2/99	27.61	24.06	23.44	23.44	23.44	23.40
2/3/99	26.01	23.36	23.56	23.52	23.48	23.44
6/3/99	27.57	23.48	23.60	23.52	23.48	23.36
10/3/99	27.69	23.71	23.44	23.44	23.44	23.36
22/3/99	28.86	28.67	27.11	28.67	27.11	24.96
26/3/99	27.69	23.60	29.72	23.60	23.48	23.48
30/3/99	27.69	23.71	23.67	23.71	23.60	23.52
3/4/99	26.01	23.67	23.48	23.52	27.92	23.36
7/4/99	27.61	23.71	23.56	23.52	23.48	23.36
11/4/99	27.61	24.06	23.48	23.52	23.56	23.36
13/4/99	23.56	23.79	23.40	23.32	23.36	23.28
ΔS	484.61	439.45	445.85	440.58	438.71	431.69

Appendix 6a: Amount of water (mm) in 0-39 cm soil profile for the six treatments at each sampling date for the first crop of tomato

Date	Treatments					
	DT1	DT2	DT3	DT4	DT5	DT6
3/11/98	38.60	27.60	0.00	0.00	0.00	0.00
4/11/98	38.60	0.00	27.70	0.00	0.00	0.00
5/11/98	38.60	30.00	0.00	31.00	0.00	0.00
6/11/98	38.60	0.00	0.00	0.00	23.60	0.00
9/11/98	37.40	0.00	0.00	0.00	0.00	0.00
10/11/98	38.60	30.00	0.00	23.80	0.00	0.00
11/11/98	38.60	0.00	30.00	0.00	0.00	0.00
12/11/98	39.00	30.00	0.00	0.00	23.50	0.00
13/11/98	38.60	0.00	0.00	0.00	0.00	0.00
14/11/98	38.20	27.60	30.00	23.80	0.00	23.40
16/11/98	39.00	0.00	0.00	0.00	0.00	0.00
17/11/98	39.00	27.60	0.00	0.00	0.00	0.00
20/11/98	39.00	0.00	0.00	0.00	0.00	0.00
21/11/98	38.60	27.00	30.00	0.00	0.00	26.10
23/11/98	38.60	0.00	0.00	0.00	0.00	0.00
28/11/98	38.60	37.40	38.60	38.60	0.00	27.70
3/12/98	39.00	27.60	0.00	27.70	0.00	0.00
4/12/98	38.60	0.00	0.00	0.00	0.00	0.00
5/12/98	38.20	30.00	25.00	0.00	23.80	23.50
8/12/98	38.60	29.10	0.00	23.60	0.00	0.00
9/12/98	39.00	0.00	30.00	0.00	0.00	0.00
10/12/98	38.60	26.00	0.00	0.00	0.00	0.00
11/12/98	37.10	0.00	0.00	0.00	27.70	0.00
12/12/98	38.20	27.60	27.60	23.70	0.00	11.90
14/12/98	37.40	0.00	0.00	0.00	0.00	0.00
15/12/98	38.60	27.70	0.00	0.00	0.00	0.00
16/12/98	38.20	0.00	27.70	0.00	0.00	0.00

