EFFECTIVENESS OF DEFICIT IRRIGATION SCHEDULING ON CROP WATER USE EFFICIENCY- A CASE OF FRENCH BEANS IN NJORO NAKURU COUNTY-KENYA

SABRI JOSHUA LADO SILLA

A thesis Submitted to the Graduate School in partial fulfilment for the requirement of the Doctor of Philosophy Degree in Agricultural Engineering of Egerton University

EGERTON UNIVERSITY

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DECLARATION AND RECOMMENDATION

DECLARATION

I hereby declare that this thesis is entirely my original work with the exemption of such references and quotations that have been attributed to authors or sources. This thesis has never been submitted for any degree for examination here in Egerton or any other university.

Signature: ……………………………………. Date: …………………………………….
SABRI JOSHUA LADO
Reg No BD11/0454/14

RECOMMENDATION

This research Thesis is the candidate's original work and has been submitted for examination with our approval as official University supervisors.

Signature: …………………………. Date: …………………………
Dr. A. K. Karanja
Department of Agricultural Engineering
Egerton University

Signature: …………………………. Date: …………………………
Prof. Eng. J.O. Onyando
Department of Agricultural Engineering
Egerton University

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DEDICATION

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ABSTRACT

Producing enough food in Kenya to better feed people and generate adequate income for the farmers is a great challenge. This challenge is likely to intensity, with a population that is projected to increase to 66.3 million in 2030. Scarce water resources and growing competition for water will be reduce its availability for irrigation, which necessitating major changes in irrigation management and scheduling in order to increase the efficiency of use of water that is allocated to agriculture, one of the options that can be used to reduce the demand of irrigation water is deficit irrigation. Agriculture needs to increase its production with a small amount of available fresh water. Deficit irrigation is now widely been investigated as one of solution for this problem. Relatively few farmers are equipped to deal with it effectively In this study deficit irrigation was investigated to determine its effectiveness in meeting crop water requirement and saving water with minimum effect on yield. And relationship between crop yield and water supply was investigated. This research was conducted from June 2016 to March 2017 at the Agricultural Engineering department demonstration farm Egerton University, Nakuru, Kenya. The objective of the study was to investigate the effectiveness of deficit irrigation scheduling and water use efficiency of French bean (*Phaseolus Valgaris L*). The modified FAO Penman Montieth Method was used to calculate evaporation ETo using ETo calculator. Crop coefficients were used to calculate reference evapotranspiration (ETc), the water application levels were 100% of evapotranspiration (ETc), 80% of ETc, 60% of ETc, and 40% of ETc. Based on these irrigation levels, the experiment was laid out using complete randomize block design(CRBD) with six treatments and three replications. Three plants from the inner rows of each experimental unit were randomly selected and tagged for measurement of plant growth variables, which included; plant height, number of branches, leaf area, canopy cover, yield and above ground biomass. Data from the experiment was subjected to analysis of variance (ANOVA) using the GLM procedure of SAS. Data obtained from field experiment was used to calibrate and validate Aqua Crop model to simulate the crop growth. The deficit irrigation levels which were applied throughout the growing season of French beans had significantly ($P < 0.001$) affected plant height, number of branch , leaf area index and yield. From the results the highest yield was found in treatment 100 of % ETc (8680 kg/ha) while the lowest yield was found in treatment 40%ETc (3158 kg/ha). The highest and lowest crop water use efficiency (3.05 kg/m^3) and (2.44kg/m^3) respectively were found in 80% of ETc and 40%of ETc. Therefore in water scars areas irrigation levels for French beans can be reduced by 20% water requirement without much effecting on yield**.** The performance of Aqua crop model was good in simulation of final biomass, pod yield and canopy cover for non-stress treatments but it performed less in simulation biomass and pod yield of the treatments less than 60% of ETc (under the severe water stress throughout the season). The findings verify use of deficit irrigation at 80% in water scare areas with French beans such crop to adopting conditions.

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ABBREVIATIONS AND ACRONYMS

ASALs	Arid and Semi-Arid Lands
CC	Canopy Cover
CDC	Canopy Decline Coefficient
CGC	Canopy Growth Coefficient
CU	Uniformity Coefficient
CV	Coefficient of Variation
DI	Deficit Irrigation
DU	Distribution Uniformity
ETo	Reference Evapotranspiration
FAO	Food and Agricultural Organization
Fedd	Fadden
GIR	Gross Irrigation Requirement
GLM	Geo linear model
ha	Hectare
HI	Harvest Index
Kc	Crop Factor
Km	Kilometer
LGP	Length of Growing Period
LPDI	Low pressure Drip Irrigation
MAD	Maximum Allowable Depletion
mm	Millimeter
NIR	Net Irrigation Requirement
Qvar	Emitter Discharge Variation
CRPD	Complete Randomize Block Design
RMSE	Root Mean Squire Error
R^2	Coefficient of Determination
RAW	Readily Available Water
TAW	Total Available Water
WP	Water Productivity
WR	Water Requirement
USAID	Unite States of America for International Development
WUE	Water Use Efficiency

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

As population increases in the world, so is the need for food production. The world natural resources, under their normal climatic conditions have proved inadequate and thus the need for irrigation to increase food production for meeting the increasing demand. Irrigation is an agricultural technology of supplementing natural sources of water available for growth and production of crops (Ronald, 2011). Irrigation is needed where water from natural sources is inadequate (Woodhouse and Ganho, 2011). Irrigation can also be used to lengthen the crop-growing period thus, making it possible to widen the range of crops, which can be grown in a given area. The amount of water needed for irrigation, and the timing of its application depends on several climatic, soil, and crop factors.

Irrigation is considered the greatest user of water resources in the world, with 70% total withdrawals and over 80% of consumptive use (Geert *et al*., 2006). Water scarcity is not only due to physical constraints of fresh water resources, but also due to inefficient use and poor management (Woodhouse and Ganho, 2011). The increasing demand for water on one hand and the inefficient use of the some on the other hand, are likely to widen the gap between supply and demand in most parts of the world (Yang and Zenhnder, 2002). Furthermore, the increasing worldwide shortage of water and costs of irrigation have led to an emphasis on developing irrigation techniques that economize water use and maximize its use efficiency (Hess, 1996). As per capita water resources around the world are threatened by scarcity (degradation and decrease), it is important to farmers to improve their ability to produce more food with less water.

An important strategy to address the problem of inevitable water scarcity is to device better water management strategies, which can lead to increased water use productivity (Rockstrum *et al*., 2010). There is an urgent need to develop and adopt suitable water conservation measures. This should be taken as a major approach in the design of irrigation water distribution and management systems. It can be accomplished by improving water use efficiency through implementation of appropriate technologies. Adoption of modern water-saving technologies is often cited as the key to increasing water use efficiency while maintaining current levels of production (Cason and Uhlaner, 1991). With the increase of urbanization and industrialization, there is a corresponding increase in demand for water, thereby further reducing per capita water availability among the various fresh water users. Agricultural water demand could be met by increasing the effectiveness of irrigation. Water use efficiency is a major factor for identifying the best irrigation scheduling strategies and identifying the most appropriate supplemental irrigation method (Pereira *et al.,* 2002). Irrigation scheduling is a water management technique for determining the time to irrigate and how much water to apply per irrigation and is essential for the efficient use of water, energy, and other production inputs such as fertilizer (James, 1988).

Lack of proper irrigation scheduling decisions and appropriate evaluation of their performance and economic impacts at farm level are the main constraints for the adoption of efficient irrigation strategies (Boyer *et al.*, 2011). Irrigation scheduling can be approached from one of the two objectives. The first objective is to maximize yield per unit area. This objective is economically justified when water supplies are readily available and irrigation costs are low. The second objective is to maximize yield per unit of water applied (Hygen *et al*., 1995). This becomes necessary when irrigation water supply becomes more limited or as water costs increase in an area. The objective of maximizing yield per unit of water applied has led to the development of deficit irrigation concept. Deficit irrigation technique is an irrigation scheduling strategy in which only a fraction of seasonal net crop water requirement is achieved through applied irrigation water (English, 1990) and (Hisao *et al*,.2007) . This technique matches the level of irrigation, the amount of land and the crop mix, which maximizes the benefits of irrigation. Correct application of deficit irrigation requires the understanding of yield and economic impact of the reduction of harvested produce (Deumier and Peyremarte, 1996). According to Blum, (2009) where less water than required is to be applied during growing season, high yield can still be obtained by supplying the required amount of irrigation water during sensitive crop growth stage.

1.2 Statement of the Problem

Irrigated agriculture places the greatest demand on the world's fresh water resources. This demand is unsustainable considering the rapid increase of urbanization and industrialization, which are both ranked higher in priority than irrigated agriculture. Currently, there is inadequate information and knowledge on appropriate water management techniques and knowledge gaps exist on specific crop water requirements (amount and timing of irrigation) under local environmental conditions. Food insecurity in Kenya like in many other sub-Saharan African countries continues to loom. Water use by irrigated agriculture must be decreased to

33 present by the year 2025 (Rosegrant *et al*., 2002). Many of the existing irrigation systems do not use water efficiently thus prompting the need for the current study. The purpose of the current study therefore, was to determine the effectiveness of adopting efficient and economical irrigation water application techniques and developing water management technologies, which can be used in combination with an appropriate crop simulation model to maximize the benefits of irrigation while improving water use efficiency.

1.3 Objectives of the Study

1.3.1 Broad Objective:

To evaluate the effectiveness of deficit irrigation scheduling on crop water use efficiency of French beans in Njoro Nakuru County- Kenya.

1.3.2 Specific Objectives

i. To determine the effectiveness of deficit irrigation on French bean performance.
ii. To determine the water use efficiency of French beans under deficit irrigation.
iii. To calibrate and validate Aqua Crop model for simulating the yield of French bean.
iv. To determine the crop water production function for French beans using irrigation scheduling.

1.4 Research Questions

i. How effective is deficit irrigation on crop growth of French bean?
ii. How does deficit irrigation affect the water use efficiency of French beans?
iii. How does Aqua Crop Model be used to simulate yield and growth of French bean under deficit irrigation?
iv. How does the crop production function of the French beans change with deferent irrigation scheduling?

1.5 Justification of the Study

One of the most serious drawbacks to irrigation development, sustainability and expansion is the large quantities of water involved in the face of other competing higher priority water uses. Irrigation is however necessary for expanding the range of crops to be grown in arid and semi-arid lands (ASALs), for ensuring food security. Given that the total world fresh water resources are fixed, the current study was aimed at contributing towards the understanding of how the available limited water could be put to maximum use in sustaining the already established irrigation projects and bringing under irrigation, large tracks of land in marginal agricultural areas. The study also helps to demonstrate deficit irrigation scheduling as available technology under situations of shortage of available water during irrigation. Results of the study will be published and thus make valuable contribution to knowledge in the academic world.

1.6 Scope and Limitation of the Study

In this study, irrigation strategies (full and deficit irrigation) have been applied to optimize irrigation benefits. Four treatments 100%Etc, 80%ETc, 60%ETc and 40%ETc were used in objectives one, two and three. 20%ETc and 120%ETc plus first four were used in objective four. For irrigation water requirement historical data was used instead of soil water balance, for Aquacrop model yield biomass and canopy cover at the end of the seasons were used to validate the model. Field experiments were carried out under a rain shelter of size 10×22m and 2 m height under the climatic condition of Njoro Nakuru county Kenya. Duration of the experiments was three seasons. The test crop was French bean source variety from Amiran Company Kenya. French bean *(Phaseolus vulgaris L*) was chosen because it’s the most widely cultivated type of bean in Kenya, it is also considered the second most important crop after maize and it is a major export crop in Kenya and local consumption is gradually being adopted. For the experiment it takes three month maximum so it will make possible to grow three times a year. Fertilizers application and other agronomical practices were carried out on time so as not to affect the experimental results.

CHAPTER TWO
LITERATURE REVIEW

2.1 Crop Factors Affecting Irrigation Water Requirement

About 75 per cent of a physiologically active plant material is water Feddes, (1987) argues that water is required by the plant for such processes as metabolism, growth, structural support, photosynthesis and transport of products of photosynthesis and transpiration. The largest proportion of water required by the plant is used in the process of transpiration, which takes about 90 per cent of the total water quantity absorbed by the plant from the soil. The rate of transpiration is expressed by equation 2.1.

$$T = \frac{e_{leaf} - e_{air}}{r_{leaf} - r_{air}} \tag{2.1}$$

Where

T = transpiration rate

e_{leaf} = vapour pressure within the leaf

e_{air} = vapour pressure of air

r_{leaf} = resistance of vapour flow through the stomata

r_{air} = resistance of vapour flow through the air boundary layer around the leaf

Vapour pressure within the leaf, e_{leaf}, is equal to saturation vapour pressure for the temperatures within the leaf and usually exceeds the vapour pressure of the surrounding air, e_{air} (Gouttevin *et al.,* 2015). The plant absorbs water from the soil to replenish water lost through transpiration. Water moves through the soil into the roots and up the xylem vessels into the leaves due to differences in water potential between the leaf and the soil Jensen *et al*., (1990) stated that the movement of water from the soil into the roots due to water potential gradient between these two interfaces is passive absorption Taize and Zeiger, (2002) reported that The rate of this passive absorption is expressed by equation 2.2.

$$Q = \frac{\psi_{leaf} - \psi_{soil}}{r_{plant} - r_{soil}} \tag{2.2}$$

Where

Q = rate of flow

Ψ_{leaf} = water potential in the leaf

Ψ_{soil} = water potential in the soil

Ψ_{leaf} = $\psi_T + \psi_o$

ψ_T = turgor pressure within the leaf

ψ_o = osmotic pressure within the plant

r_{plant} = resistance to water movement into the roots, up the xylem, and into the leaf

r_{soil} = resistance of water movement in the soil

2.2 Soil Factors Affecting Irrigation

Research shows that soil acts as the reservoir for water needed by the plants. Water in the soil is stored in the interspaces between individual soil particles, also called voids. Water is held in these voids by combined adsorptive and capillary forces called matric forces. Matric forces have to be overcome to remove water from the soil. The minimum force required to remove water from the soil varies with the amount of water in the soil (Ritchie and Jonson, 1990). As the voids are filled with water and the soil approaches saturation the matric forces holding the water in the soil approach zero. Conversely, as the water content in the soil approaches zero, the matric forces approach negative infinity. A plot of soil water content versus the matrices forces required to extract the water from the soil is referred to as a soil-water characteristic curve. Two important water content levels on soil water characteristic curve have been defined relative to plant water availability and uptake. The field capacity, θ_{fc}, is the upper limit of soil water availability to plants on the soil water characteristic curve. Conversely, the permanent wilting point, θ_{pwp}, is the lower limit of soil water availability. The total amount of water available for plant uptake and use is that held between the soil field capacity and the permanent wilting point (Jensen *et al*., 1990) and is computed using the equation 2.3.

$$TAW = D_{rz}\left(\theta_{fc} - \theta_{pwp}\right) \times 10 \tag{2.3}$$

Where

TAW = total available water in soil (mm)

D_{rz} = depth of root zone (m)

θ_{fc} = volumetric water content at field capacity (%)

θ_{pwp} = volumetric water content at permanent wilting point (%)

Plants are theoretically able to obtain water from the soil whenever the water content exceeds θ_{pwp}. However, the rate of water uptake decreases as more and more water is removed from the soil. Soil water content between θ_{fc} and θ_c is called readily available water (RAW) and is computed by equation 2.4

$$RAW = D_{RZ}\left(\theta_{fc} - \theta_c\right)\times 10 \tag{2.4}$$

Where

RAW = readily available water in soil (mm)

θ_c = critical soil moisture content (mm)

Readily available water represents the amount of water in the soil managed by irrigation. The ratio of RAW to TAW is called maximum allowable depletion, MAD, and is computed using equation 2.5. This is the fraction of TAW that can be removed from the soil without affecting crop yield.

$$MAD = \frac{RAW}{TAW} \tag{2.5}$$

2.3 Climatic Factors Affecting Irrigation

Solar energy is required by the plant to withdraw water from the soil through transpiration. The most important climatic factors affecting transpiration include relative humidity, temperature, humidity of air carried to plant by the wind and the net radiation available to the plant (Allen, 1996), (Jones, 2013). Increasing the humidity of the air surrounding the leaf decreases the vapour pressure difference between the leaf and the surrounding air therefore reducing the rate of transpiration. The wind sweeps away any layer of water vapour accumulated around the leaf and either increases or decreases the transpiration rate. If the air around the leaf is replaced by warmer and/or dryer air, the transpiration rate increases. Conversely, if the wind brings cooler and/or humid air, the transpiration rate decreases. Radiation raises leaf temperature above that of the surrounding air and hence increases transpiration rate. The presence or absence of short wave radiation in light triggers the opening or closing of stomata respectively. Thus, stomata of most plants are open during the day and closed at night.

2.4 Evapotranspiration

Water is transferred to the atmosphere from the land surface by direct evaporation of solid and liquid water from the soil and plant surfaces, and by transpiration. Since these two processes involve evaporation and are not easily separated, they are combined and referred to as evapotranspiration (ET) (FAO, 2006). The water used consumptively by the crop exceeds ET by the amount of water used for other plant processes such as metabolism, transport of minerals, photosynthesis, structural, support and cell expansion. The difference between ET and consumptive use (CU) is very small, less than 1 per cent. Therefore, for all practical purposes, ET and CU are assumed to be equal. Evapotranspiration can be determined by either direct measurement or calculated from crop and climatic data. According to Howell *et al.*, (1991) lysimetric method is the most widely used direct technique for measuring evapotranspiration. It is based on the principle conservation of mass principle in a hydrological isolated soil-filled control tank called a lysimetric. Under irrigated management ET derived by this method can be computed from equation 2.6

$$ET = I + P_e - D_{rz}(\theta_f - \theta_i) \times 10 \tag{2.6}$$

Where

ET = evapotranspiration during time interval considered (mm)
I = irrigation application during the period (mm)
P_e = effective precipitation during the period (mm)
D_{rz} = depth of root zone below soil surface (m)
θ_f = volumetric soil water content at the end of the time interval being Considered vol (%)
θ_j = volumetric soil water content at the beginning of the time interval being considered vol (%)

Determination of ET by calculation from crop and climatic data has seen the development of several theoretical and empirical equations. These equations are used to estimate ET for crops in locations where measured ET data are not available (Allen *et al.*, 1998). They all involve equation 2.7 as follows:

$$ET_c = K_c \times ET_o \tag{2.7}$$

Where

ET_c = evapotranspiration for a specific crop for non-limiting water (mm)
ET_o = reference crop evapotranspiration (mm)
K_c = specific crop coefficient

Reference crop ET where the reference crop is grass has been defined as the ET 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 (Allen *et al*., 1988) ,(Chiew *et al*., 1995). Many different methods for estimating ET_o have been developed at different levels of sophistication depending upon the available database (Phene *et al*., 1996) and (Allen et al., 1988). Some of the methods require daily relative humidity, solar radiation, wind and temperature data, while others only require mean monthly temperatures. The methods may be classified as (1) aerodynamic, (2) energy balance, (3) combination, and (4) empirical methods. In selecting the most appropriate method to use, emphasis should be placed upon those, which have been calibrated and applied over a wide range of climatic conditions. The earliest form of the aerodynamic method was based on Dalton Law on evaporation (Chiew *et al.*, 1995). It combines information on vapour pressure deficit (i.e. difference in vapour pressure at the plant surface and that of air measured at some height above the plant) and a function of horizontal wind velocity to estimate ET. When vapour pressure gradient has been determined and water is readily available, ET is controlled by availability of energy for vaporizing the water.

In the energy balance method, the energy available for ET is the balance of the solar radiation reaching the earth's surface after subtracting heat flux to the soil, heat flux to the air, heat storage in the crops and photosynthetic requirements. Most of these components are either negligible or too difficult to evaluate (Jensen *et al.*, 1990). The most significant component among these is the heat flux to the air. In the energy-balance method, the net energy reaching the earth's surface has been partitioned into energy used in ET and energy used in heating the air. Bowen proposed the relationship between these two into what is now called the Bowen ratio. Both Aerodynamic and energy balance methods are limited to research situations because of the difficulties in the determination of the wind function, leaf temperature and the vapour pressure on the evaporating surface.

Penman, (1948) combined the aerodynamic and the energy balance methods to form a new method for computing ET, referred to as the combination, or the Penman method. Its primary attributes are that it is based on reasonable physical principles and therefore does not need the measurements of leaf temperature and the vapour pressure at the leaf surface or within the boundary layer surrounding the leaf as was the case with aerodynamic and energy balance methods. Since it was first formulated, Penman method has undergone several modifications. The different forms of the original Penman equation are based on the method used to evaluate net radiation (R_n) and the aerodynamic term (E_a). Difficulties in obtaining data needed for use with Penman equation led to the development of many simpler methods for estimating ET based on one or more of the basic weather parameters controlling ET (Allen *et al*., 1994). The most commonly used parameters are solar radiation, pan evaporation and air temperature (e.g. FAO modified Blaney Criddle shown in equation 2.8 below). These methods, also referred to as empirical methods, are more convenient to use but, they are not regarded as being as accurate as the Penman equations for periods less than 5 days. They are therefore used when all the data needed for a Penman-type equation is not available.

$$ET_O = a + b(p(0.46T_m + 8.13)) \tag{2.8}$$

Where:

ET_o = grass based reference crop ET. (mm/d)
P = per cent of annual sunshine during the month on daily basis
T_m = mean temperature. ^oC
a and b = climatic calibration coefficients

The specific crop coefficient K_c in equation 2.7 relates the actual rate at which the crop uses water ET_c to reference crop ET_o. K_c of a crop is determined experimentally and reflects the physiology of the crop, the degree of crop cover, the location where the data were collected and the method used to compute ET_o. Values of K_c for field and vegetable crops generally follow the sigmoid growth curve characteristic of the various growth stages, of a crop. Grass based reference values of Kc for various field and vegetable crops have been determined based on growth stage information. Four growth stages, the emergence, the development, the early maturity and the late maturity have been identified for most annual crops and their durations, tabulated in FAO irrigation and Drainage Paper No. 24 by Doorenbos, and Pruitt, (1977).

2.5 Irrigation Water Requirements

Diaz *et al*., (2007) have defined irrigation water requirement of a crop as the total amount of water that must be supplied by irrigation to a disease free crop, growing in a large field with adequate soil water and fertility and achieving full production potential under the given growing environment. Irrigation requirement includes water used for crop consumptive use, maintaining favourable salt balance within the root zone and overcoming non uniformity and inefficiencies of irrigation. Irrigation requirement (IR) can be computed when ET is known using equation 2.9.

$$IR = \left[\frac{ET_c - [\,P_e + LR + D_{rz}\left(\theta_i - \theta_f\right)\times 10\,]}{E_s}\right] \tag{2.9}$$

Where

IR = overall irrigation requirement for time interval under consideration (mm)

ET_c = evapotranspiration for the period under consideration (mm)

P_e = precipitation for same time interval under consideration (mm)

E_s = overall irrigation system efficiency (%)

LR = Leaching requirement (amount of water that must flow from the root zone to maintain favourable salt balance in root zone) mm.

2.5.1 Net Application Requirement (NAR)

Overall irrigation requirement can also be determined from net irrigation requirement, which is the quantity of water required to increase the moisture content in the effective root zone to the desired soil moisture level (FAO, 2002). It is calculated using equations (2.3) + (2.5)

$$NIR = MAD \times D_{rz}(\theta_{fc} - \theta_{pwp}) \times 10 \tag{2.10}$$

Where:

NIR = net application requirement (mm).