17/12/98	38.60	27.60	0.00	23.80	23.60	0.00
18/12/98	38.60	0.00	0.00	0.00	0.00	0.00
19/12/98	38.60	27.70	30.00	0.00	0.00	23.50
22/12/98	39.00	30.00	0.00	27.70	0.00	0.00
23/12/98	38.60	0.00	30.40	0.00	23.80	0.00
24/12/98	38.60	27.70	0.00	0.00	0.00	0.00
25/12/98	37.10	0.00	0.00	0.00	0.00	0.00
26/12/98	38.60	27.60	27.70	24.20	0.00	23.60
28/12/98	38.60	0.00	0.00	0.00	0.00	0.00
30/12/98	38.60	0.00	32.20	0.00	0.00	0.00
31/12/98	37.10	28.10	0.00	30.90	0.00	0.00
1/1/99	38.60	0.00	0.00	0.00	0.00	0.00
2/1/99	39.00	27.70	25.00	0.00	0.00	23.60
4/1/99	38.60	0.00	0.00	0.00	27.70	0.00
5/1/99	37.40	27.40	0.00	28.70	0.00	0.00
6/1/99	38.60	0.00	25.00	0.00	0.00	0.00
7/1/99	37.10	26.10	0.00	0.00	0.00	0.00
8/1/99	38.60	0.00	0.00	0.00	0.00	0.00
11/1/99	38.60	0.00	0.00	0.00	0.00	0.00
12/1/99	38.20	27.60	0.00	0.00	0.00	0.00
13/1/99	38.60	0.00	26.10	0.00	0.00	0.00
14/1/99	37.10	25.90	0.00	26.10	0.00	0.00
15/1/99	38.60	0.00	0.00	0.00	23.80	0.00
16/1/99	38.60	25.90	26.10	0.00	0.00	23.60
18/1/99	38.60	0.00	0.00	0.00	0.00	0.00
19/1/99	38.20	27.70	0.00	23.60	0.00	0.00
20/1/99	33.90	0.00	26.10	0.00	0.00	0.00
21/2/99	39.00	27.60	0.00	0.00	23.70	0.00
22/1/99	38.20	0.00	0.00	0.00	0.00	0.00
23/1/99	37.10	27.60	27.10	25.00	0.00	23.50
25/1/99	38.60	0.00	0.00	0.00	0.00	0.00
26/1/99	38.20	27.70	0.00	0.00	0.00	0.00
ΔS (mm)	2260.80	844.90	542.00	402.20	221.20	230.20

Appendix 6b: Amount of water (mm) in 0-39 cm soil profile for the six treatments at each sampling date for the second crop of tomato

Date	Treatments					
	DT1	DT2	DT3	DT4	DT5	DT6
9/2/99	38.61	27.57	0.00	0.00	0.00	0.00
10/2/99	38.61	0.00	23.56	0.00	0.00	0.00
11/2/99	39.00	27.57	0.00	23.48	0.00	0.00
12/2/99	37.44	0.00	0.00	0.00	23.56	0.00
13/2/99	38.61	26.01	23.44	0.00	0.00	23.44
15/2/99	38.61	0.00	0.00	0.00	0.00	0.00
16/2/99	39.00	26.05	0.00	23.40	0.00	0.00
17/2/99	38.61	0.00	23.48	0.00	0.00	0.00
18/2/99	39.00	27.57	0.00	0.00	23.40	0.00
19/2/99	39.00	0.00	0.00	0.00	0.00	0.00
20/2/99	38.61	26.01	23.44	23.52	0.00	30.03
22/2/99	38.61	0.00	0.00	0.00	0.00	0.00
23/2/99	37.83	27.69	0.00	0.00	0.00	0.00
24/2/99	38.61	0.00	23.40	0.00	23.44	0.00
25/2/99	37.44	26.13	0.00	23.56	0.00	0.00
26/2/99	38.61	0.00	0.00	0.00	0.00	0.00
27/2/99	38.61	24.96	23.44	0.00	0.00	23.44
1/3/99	38.61	0.00	0.00	0.00	0.00	0.00
2/3/99	37.83	26.01	0.00	23.36	23.44	0.00
3/3/99	38.61	0.00	23.56	0.00	0.00	0.00
4/3/99	37.83	27.69	0.00	0.00	0.00	0.00
5/3/99	38.61	0.00	0.00	0.00	0.00	0.00
6/3/99	37.83	27.61	23.71	23.56	0.00	23.44
8/3/99	38.61	0.00	0.00	0.00	23.52	0.00
9/3/99	37.83	26.05	0.00	0.00	0.00	0.00
10/3/99	38.61	0.00	23.71	0.00	0.00	0.00
12/3/99	39.00	0.00	0.00	0.00	0.00	0.00

13/3/99	38.61	28.08	28.86	0.00	27.69	25.70
15/3/99	38.61	0.00	0.00	0.00	0.00	0.00
17/3/99	37.44	0.00	28.86	0.00	0.00	0.00
20/3/99	38.61	26.09	28.86	37.44	0.00	29.84
22/3/99	38.61	0.00	0.00	0.00	0.00	0.00
23/3/99	38.61	26.09	0.00	0.00	0.00	0.00
24/3/99	37.83	0.00	23.48	0.00	23.32	0.00
25/3/99	39.00	26.13	0.00	26.05	0.00	0.00
27/3/99	38.61	29.99	27.73	0.00	0.00	29.84
29/3/99	38.61	0.00	0.00	0.00	0.00	0.00
30/3/99	37.44	25.04	0.00	23.48	32.18	0.00
31/3/99	38.61	0.00	23.48	0.00	0.00	0.00
1/4/99	38.61	25.04	0.00	0.00	0.00	0.00
2/4/99	38.61	0.00	0.00	0.00	0.00	0.00
3/4/99	39.00	25.04	23.44	24.06	0.00	23.44
5/4/99	39.00	0.00	0.00	0.00	23.56	0.00
6/4/99	33.93	26.05	0.00	0.00	0.00	0.00
7/4/99	37.05	0.00	23.52	0.00	0.00	0.00
8/4/99	38.22	25.00	0.00	23.52	0.00	0.00
9/4/99	37.05	0.00	0.00	0.00	0.00	0.00
10/4/99	38.61	24.10	23.48	0.00	23.44	23.44
12/4/99	38.61	0.00	0.00	0.00	0.00	0.00
13/4/99	37.44	27.65	0.00	23.36	0.00	0.00
14/4/99	38.61	0.00	23.48	0.00	0.00	0.00
15/4/99	38.61	25.04	0.00	0.00	0.00	0.00
16/4/99	33.93	0.00	0.00	0.00	23.56	0.00
17/4/99	38.61	27.65	23.44	23.44	0.00	23.52
19/4/99	38.61	0.00	0.00	0.00	0.00	0.00
20/4/99	38.61	25.04	0.00	0.00	0.00	0.00
21/4/99	37.44	0.00	23.40	0.00	0.00	0.00
22/4/99	38.61	27.65	0.00	23.48	23.56	0.00
23/4/99	38.22	0.00	0.00	0.00	0.00	0.00
24/4/99	37.05	27.61	23.52	0.00	0.00	0.00
26/4/99	37.05	0.00	0.00	0.00	0.00	0.00
ΔS (mm)	2330.25	794.24	513.75	345.70	294.65	256.11

Appendix 7a: Yield of the first crop of tomato planted on 3/10/98

Date	Treatments																	
	PIDT1	P2DT1	P3DT1	PIDT2	P2DT2	P3DT2	PIDT3	P2DT3	P3DT3	PIDT4	P2DT4	P3DT4	PIDT5	P2DT5	P3DT5	PIDT6	P2DT6	P3DT6
28/12/98	0.2	1	0.1	0.5	3.5	1.5	0.8	4.5	0.5	1.5	0.2	6	0.1	1	0.2	7.5	3.5	2
30/12/98	0.5	0.5	0.5	3.5	3	3	1	0.3	0.3	1	0.5	6	0.2	1	0.3	1.5	0.1	1
4/1/99	1.5	3	2	14	10.5	6	9	9	2	5	2.5	12	1.5	4	3.5	8	0.5	4
6/1/99	2	2	2	16	9	5	6.5	10	2.5	2.5	6.5	15	2	3	3.5	7	0	7
8/1/99	1.5	3	2	13	10	4	7	29.5	2.5	5	2.5	6	2.5	3	7	5.5	4	13
11/1/99	6	8	10	0	0	0	21	0	0	16	8	24	6	0	7	0	16	0
13/1/99	0	0	0	41.5	38	36		23.5	22.5	0	0	10.5	0	10	0	11	10	26
15/1/99	18.5	26.5	14.5	0	0	0	44	0	0	27	36	0	22	25.5	38.5	0	0	0
18/1/99	23	17	24.5	38.5	45	37	27	55	25.5	31.5	30	24.5	31	23	31	42	13	37.5
21/1/99	8.5	13	18	28	25	18	26	22	14	23.5	16	12.5	20	15	21	27	8.5	14
25/1/99	44	36	47	30	39	55	71	66	42	44	52	34	51	35.5	56	26	22	14
27/1/99	51	35.5	40	8	11	20.5	19	10	13	55	52	4.5	0	0	0	0	0	0
2/2/99	41	54	77	40	34	33.5	35	32.5	39.5	73	79.5	16.5	0	0	0	0	0	0
Total(kg)	197.7	199.5	237.6	233	228	219.5	267.3	262.3	164.3	285	285.7	171.5	136.3	121	168	135.5	77.6	118.5
Ton/ha	19.77	19.95	23.76	23.3	22.8	21.95	26.73	26.23	16.43	28.5	28.57	17.15	13.63	12.1	16.8	13.55	7.76	11.85