MAD = maximum allowable depletion (fraction).

D_{rz} = effective root zone depth (m).

$ø_{fc}$ = volumetric moisture content of field capacity moisture level vol(%)

$ø_{pwp}$ = volumetric moisture content of soil at permanent wilting point moisture level vol(%)

2.5.2 Gross Irrigation Requirement (GIR)

This is the total amount of water applied for crop growth throughout irrigation (Martin and Gilly, 1993). It is computed using equation below:

$$GIR = \frac{NIR}{E_s} = \frac{MAD \times D_{rz}(\theta_{fc} - \theta_{pwp}) \times 10}{E_s} \tag{2.11}$$

Where:

GIR = gross irrigation requirement water (mm)

NIR = net irrigation requirement water (mm) and

E_s = irrigation system efficiency (%)

2.5.3 The Irrigation Interval

The irrigation interval is the number of days between two consecutive irrigation events. It is computed using equation 2.12

$$I = \frac{NIR}{ET_c} \qquad (2.12)$$

Where:

I = irrigation interval (days) and

NIR = Net irrigation requirement (mm)

ET_c = average evapotranspiration rate of the crop (mm/day)

2.6 Performance of Irrigation Systems

Farm irrigation systems are designed to supply the desired irrigation requirement of each field on the farm while controlling deep percolation, runoff, evaporation and operational losses. The performance of a farm irrigation system is determined by the efficiency with which water is diverted, conveyed and applied, and by the adequacy and uniformity of application in each field on the farm.

2.6.1 Irrigation Efficiency

The overall efficiency of a farm irrigation system is the fraction of water supplied to the farm that is beneficially used for irrigation on the farm expressed in per cent (Solomon, 1988). Overall system efficiency also called irrigation efficiency is computed using equation 2.13.

$$E_s = 100\left(\frac{(S - DP - RO - O)}{S}\right) \qquad (2.13)$$

Where

E_s = irrigation system efficiency (%)

S = amount of water supplied to the farm (m^3)

DP = total deep percolation on the farm (m^3)

RO = total runoff from the farm (m^3)

O = operation losses due to planned and/or accidental spillage from open channels and pipelines (m^3)

When evaluating the performance of farm irrigation systems, it is useful to examine the efficiency of each system component. This allows for components that are not performing, to be identified. Important components, which are often evaluated, are conveyance and the application systems. The overall system efficiency is considered a product of individual component efficiencies as shown in equation 2.14

$$E_s = 100\left(\frac{E_c}{100}\right)\left(\frac{E_a}{100}\right) \tag{2.14}$$

Where

E_s = irrigation efficiency (%)
E_c = conveyance efficiency (%)
E_a = application efficiency (%)

2.6.2 Conveyance Efficiency

This is the ratio in percent of the quantity of water delivered by a conveyance system to the quantity delivered to the conveyance system. It is computed with equation 2.15.

$$E_c = 100\left(\frac{V_{co}}{V_{ci}}\right) \tag{2.15}$$

Where

E_c = conveyance efficiency (%)
V_{co} = volume of water out of conveyance system (m^3)
V_{ci} = volume of water into conveyance system (m^3)

2.6.3 Application Efficiency

Water application efficiency for an irrigated area (E_a) is the ratio, expressed as a percent of the volume of water beneficially used by the crop to the volume of water delivered to the area. Application efficiency can be computed for each field of the farm or for the entire farm. Application efficiency is computed using equation 2.16

$$E_a = 100\left(\frac{V_{bu}}{V_a}\right) = 100\left(\frac{I + L}{I_g}\right) \tag{2.16}$$

Where

E_a = application efficiency (%)

V_a = volume of water applied in the field (m^3)

V_{bu} = volume of water beneficially used by the crop(s) in the field (m^3)

I = net application requirement for the field (mm)

L = leaching requirement for the field (mm)

I_g = gross application requirement (mm)

2.6.4 Application Uniformity

The uniformity of application describes how evenly an application system distributes water over a field. Uniformity of application is evaluated using the Christiansen's uniformity coefficient (C_U) (Napier *et al.*, 1983) and (Solomon, 1983). C_u is computed using equation 2.17

$$C_u = 100\left(1.00 - \frac{\sum \left[\left|X_i - \overline{X}\right|\right]}{n\overline{X}}\right) \tag{2.17}$$

where

C_u = Christiansen uniformity coefficient (per cent)

X_i = depth caught/infiltrated at observation point i.(mm)

$\overline{X}$ = average depth caught/infiltrated (mm)

n = number of observation points

The coefficient C_u for the sprinkler system is often evaluated using a grid of catch cans. The volume in each can is divided by the area of the can opening to calculate the depth of catch. When catch cans are not used or when the uniformity of surface application methods is being considered, the amount of infiltration at each observation point is used (rather than catch cans) to compute C_u. For trickle system, the volume of water discharged in a specified interval of time at several emission device locations is used. When numerous observation points are being utilized to evaluate sprinkler or trickle system uniformity and the distribution pattern is nearly normal, and C_u can be estimated using equation 2.18

$$C_u = 100 - 80.0\frac{S}{\overline{X}} \tag{2.18}$$

Where

S = standard deviation of the observations

$\overline{X}$ = average depth caught/infiltrated (mm)

The above equation is not recommended for use with surface systems since their wetting patterns are rarely normally distributed. Distribution uniformity (Du) is another index of application uniformity. Du is the ratio, expressed in the percent, of the average low-quarter amount caught/infiltrated to the average amount caught/infiltrated and it is computed using equation 2.19.

$$D_u = 100 \frac{\overline{X}_{LQ}}{\overline{X}} \tag{2.19}$$

Where:

D_u = distribution uniformity (%)

$\overline{X}_{LQ}$ = low-quarter average depth amount caught/infiltrated (mm)

$\overline{X}$ = overall average depth caught/infiltrated (mm)

2.6.5 Adequacy of Irrigation

The adequacy of irrigation is the per cent of the field receiving sufficient water to maintain the quantity and quality of crop production at a “profitable” level (Keller and Bliesner, 1990). Since this definition requires crop, soil, and market conditions to be specified, the adequacy is normally defined to be the percentage of the field (farm) receiving the desired amount of water or more. The adequacy of irrigation is evaluated using a cumulated frequency distribution. This shows the percentage of the field (farm) receiving a specified amount of water or more. Cumulative frequency distribution patterns are constructed by determining the amount of water caught/infiltrated at locations around the field (farm) and the total area represented by each location. The amounts are then arranged in descending order and the percentage of the field (farm) receiving each amount or more is computed. These values are then plotted. Amount caught/infiltrated on the y-axis and the percent of field area on the x-axis. When the desired depth of irrigation fills the soil to field capacity, the term Storage Efficiency (E_s) is often used as an index of adequacy. Soil storage efficiency is calculated using equation 2.20

$$E_s = 100\left(\frac{S_{rz}}{S_{fc}}\right) \tag{2.20}$$

Where

E_s = soil storage efficiency (per cent)

S_{rz} = amount of water stored in the root zone during irrigation (mm)

S_{fc} = amount of water required to fill the root zone to field capacity (mm)

2.6.6 Effectiveness of Irrigation

Effectiveness is a term used to qualitatively describe the application efficiency, uniformity and adequacy of irrigation (Solomon, 1990). The desired effectiveness of irrigation (i.e. the desired combination of efficiency, uniformity, and adequacy) maximizes the net farm profit. Irrigations with highest application efficiencies, uniformities and adequacies are not always desirable since they do not always maximize net farm profit. An understanding of the relationship between application efficiency, uniformity and adequacy is needed to identify irrigation systems and strategies that maximize net farm profit. There are several alternative irrigation system types and configurations, which will satisfactorily meet the above requirements. Identification of the most appropriate system for a given situation begins with the selection of the application method. The primary application methods are the Surface (gravity), Sprinkler (overhead) and Trickle (drip)

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2.7 Irrigation Application Methods

The primary objective of irrigation is to supplement or substitute for natural rain in order to increase crop production (Burt *et al*., 1992). Irrigation systems must therefore be designed to meet crop water requirement during the peak period to avoid crop water stress. Depth of water to be applied is dependent on crop water use rate, water-holding capacity of the soil root zone depth, and the management allowed depletion (MAD). The design and operation of efficient irrigation systems require the knowledge of the factors and processes controlling the movement and storage of water in the soil (Merriam and Keller, 1978). The rate of application of irrigation water as well as the method of application is often dictated by the infiltration characteristics of the soil. Soil acts as a reservoir in which irrigation water is stored for uptake by the plants. The final design of any irrigation system must balance the physical and biological requirements of the system with, reasonable economic cost and convenience to the operator. Considerations must be given to the labour requirement and accessibility, initial cost of equipment and installation, operation cost and annual maintenance cost.

2.7.1 Sprinkler Irrigation System

A sprinkler system comprises of a pressurized water source in form of an elevated supply or an output pressure of a pump, a mainline and sub-mains to convey water from the pressurized source to the field. A lateral line to deliver water to the application devices and sprinklers which are the application devices (Solomon, 1983). Sprinkler application rate depends on nozzle size, operating pressure and sprinkler spacing (Keller and Bliesner, 1990). The system must be designed to give maximum reasonable uniformity and minimize deep percolation losses. Uniformity is dependent on the velocity of the prevailing wind, sprinkler spacing and pressure variation along the lateral which on its part is dependent on the design criteria, land topography and pump selection. For many subsistence farmers, a standard pressurized system is too expensive and complicated. Pressurized systems are intended for large areas of land and therefore do not match the needs of small subsistence farming (Bustan and Pasternk, 2008).

2.7.2 Surface Irrigation Method

Surface irrigation includes all field application methods where water is distributed by means of open conduit flow under atmospheric pressure (Pereira *et al*., 1992). A surface irrigation system comprises of lined or unlined open channels or low-pressure pipelines, which convey water by gravity from a source to the fields. Surface irrigation is the most widely used application method accounting for 230 million hectares or close to 90 per cent of the total irrigated area globally. It generally requires a smaller initial investment compared to other irrigation methods except, when extensive land smoothing is needed. It is however, more labour intensive and applies water less efficiently than other irrigation systems.

The primary methods for applying water by surface systems are basins, borders and furrows. The engineering design procedures for surface irrigation are relatively simple. However, they all require high-level skill and experience on the part of the design engineer and the farmer, to operate them efficiently (Phocaides, 2007). Surface irrigation systems are best suited to soils of low to moderate infiltration capacities and lands with relatively uniform terrain and slopes less than 2 to 3 per cent (Morgan, 2009). The components of a typical surface irrigation system include; the unit for diverting water from the source to the conveyance system, the conveyance unit comprising of a network of open channels and/or closed conduits, which conveys water from the point of diversion to the farm or groups of farms and distribute it within the farm. There is also the application unit, which applies water delivered to the farm over irrigated fields into the soil and the disposal system that drains excess or unused surface or subsoil water. Both border and basin application methods are best suited to closely spaced crops. Furrow application method on the other hand, is ideal for row crops. However, varying soil infiltration and resistance to water flow over the soil surface hamper the even distribution of water in furrows (Hoffman *et al.,* 2007).