Appendix 7b: Yield of the second crop of tomato planted on 9/1/99

Date	Treatments																	
	PIDT1	P2DT1	P3DT1	PIDT2	P2DT2	P3DT2	PIDT3	P2DT3	P3DT3	PIDT4	P2DT4	P3DT4	PIDT5	P2DT5	P3DT5	PIDT6	P2DT6	P3DT6
29/3/99	3	0	5	0	0	0	2.5	6	0	5.5	4	1.5	11.5	7.5	3	0	0	0
3/4/99	0	0	5.5	5	8	8.5	10	0	0	25	0	0	0	0	0	5	6	6
6/4/99	6	16	6	7	12.5	2	4	21	11	3	12	24	10	6	6	5	5	3
9/4/99	8	9	7.5	5	1	6.5	3	15		3	8	16	2.5	6.5	1.2	0	2	0
13/4/99	14	21	21	25	35	20	20.5	30.5	1	16	35	23.5	2	8	0	4	2	0
22/4/99	19	14	6	12	1.5	17	15	16	19	11	10	18	5	8	21	8	10	11
26/4/99	20	14	13	21	22	15	25	5	16	26.5	20	14	14	14	7	10	15	17
Total(kg)	70	74	64	75	80	69	80	93.5	47	90	89	97	45	50	38.2	32	40	37
Ton/ha	7	7.4	6.4	7.5	8	6.9	8	9.35	4.7	9	8.9	9.7	4.5	5	3.82	3.2	4	3.7

Appendix 8a: Fresh ear yield of the first crop of sweet corn planted on 3/12/98

Date	Treatments																	
	PIST1	P2ST1	P3ST1	PIST2	P2ST2	P3ST2	PIST3	P2ST3	P3ST3	PIST4	P2ST4	P3ST4	PIST5	P2ST5	P3ST5	PIST6	P2ST6	P3ST6
8/2/99	5	0	0	2	3.5	1.5	1.5	6.5	0	6.5	2	0	0	1.5	2	4	0	0
10/2/99	0	9	7.5	0	6.5	0	4	6.5	4	0	0	5.5	0	0	0	0	3	5
13/2/99	3.5	6	0	6	0	5	2.5	0	6	7	0	0	4	5.5	0	2	9	0
15/2/99	22.5	11	16.5	19	19	23.5	25	20	20	20	23	28.5	17	12	18	6.5	5	9
Total (kg)	31	26	24	27	29	30	33	33	30	33.5	25	34	21	19	20	12.5	17	14
Ton ha^{-1}	10.54	8.84	8.16	9.18	9.86	10.2	11.22	11.22	10.2	11.39	8.5	11.56	7.14	6.46	6.8	4.25	5.78	4.76

Appendix 8b: Fresh ear yield of the second crop of sweet corn planted on 19/1/99

Date	Treatments																	
	PIST1	P2ST1	P3ST1	PIST2	P2ST2	P3ST2	PIST3	P2ST3	P3ST3	PIST4	P2ST4	P3ST4	PIST5	P2ST5	P3ST5	PIST6	P2ST6	P3ST6
8/4/99	5	2	0	1.5	0	1.5	0	2	3.5	1	0	2	3	4	3	7	4	5.5
10/4/99	2	7	2	2	7	6	3	4	5	1	2.5	2	3	4	1.5	2	1	1.5
12/4/99	28	23	29	35.5	27	24	30.5	28	25	34	32.5	29.5	15	9	10	2.5	5.5	7
Total (kg)	35	32	31	39	34	31.5	33.5	34	33.5	36	35	33.5	21	17	14.5	11.5	10.5	14
Ton ha^{-1}	11.9	10.88	10.54	13.26	11.56	10.71	11.39	11.56	11.39	12.24	11.9	11.39	7.14	5.78	4.93	3.91	3.57	4.76

Appendix 9a: Total crop water use (ET), mean marketable fresh ear yield at harvest and crop water productivity (CWP) for sweet corn during the first and second period