2.7.3 Drip Irrigation System

Drip irrigation is a type of trickle irrigation method. It refers to a method of application where water is applied slowly drop by drop but frequently, directly into the vicinity of the root zone of the crop, wetting only a very limited fraction of the total surface area and depth of the soil. The soil factors are thus less important in deciding the frequency of irrigation. Deep percolation losses can be completely prevented and the evaporation loss reduced under drip system is based on two fundamental concepts (Edstrom and Schwanki, 1998):

i. Irrigating only the root zone area of the crop rather than the entire land surface
ii. Maintaining the water content in the root zone at near optimum levels

It is accomplished by use of pressures ranging from 15 to 200 kPa (1.5 to 20 m head of water) to drip water one-drop-at-a-time onto the land or into the root zone depth. The selection of drip irrigation system is favoured by the production of high value root crops, limited, expensive or saline water supply, need for precise application in both location and amount in order to minimize drainage and manage salinity and the need to maintain above ground portions of the plant dry, so as to control bacteria, fungi and other pests and diseases (Phociades, 2000). The use of drip irrigation is hampered by the presence in water of high concentrations of particulate matter and chemical and/or biological materials that may clog the system components thus, making it both difficult and very expensive. Drip irrigation system is adaptable to most crops, soils and terrains (Hanson *et al.*, 1997).

Drip irrigation systems consist of three components. The control unit, the distribution unit and the application unit. The control unit comprises of the pumping set with its prime mover, a chemical mixing facility with its regulators, metering devices, and a primary filter for cleaning the suspended materials from water to avoid clogging of nozzles and emitters. The distribution unit comprises of the main pipe, the sub-mains, the manifold and the laterals or drip lines, which are spread on fields in rows and fitted with drip emitters. In closely spaced crop, the emitters may be at intervals of 30 centimetres or less. The spacing between laterals depends on the row-to-row spacing of the crop (Sharma, 1985). Drip systems commonly use low flow rates and low pressures at the emitters and are typically designed to only wet the root zone and maintain this zone at or near optimum moisture level (James, 1988). Advantages of drip irrigation include a smaller wetted surface area, minimal evaporation, reduction of weed growth and potentially improved water application uniformity within the crop root zone due to better control of water application (Hoffman and Martin, 1993). Low- pressure drip irrigation (LPDI) systems have been developed for smaller farming areas. LPDI systems work with gravity head as no outside power source is needed for low-pressure operation. This leads to reduction in initial cost. A complete drip irrigation unit operating from a tank placed 1 – 1.5 meters high by gravity, can generate a flow of about 1m^3 /h (Phocaides , 2007).

The drip irrigation system design is usually the second stage in irrigation planning. The first stage being the consideration of the crop water requirement, the type of soil, the climate, the available water quantity and quality, the irrigation water delivery and supply conditions, the availability of electricity and the irrigated land topography (Megh, 2012). The economic considerations, the labour and the technical expertise also need to be taken into account (Phacaides, 2007). The performance of drip irrigation systems is heavily influenced by the uniformity of flow through each emitter along a drip line. The uniformity of drip irrigation systems is not only a function of the design characteristics but is also significantly affected by installation, maintenance and management practices. Therefore, measuring application uniformity in drip irrigation systems is an important component of performance evaluation and the assessment of the likely system longevity (Sadler *et al*., 1995).

Drip irrigation efficiency is a good measure of the effectiveness of the system in delivering water to a crop and its effectiveness in increasing crop yield (Pitts, 1997). The real efficiency of drip system can be evaluated by how it conforms to design specifications. This is a combination of engineering and hydraulic design aspects. Water use efficiency (WUE) incorporates the concepts of proper timing and duration of irrigation (management) and uniformity (design) but cannot place value directly on crop production. Application uniformity AU is affected by operating pressure, emitter spacing, land slope, pipeline size, emitter discharge rate and emitter variability (ASAE, 2001). Under most conditions the more uniformly the water is distributed the better will be the crop response.

2.8 Irrigation Scheduling

Irrigation scheduling is the process of determining when to irrigate and how much water to apply per irrigation. Proper irrigation scheduling is essential for the efficient use of water, energy and other production inputs, such as fertilizer (Pereira *et al*., 1992). Irrigation scheduling allows irrigation to be coordinated with other farming activities such as cultivation and chemical application. The benefits of irrigation scheduling include crop yield and/or quality improvement, water and energy conservation and lower production costs (Majumdar, 2012). Irrigation scheduling is approached from two different perspectives, to either fully or partially provide the irrigation requirement.

2.8.1 Full Irrigation Scheduling Strategy

Full irrigation involves providing the entire irrigation requirement and often results in maximum production. Full irrigation is economically justified when the water is readily available and irrigation costs are low (Solomon, 1987). It is accomplished by irrigating to minimize the occurrence of plant water stress. Under full irrigation scheduling strategy, all agronomical practices and inputs must be operated at yield optimizing levels and must be managed within limits conducive to maximum water productivity (i.e. the ratio of the mass of marketable yield to the volume of water applied to the crop). Improved water productivity means that there would be an increase in crop yield per unit amount of water used (Pereira *et al*., 2002). There is a need to know and supply the correct amount of water needed by the plants (plant water requirement). Therefore, there is a need to develop most suitable irrigation schedule to get optimum plant yield for different ecological regions as, plant water requirements depend mostly on plant growth, soil, and climatic conditions (Ertek *et al*., 2002).

2.8.2 Deficit Irrigation Scheduling Strategy

Deficit irrigation is partial supply of irrigation requirement. It can alternatively be defined as an agricultural water management system in which less than 100 per cent of actual crop water requirement is provided by a combination of stored water, rainfall and irrigation during the growing season (English, 1990). Before implementing deficit irrigation, it is necessary to know crop yield responses to water stress, either during defined growth stage or throughout the whole season (Kirda and Kanber, 1999). Deficit irrigation is economically justified when reducing water application below full irrigation causes production costs to decrease faster than the decline in revenue. Water application in deficit irrigation strategy is reduced to the level where the decrease in revenue due to an incremental reduction in water application equals the accompanying decline in production costs. This is the point of maximum net benefit. Therefore, correct application of deficit irrigation requires an understanding of yield response to water and economic impact of reductions in harvest. Deficit irrigation is used when the water supply or the irrigation system limit water availability. In such a situation, the level of irrigation, the amount of land to be irrigated and the crop mix that maximize the benefits of irrigation must be determined. Deficit irrigation is accomplished by allowing planned plant stress during one or more crop growth stages during the season. Adequate water is then supplied during critical growth stage to maximize water use efficiency (i.e. maximizes crop production per unit of water applied). In regions where water resources are limited, it is better for a farmer to increase crop water productivity instead of increasing the harvest per unit land (Fereres and Soriano, 2007). The saved water will be used for different purposes or to irrigate other extra units of land. Various studies have shown that, deficit irrigation might be one of the most promising irrigation water management strategies to economize scarce water supplies (Ali and Talukder, 2008; Blum 2009; Farre and Faci 2009; Fereres and Soriano, 2007). Under deficit irrigation scheduling strategy, less water than required can be applied during the growing period. Although this inevitably results in crop water stress and yield depression, high yield can still be obtained by supplying the amount of irrigation water that is needed during sensitive crop growth stages and restricting water during tolerant growth stages. Research in yield response to different water applications in the field and/or in controlled experiments has been found to be both laborious and expensive (Geerts and Raes, 2009). The challenge is to create a management system that will reduce the negative impact of the expected water stress to crop.

2.9 Methods of Irrigation Scheduling

There are several different methods for determining when to irrigate. These may be classified as direct methods, indirect methods and water budget techniques (Deumier *et al*., 1996). The direct methods include the plant and soil indicators. Using plant indicators is based on the premise that, since the primary objective of irrigation is to supply plants with the water they need, when they need it, then the plants are best placed to provide such information (Lundstrom and Stegman, 1995). Some of the parameters used in plant indicator methods include; appearance and growth of the plant, leaf temperatures, leaf water potential and stomatal resistance. The plant parameters should be integrated with soil water content in order as to determine the amount of water per irrigation (Raine, 1999).

2.9.1 Irrigation Scheduling by Gravimetric Sampling

Gravimetric sampling is a direct soil-based irrigation scheduling method (Hoffman *et al*., 2007). It involves determining the current water content of the soil and comparing it to predetermined minimum water content such as the critical soil water content, θ_c. Irrigation is carried out to maintain soil water content above the critical level. The critical water level for deficit irrigation schedules is often varied depending on the growth stage of the crop. Determination of when to irrigate by gravimetric sampling also provides data for estimating the amount of water to apply per irrigation. Effective and accurate scheduling, in order to maximize water use efficiency, is best achieved by physically monitoring the integrated soil, plant, and atmosphere. The procedure for gravimetric sampling involves taking soil samples from the field, weighing them, drying them at between 105 and 110°C, and reweighing after drying, to ensure the samples attain a constant weight. The gravimetric soil water content on a dry basis is computed using equation 2.21

$$\theta_w = \frac{W_w - W_d}{W_d} \times 100 \qquad (2.21)$$

Where

θ_w = gravimetric soil water content (or soil water content on dry weight basis) (%)

W_w = wet weight of the soil sample (g)

W_d = dry weight of the soil sample (g)

Soil water content on volume basis is computed using equation 2.22

$$\theta_v = \frac{V_w}{v_t} \times 100 \qquad (2.22)$$

Where

θ_v = soil water content on a volume basis (%)

V_t = total volume of soil solids, water, and voids (cm^3)

V_w = volume of water fraction in soil (cm^3)

The relationship between θ_w and θ_v is obtained by solving equation 2.23 for the weight of water ($W_w - W_d$) and taking into account that

$$V_w = \frac{W_w - W_d}{\rho g} = \frac{\theta_w W_d}{100} \qquad (2.23)$$

Where

ρ = density of water (g/cm^3)

g = acceleration due to gravity

Substituting the volume term back into equation 2.22 results in the equation 2.24

$$\theta_v = \frac{\theta_w W_d}{(100)\rho g V_t}(100) = \frac{\rho_b}{\rho}\theta_w = S_p \theta_w \qquad (2.24)$$

Where:

$$\rho_b = \frac{W_d}{gV_t} \tag{2.25}$$

where

ρ_b = bulk density of the soil (g/cm^3)

$$S_p = \frac{\rho_b}{\rho} \tag{2.26}$$

Where

S_p = apparent specific gravity of soil

Gravimetric sampling though simple and reliable is time consuming and involves repeated and continuous removal of soil from the field, which is destructive (Phene *et al*., 1989). Data from gravimetric sampling has a waiting period before it can be used for scheduling due to time taken while drying the samples. This has led to the development of other methods, which do not directly involve handling the soil. Instead, such methods exploit the relationship between soil water content and some other physical property. Indirect soil moisture measuring methods include tensiometric method, which uses the relationship between soil water content and soil water potential. Examples of other indirect methods, according to Phene and colleagues, (1989), are the gypsum blocks relating soil water content to electrical resistance, and neutron scattering method relating soil water content to the amount of hydrogen ion concentration in the soil.

2.9.2 Irrigation Scheduling by Water Budget Technique

The water budget technique for irrigation scheduling combines the soil indicator methods with climatic estimates of crop water requirement, ET$_c$ to determine when to irrigate (Camp *et al*., 1996). The soil water content at the end of the day is computed from equation 2.27.

$$SWC_i = SWC_{i-1} + P_{ei} + IR_i - ET_{ci} - DP_i \tag{2.27}$$

SWC_i = soil water content at day (i) (mm)

$SWC_{(i-1)}$ = soil water content at day (i-1) (mm)

P_{ei} = effective precipitation at day (i) (mm)

IR_i = irrigation at day (i) (mm)

ETc_i = crop evapotranspiration at day (i) (mm)

DP_i = deep percolation, water lost beyond the root zone at day (i) (mm)

The term ET_c is computed with equation 2.7 while ET_o is determined using one of the Penman type equations. The amount of water to apply once the time to irrigate has been determined is given by equation 2.28.

$$I_g = \frac{D_{rz}(\theta_f - \theta_i) \times 10}{E_a} \tag{2.28}$$

Where

I_g = gross application requirement (mm)

D_{rz} = root zone depth (m)

θ_f = volumetric soil water content after irrigation (%)

θ_i = volumetric soil water content prior to irrigation (%)

E_a = irrigation application efficiency (fraction)

2.10 Crop Growth Stages

Crop development during the growing period involves changes in ground cover, crop height and leaf area. The growing period for an annual crop can be divided into four distinct growth stages; initial, crop development, mid-season, and late season (Doorenbos and Pruitt, 1977; Allen *et al*., 1998). The initial stage covers the period between planting date and 10 per cent ground cover. The length of the initial period is highly dependent on the type of crop, the crop variety, the planting date and the climate. The end of the initial period is the time when approximately 10 per cent of the ground surface is covered by green vegetation (Ritchie and Jonson, 1990). The beginning of the initial stage for perennial crops is the time when initiation of new leaves occurs. The leaf area during the initial period is small and the evapotranspiration is predominantly in the form of evaporation.

The crop development stage is the time between 10 per cent ground cover and effective full cover. Effective full cover for many crops occurs at the initiation of flowering. For crops such as beans, the effective cover is defined as the time when some leaves of plants in adjacent rows begin to intermingle or when plants reach nearly full size. The occurrence of the effective cover is also estimated through leaf area index (LAI) when it reaches three. LAI is defined as the average area of leaves (one side) per unit area of ground surface.

The mid-season stage is the period of plant growth from effective cover to the end of maturity. The end of maturity is indicated by the beginning of aging, yellowing or senescence of leaves, leaf drop or browning of fruits to the degree that the crop evapotranspiration is reduced relative to reference ETo. The mid-season stage is longest for perennials but, for many annuals, it may be relatively short e.g. for vegetable crops that are harvested fresh for their green vegetation. The late season stage is the period of crop growth between end of maturity to harvest or full senescence. The late season stage is presumed to the end when the crop is harvested, dries out naturally, reaches full senescence or experiences leaf drop. The duration for the four distinct growth stages and the total growing period for selected crops have been presented in FAO Irrigation and Drainage Paper Nos. 24 and 56 by (Doorenbos and Pruitt,1977) and (Allen *et al*., 1998) respectively, for various types of climates and locations.

2.11 French Beans

French bean *(Phaseolus vulgaris L*) is the most widely cultivated type of bean in Kenya (Dorenbos and Kassm, 1979). It is also considered the second most important crop after maize. A French bean is a major export crop in Kenya and local consumption is gradually being adopted. French bean is popularly grown by both large and smallholder farmers. The common bean is an herbaceous annual plant grown worldwide for its edible dry seed (known as beans) or unripe fruit (green beans). Its leaf is also occasionally used as a vegetable, and its straw as fodder. The optimum temperature range for growing French beans is 20-25ºC, but can be grown in a temperature range between 14 and 32ºC. The crop matures faster in warmer areas. French bean can be grown between 1000 - 2100 meters above sea level. To maintain a continuous production especially during the dry season, irrigation is essential. French beans grow best on well-drained, silt loams to heavy clay soils high in organic matter with pH ranging from 6.5 – 7.5. Planting is done in single rows of spacing 30 by15 cm (one seed per hill) or in double rows 60 by30 by10 cm at a seed rate of 50-60 kg per hectare. Planting population density range between 150,000 – 200,000 plants/ ha. French beans are harvested before the pods are fully-grown. Harvest starts 7 to 8 weeks after sowing in early cultivars. Pods should be picked every 2 to 3 days.

2.12 Water Use Efficiency (WUE)

According to Lamers *et al*., (2008), water use efficiency refers to the ratio of water used in plant metabolism to water lost by the plant through transpiration. Water availability is the most important factor limiting crop growth, productivity and expansion of agriculture to environments where water is scarce (Molden *et al*., 2010). More efficient use of water, for both rain-fed and irrigated agriculture, is essential. Measures to improve water use efficiency include water conservation, reduction of irrigation water loss and adoption of cultural practices that enhance water use efficiency (Kijine *et al*., 2003). Water use efficiency is expressed as the amount of crop product (yields) per unit of crop water use. WUE for the crop can be determined by dividing the harvested crop yield by its seasonal evapotranspiration.

$$WUE = \frac{Yield\ \Pr oduced\ (kg)}{Seasonal\ \ Evapotrans\ \ piration\ \ (m^3)} \tag{2.29}$$

2.13 Water Productivity

In agriculture, the term water productivity is defined as the ratio of the mass of marketable product to the volume of water consumed by the crop. Improved water productivity means that there would be an increase in crop yield per unit of water consumed by the crop (Pereira *et al*., 2002). Crop water-consumption rate depends mostly on stage and vigour of crop growth, soil fertility, moisture condition and climatic conditions. Therefore, for optimum crop yield for different ecological regions, it is necessary to develop the best irrigation schedule based on available supply and the rate of crop consumptive use. Water productivity is the ratio of biomass produced to amount of evapotranspiration as expressed in equation (2.30)

$$WP = \frac{Biomass\ \ produced\ \ (kg)}{Water\ \ transpirat\ \ ion\ \ (m^3)} \tag{2.30}$$

2.14 Crop water modelling

Several sophisticated crop growth models based on physiological processes have been developed and applied in water management projects with varying degrees of success (Hsiao *et al*., 2009). Most of these models, however, have not been tested under deficit irrigation conditions in Sub-Saharan Africa. Some of the widely accepted crop models are the hybrid model, such as CERES (Gabele, 2002), and the DSSAT model performance. These two simulate the growth of crop under water-limited conditions (Setiyono, 2007). Stockle *et al*., (2003) stated that WOFOST model, Crop System model and the Hybrid Maize model have been used for the prediction of the yield of maize crop. CROPWAT model is an appropriate tool for irrigation planning. All these models are however, quite sophisticated and require advanced modelling skills for their calibration and subsequent application. They also require a large number of model input parameters. In this context, the recently developed FAO

AquaCrop model (Raes *et al*., 2009), (Steduto *et al*., 2009) which is more user friendly and practitioner oriented is preferred. It is designed to balance simplicity, accuracy, and robustness, and is practically suited to address conditions where water is a key limiting factor in crop production.

2.14.1 AquaCrop Model

The recently developed FAO Aquacrop model (Raes *et al*., 2006; and Steduto *et al*., 2009), which is more user friendly and practitioner oriented was preferred for this study. It is designed to balance simplicity, accuracy, and robustness and is practically suited to address conditions where water is a key limiting factor in crop production.

AquaCrop is a simulation model that quantifies the effects of water on yield at the farm level, and so can be a valuable tool in water and irrigation water irrigation management. It is a new decision support tool used in modelling and devising strategies for efficient management of crop water productivity at farm level (Steduto *et al*., 2009). AquaCrop can be used as a planning tool to assist in irrigation water management decision making for both irrigation and rain-fed agriculture (Garcia-Vila *et al*., 2009). The model is particularly useful in developing irrigation strategies under water deficit condition (Paredes *et al*., 2014). It can also be used to study the effect on crop yield of various land management techniques, to compare the attainable against actual yields in a field, farm or a region. It can also be used to identify the constraints limiting crop production and water productivity and to predict climate change impacts on crop production (Khoshravesh *et al*., 2013). Therefore, AquaCrop model is applicable in irrigation development technology to achieve increased crop productivity, which may lead to poverty mitigation.

Scientific modelling is meant to be more mechanistic, based on laws and theories of how the systems function. Engineering modelling is meant to be more functional, based on a mixture of well-established theory and robust empirical relationships. According to Raes *et al.,* (2009), Aquacrop modelling approaches depend on the purpose and objectives of the crop modelling. The scientific approach focuses on improving the understanding of crop behaviour, physiology, and its response to environmental change. The other approach provides good management advice to the farmer or provides prediction to policy makers.

2.14.2 Operational structure of AquaCrop Model

As in other crop models, AquaCrop is structured around the atmosphere (weather) and the soil (Araya *et al.,* 2010). AquaCrop is a FAO crop water productivity model, based on the crop growth engine. It is basically water driven where crop growth and production are based on the amount of water used through consumptive use of the plant. Concepts and application of Aqua Crop Model for predicting attainable yield under water limiting conditions is an important goal in arid, semi-arid and drought prone environments. FAO developed AquaCrop Model simulates attainable yield of major herbaceous crops in response to water. Doorenbos and Kassam, (1979) presented a method for determining the yield response to water in field, vegetable and tree crops, through equation 2.31

$$\left(\frac{Y_X - Y_a}{Y_x}\right) = Ky\left(\frac{ET_X - ET_a}{ET_x}\right) \tag{2.31}$$

Where

Y_x and Y_a = the maximum and actual yields respectively

ET_x and ET_a = the maximum and actual evapotranspiration respectively and

Ky = proportionality factor between relative yield loss and relative reduction in Evapotranspiration.

AquaCrop Model evolves from the Doorenbos and Kassam approach by separating the Evapotranspiration into soil evaporation (E) and crop transpiration (T_r) as shown in equation 2.32

$$ET = E + T_r \tag{2.32}$$

The separation of ET to soil evaporation and crop transpiration avoids the confounding effect of the non-productive use of water (soil evaporation) especially during incomplete ground cover and the final yield (Y) Final yield is the product of biomass (B), and harvest index (HI) to equation 2.33.

$$Y = HI \times B \tag{2.33}$$

The separation of Y (yield) into B (biomass) and HI(harvest index) allows the distinction between basic function relations of environment B and those of environment HI and avoids the confusing effects of water stress on B and HI (Steduto *et al.*, 2009). These changes lead to equation 2.34 for AquaCrop model

$$B = WP * \sum T_r \tag{2.34}$$

Where

T_r = crop transpiration (mm) and

WP = water productivity parameter (kg of biomass per m^2 per mm of accumulated water transpired over the time period in which the biomass is produced).

Evapotranspiration has been separated into soil evaporation (E) and crop transpiration (T_r) and the attainment of yield (Y) into biomass (B) and harvest index (HI). There is another structure of Aqua Crop model based on soil, plant and atmosphere continuum. It consists of soil with its water balance, the plant with its development, growth and yield processes, and the weather with its thermal regime, rainfall, evaporative demand, and carbon dioxide concentration. In addition, some management aspects are explicitly considered like irrigation and fertigation as they affect the soil water balance, crop development and final yield. The flow chart, Figure 2.1 shows the functional relationships between the different model components.

AquaCrop simulates the soil water balance by considering climate, soil, crop, and management characteristics. The amount of water stored in the root zone (soil reservoir) is expressed in equivalent depth as total available water (TAW) and readily available water (RAW) (Raes *et al*., 2010) as explained in equations 2.3 and 2.4respectvily. In the analysis by Steduto *et al*., (2009) the operation of AquaCrop model requires input data consisting of climatic parameters, crop, soil, field and irrigation management data. However, the model contains a complete set of input parameters that can be selected and adjusted for different soil or crop types.