Period	Treatment	Total water use (ET) (mm)	Fresh ear yield (ton ha^{-1})	CWP (kg m^{-3})
1st	ST1	284.01	4.08^{ab}	1.44
	ST2	294.07	5.95^{ab}	2.02
	ST3	436.31	11.84^{a}	2.71
	ST4	441.09	11.45^{a}	2.60
	ST5	456.99	11.84^{a}	2.59
	ST6	442.87	11.11^{a}	2.51
2nd	ST1	486.02	4.93^{ab}	1.01
	ST2	487.31	6.80^{ab}	1.40
	ST3	531.92	10.48^{a}	1.97
	ST4	592.45	10.88^{a}	1.84
	ST5	614.47	9.75^{a}	1.59
	ST6	585.10	9.18^{a}	1.57

(Means with the same letter superscript for each treatment are not significantly different at $p<0.05$ according the least Significant Difference)

Appendix 9b: Total crop water use (ET), mean marketable yield at harvest, and crop water productivity (CWP) for tomato during the first and second period

Period	Treatment	Total water use (ET) (mm)	Yield (ton ha^{-1})	CWP (kg m^{-3})
1st	DT1	581.17	21.16^{a}	3.64
	DT2	767.54	22.68^{a}	2.95
	DT3	603.98	23.13^{a}	3.83
	DT4	574.23	24.74^{a}	4.31
	DT5	543.19	14.18^{ab}	2.61
	DT6	534.22	11.02^{ab}	2.06
2nd	DT1	566.35	6.93^{a}	1.22
	DT2	787.97	7.47^{a}	0.95
	DT3	686.85	7.35^{a}	1.07
	DT4	558.10	9.20^{a}	1.65
	DT5	524.35	4.44^{ab}	0.85
	DT6	478.09	3.63^{ab}	0.76

(Means with the same letter superscript for each treatment are not significantly different at $p<0.05$ according to the least Significant Difference)

Appendix 10a: Analysis of variance yield of first crop of tomato

```
Variate: yield 1st crop of tomato
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
Treatment                   5      461.14       92.23     5.68  0.006
Residual                   12      194.77       16.23
Total                      17      655.91
```

Appendix 10b: Analysis of variance yield of second crop of tomato

```
Variate: yield 2nd crop of tomato
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
Treatment                   5      64.788      12.958    11.13  <.001
Residual                   12      13.967       1.164
Total                      17      78.755
```

Appendix 10c: Analysis of variance yield of first crop of sweet corn

```
Variate: yield
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
Treatment                   5    177.8362     35.5672    53.47  <.001
Residual                   12      7.9821      0.6652
Total                      17    185.8183
```

Appendix 10d: Analysis of variance yield of second crop of sweet corn

```
Variate: yield 2nd crop of sweet corn
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
treatment                   5     81.2283     16.2457    16.81  <.001
Residual                   12     11.5985      0.9665
Total                      17     92.8268
```

Appendix 10 e: Analysis of variance yield of tomato - first vs second crop

```
Variate: Yield tomato 1st vs 2nd season
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
Treatment                   1         30.         30.     0.01  0.924
Residual                    4      11684.       2921.
Total                       5      11714.
```

Appendix 10 f: Analysis of variance yield of sweet corn - first vs second crop

```
Variate: Yield sweet corn 1st vs 2nd season
Source of variation      d.f.        s.s.        m.s.     v.r.  F pr.
Treatment                   1       1.505       1.505     0.17  0.685
Residual                   10      86.307       8.631
Total                      11      87.812
```

Appendix 10g: Correlation coefficient (r) for ET against CWP and ET against yields for the crop of sweet corn and tomato across seasons

Season	Correlation coefficient (r) for ET against CWP	Correlation coefficient (r) for ET against yield
SW1	0.925	0.986
SW2	0.550	0.779
TMI	0.089	0.523
TM2	0.014	0.530

Significant r at $p < 0.05$

Appendix 10h: Correlation coefficient (r) for TI against yields for the crop of sweet corn and tomato across seasons

Season	Correlation coefficient (r) for TI against yield
TMI	0.394
TM2	0.285
SW1	0.960
SW2	0.734

Significant r at $p < 0.05$