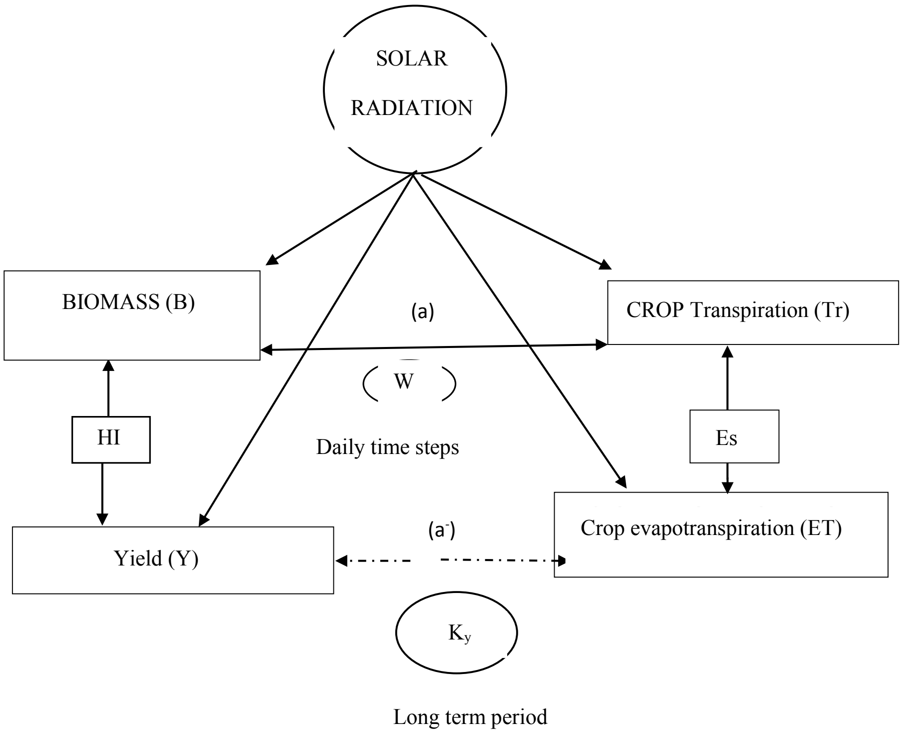

Figure 2.1: A schematic diagram showing the functional relationships between the different components of AquaCrop Model

2.14.3 Calibration and Validation of Aqua Crop Model

Calibration involves adjusting certain model parameters to make the model output match the measured values at the given location. Aqua Crop has parameters falling into two categories. One is a set of conservative parameters which are crop specific and do not change with time, management practices, geographic location, climate or cultivar (Doorenbos and Kassam, 1979). The other category comprises of non-conservative parameters occurring predominantly during time duration in calendar days, of each growth stage; (i.e. time to emergence, time to attain maximum canopy cover, time to flowering, senescence and physiological maturity). These parameters, which can be directly obtained from field observations, are used to describe the crop development under non-limiting conditions. Water stress coefficients for leaf expansion, stomata closure and canopy senescence are calibrated in an iterative way by comparing observed canopy cover and soil water content, with simulated outputs of AquaCrop for the fully irrigated treatment (Garcia-Vila *et al*., 2009). The observations of canopy cover, soil water content, Biomass and Yield are used as benchmarks during the calibration process. Validation of the model is carried out to assess the accuracy of the calibrated model.

2.14.4 Model Evaluation Criterion

Various statistical methods can be used to compare how good the model simulates the crop CC, SWC, B and Y. By comparing simulated and measured data from the experimental fields, the performance of the model is determined.

2.14.5 Model Efficiency Coefficient

The Nash-Sutcliffe model efficiency coefficient (E) is used to quantify the proportion of variance in the observed values that will be counted by the model

$$E = 1 - \frac{\sum_{i-1}^{N} \left(O_i - S_i\right)^2}{\sum_{i-1}^{N} \left(O_i - \overline{O}_i\right)^2} \tag{2.35}$$

Where:

S_i and O_i = predicted and actual (observed) data respectively

$\overline{O}_i$ = mean value of and Oi

N = the number of observations.

E = model efficiency coefficient.

An efficiency of 1 (E = 1) corresponds to a perfect match of model results and observed data. An efficiency of 0 (E = 0) indicate that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (E < 0) occurs when the observed data are as accurate as the mean of the model.

2.14.6 Coefficient of determination

The coefficient of determination (R^2) signifies the proportion of the variance in measured data explained by the model. Values for this coefficient range from zero to one with values close to one indicating a good agreement with the model.

$$R^2 = \left[\frac{\sum_{i-1}^{n} (M_I - \overline{M})(S_i - \overline{S})}{\sqrt{\sum_{i-1}^{n} (M_i - \overline{M})^2 \sum_{i-1}^{n} (S_i - \overline{S})^2}} \right]^2 \qquad (2.36)$$

Where:

M_i = Measured values

S_i = Simulated values

$\overline{M}$ = Measured mean

$\overline{S}$ = Simulated mean

n = number of observations

2.14.7 Root mean square Error

The root mean square error (RMSE) measures the average magnitude of difference between simulations and measured values. It ranges from zero to positive infinity, with the former indicating good model performance.

$$RMS = \sqrt{\frac{1}{n} \sum_{i-1}^{n} (M_i - S_i)^2} \qquad (2.37)$$

The units of RMSE are the same as for those of the parameters being compared.

2.15 Conceptual framework

Deficit irrigation has been defined as a water management technique whereby less than 100 present of actual crop water requirement is provided by a combination of stored water in the soil, rainfall and irrigation during the growing season (English 1990). Implementing deficit irrigation requires knowledge of crop yield responses to water stress, either during defined growth stage or throughout the whole season (Kirda and Kamber, 1999) and understanding of economic impact of reduction in harvest due to water supplies (Ali and Talukder, 2008, Blum, 2007). This study is based on the above concept especially for arid and semi-arid areas of sub-Sahara and East Africa. Aqua Crop model is included in the study as a tool to reduce the tediousness of data acquisition.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Location of the study area

The experiment was conducted at Egerton University Njoro campus Field Station. Is located at Latitude 0º23S, Longitude 35º 55E, and at an altitude of 2200 m above sea level. The area receives average precipitation of about 1000 mm with a mean annual temperature of 15.9 ºC. The rain distribution is bimodal, with the long rain season occurring from April to August while the short rain season occurs between October and December. (Jaetzolt and Schmidt, 2006).

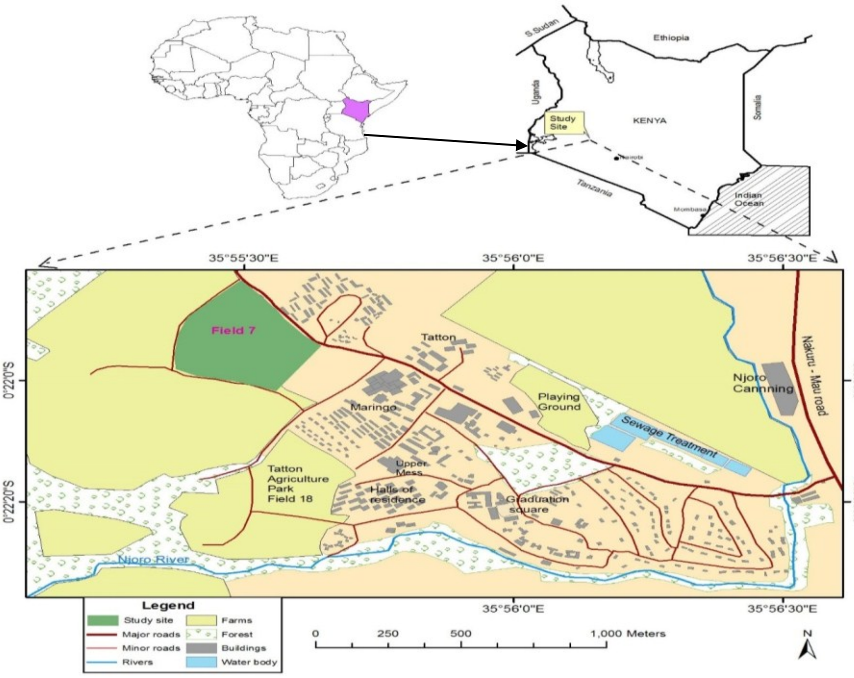

Figure 3.1 Map of Kenya showing location of study site

3.1.1 Soil analysis

Soil sample collected from experimental site were analysed for bulk density, soil moisture content, field capacity, wilting point and soil texture before land preparation. Nine samples were taken in a zigzag version at 0-15, and 15-30 cm soil depths. To determine the bulk density, undisturbed soil samples of known volume were taken using a core sampler in the 0-15 and 15-30 cm depths, the sample were dried in an oven to determine the dry weight fraction. Then the bulk density was calculated as the ratio of dry weight of the soil to known cylindrical core sampler volume (Hillel, 2014). Gravimetric method was used to determine the initial moisture content of the soil before experiment was started. Soil samples were taken from each depth of 0-15 and 15-30 cm of soil profile depending on the rooting depth of the French beans, after weighing the soil sample, it was placed in an oven at 105 ^{0}C for until the constant weight is obtained. After drying the soil sample was weighed again. The gravimetric water content in fraction (θ_m) was computed using equation 3.1 (Hillel, 2014).

$$\theta_M = \frac{M_W - M_S}{M_S} \tag{3.1}$$

Where: M_W is weight of soil sample (g) and M_S is weight of dry sample soil (g). The initial volumetric water content of the soil was determined from the gravimetric water content by multiplying with the apparent specific gravity of the soil.

Soil moisture content at field capacity and permanent wilting point were done using pressure plate apparatus by applying suction of 0.33 and 15 bars respectively to saturated soil sample, whet water no longer leaves the soil samples, the soil moisture were taken as field capacity and permanent wilting point.

Soil texture was determined by using Bouyoucos Hydrometer method (Boyoucos, 1962) in Soil laboratory of Egerton University. The textural class was designated based on the mass ratio of the three particles (clay, silt and sand) with the help of soil textural triangle (Hillel, 2014).

The soil chemical properties were determined in the Kenya Agricultural and Livestock Research Organization (KALRO) in Njoro station. Titration method which is oxidation under standardized condition with potassium dichromate in sulphuric acid was used for organic carbon determination.

For Ca, K, Mg, Na, Cu, Mn and Fe Atomic Absorption Spectrophotometer model (AA633) was used. And for the Organic matter U/V visible model (1700 SHIMADZU) was used. And for Nitrogen Digestion Block VELP KJETEC system model (1002 Digestlling Unit) was used.

Figure 3.2 Atomic Absorption Spectrophotometer

Figure 3.3 U/V visible Spectrometer

3.1.2 Analysis of irrigation water Quality

The source of water for irrigation was from Egerton University dam main campus Njoro. To test water quality for irrigation, samples of water was taken to Egerton University soil laboratory for analysis the following: pH, Total dissolved salt (ppm), total alkalinity (ppm), EC,(ppm); CL-1 (ppm), Total hardness (ppm),Ca2+ (ppm), Mg2+ (ppm), Fe2+ (ppm), SO2-4 (ppm), and NO3 (ppm).

3.1.3 Experimental Layout

Total area of the experiment was about 30m×30m, which was fenced with barbed wire and chain links wooden poles. The area was ploughed and harrowed twice to make a good seedbed using mouldboard plough and disc harrow respectively. In order to carry out deficit irrigation scheduling, rainfall was eliminated. A rain shelter made of wooden framework covered with clear polythene was constructed over an area of 220 m^2 and height of 2.5 m. The polythene cover was fixed in such a way that it could be rolled-up when there was no rainfall and unrolled when rainfall accrued, and during the night.

Figure 3.4 Rain shelter

A 1000 L irrigation main tank was placed on a timber platform, at a height of 2m from the ground. A pipe- line (25 mm in diameter) was connected to the main tank using a tank connector and filter to prevent the emitters from clogging. Water was supplied to the main tank from a borehole near the field. 16mm diameter drip line with emitters spaced15cm where placed at 45 cm apart. To facilitate the process of controlling the water, each treatment had been irrigated separately from 100L tank (100L) as shown in Figure (3.2).

Figure 3.5 Main and treatments tanks

3.1.4 Experimental Design

An experiment was conducted using field trials in a randomized complete block design (RCBD) with irrigation treatments replicated three times as subplot. The plot was divided into three rows; each containing six irrigation treatments randomly distributed. The experimental plot size was 2 m × 2 m. The spacing between rows and between experimental plots was one meter. Treatment T100 where 100% of crop water requirement ET_c was applied as control. T80, 80% of ET_c was applied. Similarly T60, T40, T20 and T120, 60%, 40%, 20% and 120% of ET_c. were applied respectively each plot have five drip lines of 2m length. Planting were done at each emitter. The experimental design layout is shown in figure 3.3. All the necessary agronomic practices were observed to ensure proper crop development.

Disease and pest management, weed control and fertilizer application was done uniformly in all the sub-plots thus ensuring that the only limiting factor affecting the crop was water. The amount of water to be applied was determined using equation (3.1). The experimental area was protected from seepage and runoff using polythene covered shelters and lining the perimeter of the shelter placed at a depth of 60 cm.

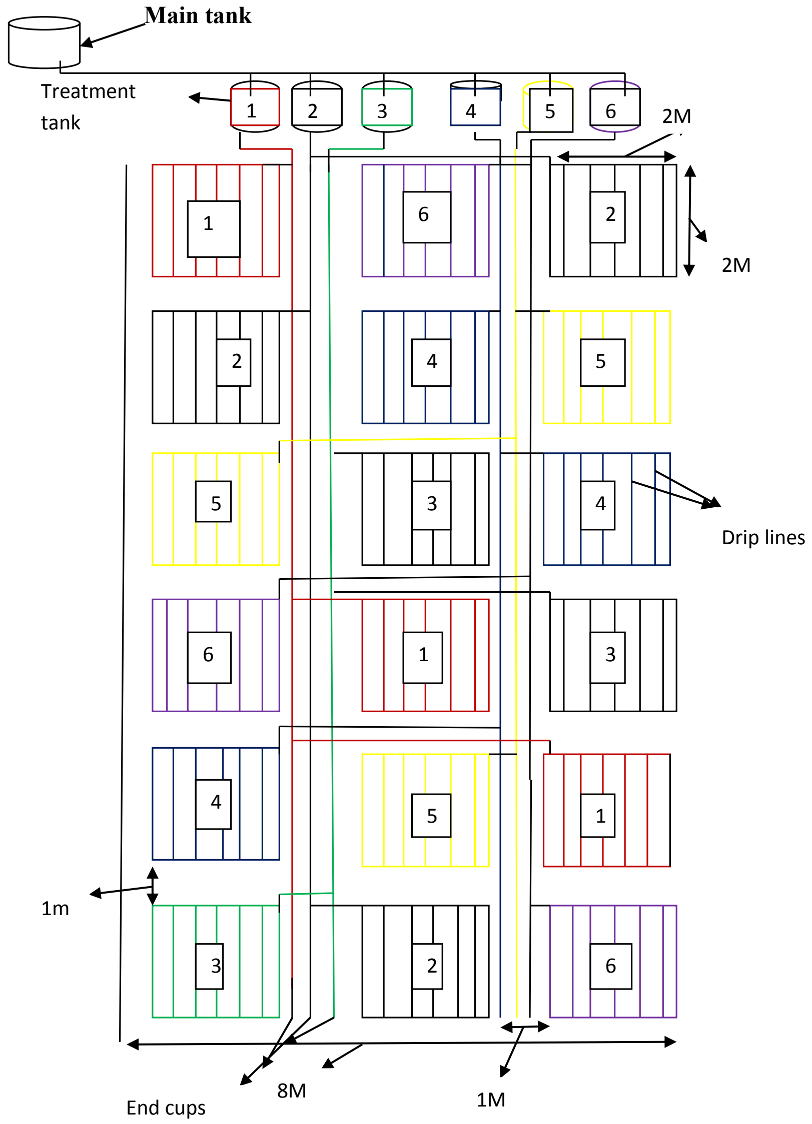

Figure 3:6Experimental design layout under irrigation system

1= T100, 2 = T80, 3 = T60, 4 = T40, 5 =T20, 6 = T120

3.1.5 Amount of Irrigation Water

The irrigation crop water requirement was determined using the following equation:

$$I = ET_C = ET_O \times K_C \times K_S \tag{3.2}$$

Where:

I = irrigation water requirement (mm)

ET_c = crop water requirement (mm)

ET_o = reference crop evapotranspiration (mm)

K_c = crop coefficient which varies according to crop development stage (range 0 to 1)

K_s = coefficient for each irrigation treatment level in the experiment.

The reference evapotranspiration ET_o was determined using FAO Peneman-Montieth method for ET_o calculations. For purposes of creating irrigation schedules historical weather data of 15 years (2000-20015) recorded at Egerton university meteorological department was used. Selected values of crop coefficients K_c were selected from the table according to FAO Irrigation and Drainage Paper no 24 Doorenbos and Pruitt (1977). The coefficient of each irrigation treatment (K_s) = 100% of ET_c no stress, K_s (0.8)= 80% of ET_c, K_s (0.6) = 60% of ET_c, K_s (0.4) = 40% of ET_c. Water was applied by drip irrigation on the same day as that of the fully irrigated plot, but the irrigation depths were reduced to 80%, 60%, and 40%, of the full irrigation treatments. The total amount of irrigation water from each treatment was recorded.

3.1.6 Deficit and Full Irrigation Scheduling

Full and deficit irrigation level was imposed throughout the season. The depth of water applied to each treatment was taken as the percentage of the predetermined optimal irrigation water. The treatments were 100%, 80%, 60%, and 40% of optimal crop water requirement. The types of data collected were the amount of water applied for different treatments and crop data, which include biomass and yield.

3.2 Effect of deficit irrigation on growth of French bean

The data collections were made on the three middle rows, leaving two outer rows in order to avoid border effects. In this objective four treatments were applied 100% ET_c to 40%ET_c .Three plants were taken randomly and tagged from the three middle rows of each experimental plot for recording observations on growth and yield parameters. Plant height was measured as the distance in centimetre from the soil surface to the top most growth point of the sample plants from 28 days (four week) after planting until full maturity at interval of Ten days. The numbers of branches and leaf number per plant were counted leaf length, width were recorded by measuring using scaled ruler, as well as maximum effective rooting depth was obtained from the experimental plots by excavating pits at the root zone during maturity (destructive sampling). Total pod yield was recorded as sum of fresh fruit weight of each successive harvesting from plot and was calculated on the basis of kg ha $^{-1}$. The leaf area A (cm^2) for French beans was therefore calculated using the relationship (Kang *et al.*, 2003)

$$A = 0.75 \sum_{i=1}^{m} L_i \times W_i$$

(3.3)

Where

L= leaf length (cm) and W= leaf width (cm)

$$LAI = \frac{\text{Measured leaf area/ plant } (cm^2)}{100 \times 100\ cm^2} \times \frac{\text{Number of plants}}{m^2}$$

(3.4)

3.3 Water use efficiency (WUE)

Final yield was determined at the end of the season after the crop was harvested. An electronic balance (0.001g sensitivity) was used to weigh the pods from the various treatments. Water use efficiency for each treatment was determined by dividing the harvested crop yield by its seasonal water use. Water use efficiency and irrigation water use efficiency was determined using the following equation (James *et al.*, 1982)

$$CWUE = \frac{Y}{NI} \qquad (3.5)$$

Where CWUE = Crop water use efficiency (kg $ha^{-1}m^{-3}$), Y= Actual yield (kg/ha), *NI* = Net irrigation (m^3)

$$IWUE = \frac{Y}{GI} \qquad (3.6)$$

Where IWUE= Irrigation water use efficiency (kg ha^{-1} m^{-3}), Y= Actual yield ($kgha^{-1}$), GI= Gross irrigation (m^3).

3.4 Operation of Aqua crop model

Input data required to carry out simulations, by Aqua Crop include climatic, crop, soil, irrigation and field management data, these were stored in files, provided in the model. In the model program the period of simulation and initial conditions at the start of the simulation, need to be specified.

3.4.1 Climatic Data

The climatic data required which included daily minimum and maximum temperature, average wind speed at 2m height and mean relative humidity, were obtained from the Egerton meteorology station. The ETo calculator which uses the FAO Penman-Montetih equation (Allen *et al*., 1998), was used for computation of the ETo. Weather parameters were recorded from beginning to end of the season.

3.4.2 Soil Data

The required data of experiment site required as input parameters for Aquacrop are soil horizons, soil texture, field capacity, permanent wilting point, and volumetric water content at saturation. The experiment site did not have any restrictive soil layer to obstruct the expansion of root growth. The data were determined at Egerton University Soil Laboratory of Egerton University (3.1.1).

3.4.3 Crop Data

Crop data required include the French beans major phonological growth stages (emergence, maximum canopy cover, duration of flowering, senescence and physiological maturity). These were specified and noted according to the observed days on the calendar. The plant population density was based on the 0.45 m by 0.15 m at the time when about 90% of the crop had emerged. Maximum effective rooting depth was obtained from the experimental plots by excavating pits at the root zone during maturity (destructive sampling).

i. Green canopy cover

Canopy cover was estimated from leaf area index based on (Hsiao *et al*., 2009):

$$CC = 1.005 \times [1 - \exp(-0.6 LAI)]^{1.2} \tag{3.7}$$

Where CC (%) is canopy cover and LAI is leaf area index of the crop.

The canopy decline coefficient, crop coefficient for transpiration at full canopy cover , soil water depletion thresholds for inhibition of leaf grown and stomatal conductance, acceleration of canopy senescence were used from Hsiao *et al*., (2009).

ii. Dry above ground biomass

The dry above ground biomass was determined by destructive sampling. One sample per plot was taken from known quadrant of the experimental plots at harvest time. (Zeleke *et al*., 2011). The samples were oven dried at a temperature of 65^0C for 48 hours and Final yield was determined at the end of the season after the crop was harvested together with the final biomass.

Figure 3.7 Fresh biomass, oven and dry biomass

3.4.4 Irrigation and field management parameters

In this study drip irrigation was used. No rain, full irrigation treatment (100% of ETc) water was applied up to field capacity level when soil moisture in the root zone approached 50% of total available water, in the deficit irrigation treatment (80%, 60% and 4 %ETc) water was applied on same day as day as fully irrigated plot, but the irrigation depths were reduced to 80%. 60% and 40% of the full irrigation. In field management there was no runoff and fertility was used as required.

3.4.5 Calibration and Validation

The non-conservative parameters, the length of growing stages (time to emergence, time to attain maximum canopy cover, time to flowering, senescence and physiological maturity), were recorded in days on the calendar days. In the calibration process these non-conservative parameters were directly available from field observations and were used to describe the crop development under non-limiting conditions. Afterwards, water stress coefficients for leaf expansion, stomata closure, and canopy senescence where calibrated in an iterative way by comparing observed CC with simulated outputs of Aqua Crop for the fully irrigated treatment. The observations of CC, B and Y were used as benchmarks during the calibration process. Calibration will stopped when the simulated output for CC, B and Y fitted (was determined by adequate statistical tests) with the observed values. Model validation was carried out to assess the accuracy of the calibrated model. The stress coefficients established during calibration were held constant as observed data from the deficit-irrigated fields (T80, T60 and T40).

3.5 Crop Water Production Function

Development of crop water production function involved full and deficit irrigation scheduling. The result from objective (ii) and (iii) (Determined, simulated yield and amount of water used) from different treatments was used to determine crop water production function by using the equation: 3.7

$$\frac{Y_X - Y_a}{Y_X} = K_Y \frac{ET_X - ET_a}{ET_X} \qquad (3.2)$$

Where

Yx = maximum yield (t ha-1) from 100% water application.

Ya = actual yield (t ha-1) from different level of water application.

ETx and ETa = the maximum and actual evapotranspiration (mm),

Ky = a yield response factor indicates the response of French beans to deficit irrigation.

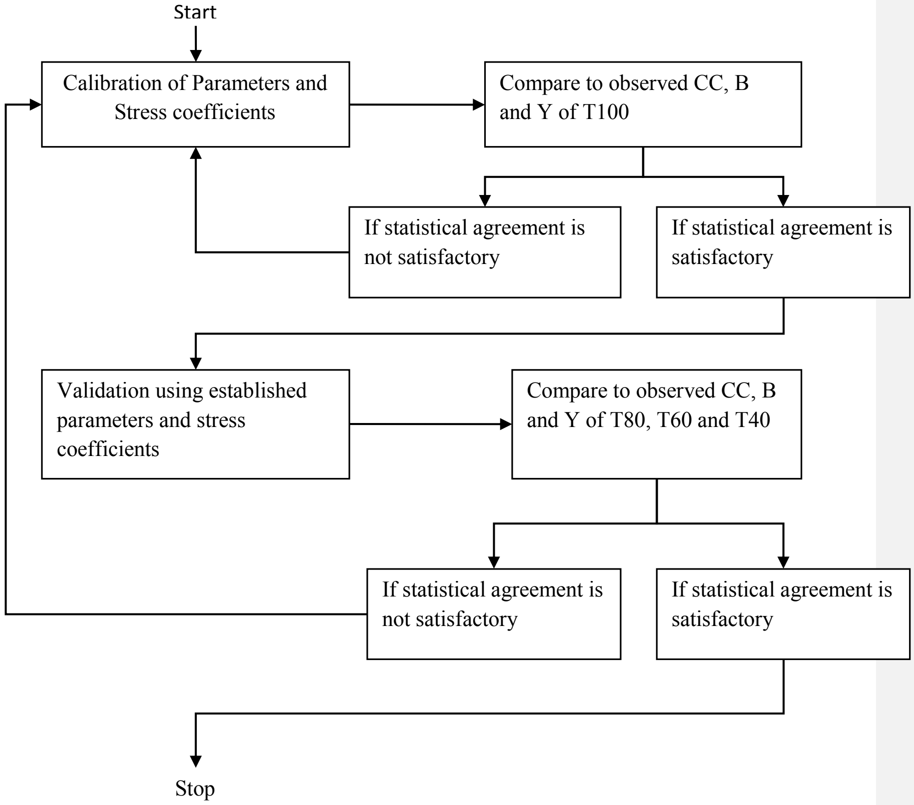

Figure 3.8 Flow chart of calibration and validation process.

3.6 Statistical Analysis

The data were analysed statistically using analysis of variance (ANOVA) procedure of SAS 9.1.3. Mean separation was being done using Tukys at the significant level at 0.5.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1.1 Characterization of the soil of the experimental area

The result of soil textural analysis is presented in Table 4.1. The average soil separated as values obtained were 64 - 59% sand, 26.5 – 29% silt and 9.5 to 12% clay. The soil textural class was sandy loam textured according to the profile investigated based on USDA soil textural classification triangle.

Table 4.1 Soil characteristics

Soil depth (cm)	**Soil texture**			**Soil type**	**FC %**	**PWP %**	**TAW%**	**pH**	**Bd g/cm^3**
	Sand %	**Silt %**	**Clay%**						
0 -15	64	26.5	9.5	SL	19.65	11.50	8.15	5.84	1.34
15-30	59	29	12	SL	20.65	10.70	9.80	5.84	1.36

SL= Sandy loam, FC = field capacity, PWP = permanent wilting point, TAW = total available water. Bd = bulk density.

The average bulk density was 1.35g/cm$^{3.}$ The bulk density of experimental site had indicated very slight increases with increase in soil depth. The average soil moisture content at field capacity was 20.65 witches in the range of soil moisture content at field capacity of sandy loam soil. Permanent wilting point 10.7% and total available water was 9.8%. The pH of the soil at experimental site was 5.84 witch indicate that it's acidity but still suitable for French beans growth.

Table 4.2: Soil Chemical Properties

Soil depth cm	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Na (ppm)	OM %	N %	Fe (ppm)	Cu (ppm)	Zn (ppm)	Mn (ppM
0-30	4.20	593.4	874.4	435.7	707.0	3.4	0.3	78.43	0.8526	6.0797	30.85

P= phosphorus, K= potassium, Ca= calcium, Mg= magnesium, Na= sodium, N= nitrogen, Fe= iron, Cu= cupper, Zn= zinc, Mn= manganese and OM organic matter.

The result indicated that the available P of the experimental site was low similarly the Organic matter content of the soil slightly less 3.39, Nitrogen (N %) was adequate 0.26. The recommended diammonium phosphate (DAP) was 50kg/acre (18-46-0).

4.1.2 Analysis of irrigation water quality

Analysis of irrigation water quality presented in table (4.3) PH was (7.03) witch indicated that the irrigation water was acidity but still suggested for irrigation means that water quality is suitable for irrigation.

Table 4.3: Irrigation water quality analysis

Parameters	Value	Method
pH	7.06	Digital pH meter model L1612
Total dissolved salt (MG/L)	101	TDS meter 308
EC (ms cm^{-1})	0.15	EC meter 308
CL $^{-1}$(PPM)	0.02	Atomic Absorption Spectrometer Emission – 210 VGP
Ca $^{+2}$(ppm)	0.023	//
Mg $^{+2}$(ppm)	1.02)	//
Fe $^{+2}$(ppm)	1.54	//
SO_4^{-2}(%)	0.0022	//
NO_3(%)	0.019	//
K (ppm)	0.84	//
Zn(ppm)	3.64	//

K= potassium, Mg= magnesium, Fe= iron, Zn= zinc, Ca= calcium, NO_3 = Nitrate, CL = chlorine, SO4 = phosphate EC = electrical conductivity.

4.1.3 Weather data

Monthly reference evapotranspiration (ETo) was computed from historical data records of 15 years using ETo calculator Penman- Monteith approach, with data as daily solar radiation, maximum and minimum temperature, wind speed, maximum and minimum relative humidity from Agricultural Engineering meteorological station of Egerton University presented in Appendix table 1

4.1.4 Irrigation water requirement of French bean

The result showed that the minimum ETo of (3.9 mm/day) and the maximum ETo of (4.7 mm/day) ETo value occurred in the month of March and June respectively. The evaporative power of the atmosphere was moderate (3-5 mm/day) (Allen *et al*., 1998).

Table 4.4 Crop growth stage of French beans

Stages	**Initial**	**Development**	**Mid-season**	**Late season**
Days	20	30	30	10
Kc	0.5	0.75	1.15	0.9

Source Allen *et al*., 1988

Table 4. 5 Calculation of seasonal water requirement for French beans for the first season

Date	**Stages**	**ETo mm/day**	**Kc mm/day**	**ETc mm/day**	**Days**	**Total ETc mm/day**
22/6-30/6	**Initial**	3.90	0.50	1.95	09	17.55
1/7-11/7	**Initial**	4.10	0.50	2.05	11	22.55
12/7-31/7	**Development**	4.10	0.75	3.08	20	61.6 0
1/8-10/8	**Development**	4.20	0.75	3.15	10	31.5 0
11/8-31/8	**Mid-season**	4.20	1.15	4.83	21	101.43
1/9 – 9/9	**Mid-season**	4.30	1.15	4.95	09	44.55
10/9 – 14/9	**Late season**	4.30	0.90	3.87	05	19.35
Total		**29.1**	**5.7**	**23.88**	**85**	**298.53**
Gross Irrigation						**351.21**

Table 4.6 Calculation of seasonal water requirements for French beans for the second season

Date	**Stages**	**ETo**	**Kc**	**ETc**	**Days**	**Total ETc**
18/9-30/9	**Initial**	4.30	0.50	2.15	13	27.95
1/10 – 7/10	**Initial**	4.30	0.50	2.15	07	15.05
8/10-31/10	**Development**	4.30	0.75	3.23	24	77.52
1/11 – 6/11	**Development**	4.20	0.75	3.15	06	18.90
7/11 – 30/11	**Mid-season**	4.20	1.15	4.83	24	115.92
1/12-6/12	**Mid-season**	4.20	1.15	4.83	06	28.98
7/12-12/12	**Late season**	4.20	0.90	3.78	06	22.68
Total		**29.7**	**5.7**	**24.12**	**86**	**307**
Gross Irrigation						**361.18**

Table 4. 7 Calculation of seasonal water requirements for French beans for the third season

Date	Stages	ETo	Kc	ETc	Days	Total ETc
4/1 – 23/1/017	**Initial**	4.30	0.50	2.15	20	43.00
24/1 – 31/1/17	**Development**	4.30	0.75	3.23	08	25.84
1 /2 – 22/2	**Development**	4.40	0.75	3.3	22	72.60
23/2 – 30/2	**Mid-season**	4.40	1.15	5.06	08	40.48
1/3 – 22/3	**Mid-season**	4.70	1.15	5.41	22	119.02
23/3 -26/3	**Late season**	4.70	0.90	4.23	04	16.92
Total		**26.8**	**5.2**	**23.38**	**84**	**317.86**
Gross Irrigation						**373.96**

For optimal condition, the total water requirement for French bean for the first, second and third season respectively were 298.53mm, 307 mm and 317.86 mm respectively. Adopting irrigation efficiency of 85%, the gross water requirement were 352.34mm, 367.83mm and 396.72mm respectively. The depth of water applied for each treatment and time of application are presented in Appendix Table 2 the depth of irrigation water applied was the sum of pre irrigation and all subsequent scheduled irrigation.

4.2 Effect of deficit irrigation on crop performance

4.2.1 Plant height

Table 4.8 summaries the evaluation of the effect of deficit irrigation level on French bean. The average measured plant height of French bean according to the analysis of variance on irrigation levels showed that the effect of deficit irrigation level on plant height was highly significant ($p<0.001$) ($R^2=0.99$, 0.97 and 0.98. CV%= 2.01, 4.39 and 4.60. RMSE=0.20, 0.45 and 0.53) for first second and third season respectively. 100%ETc and 80%ETc recorded the highest plant height (40.30 and 42.73 cm) in the first season, (43.8 and 41.53 cm) in second season and (47.73 and 44.43 cm) for the third season. Whereas the most stressed plots which received 40%ETc throughout the whole growth stages, had resulted in the shortest plant height (28.43, 27.10 and 29.76 cm) for first second and third season respectively. From the result the differences in plant height in first fourth week was small because the treatment used to have same amount of water for the period of establishment, the differences in plant height among the treatment was clear in eighth week from planting. Comparison of the three seasons the heights plant height was in season three, tow and one, due to increase in seasonal water and weather. Generally beans used to fixed nitrogen .From this finding it is clearly seen that as the deficit irrigation level increased the plant height decreased which in agreement with the finding of (Shao *et al*., 2008).

The increase in plant height could be mainly due to better availability of soil moisture and sufficient uptake of nutrient, which had enhancing effects on the vegetative growth of plants by increasing cell division and elongation.

4.2.2 Number of branches per plant

The results of analysis of variance on number of branches per plant are presented in Table 4.9. The number of branches per plant decreased significantly (p<0.001) as deficit irrigation level increased. The number of branches per plant was highest in the treatments 100% ETc and 80% ETc whereas (9.33and 7.66 cm) in the first season, (9.66 and 8 cm) for second season and (10 and 8.66 cm) branches per plan in third season. The lowest number of branches was recorded from plots that received 60% and 40%. (Between 5 to 7 branches per plant), for the three season. Among irrigation levels, 100%ETc gave significantly (<0.001) higher number of branches per plant than the 80%, 60 and 40% ETc. However, there was non-significant difference in number of branches per plants that received 80% and 60%ETc after eight week after planting.

Table 4.8 Plant height for three seasons

Seasons		Weeks after planting		
1st (June – September 2016)	Treatment	4	6	8
	40%ETc	6.10d	13.53d	28.43c
	60%ETc	9.53c	19.56c	37.43b
	80%ETc	11.33b	27.00b	40.30a
	100%ETc	12.40a	30.00a	42.73a
	R^2	0.99	0.99	0.97
	CV%	2.01	1.91	2.74
	RMSE	0.20	0.43	1.02
	Mean	9.84	22.53	37.23
Second season (September –December 2016)	40 ETc	6.47c	13.53c	27.10c
	60%ETc	9.73b	19.80b	36.40b
	80%ETc	11.73a	27.70a	41.35a
	100%ETc	12.87a	30.43a	43.80a
	R^2	0.97	0.96	0.97
	CV%	4.39	6.35	3.75
	RMSE	0.45	1.45	1.40
	Mean	10.20	22.86	38.95
Third season (January – April 2017)	40 ETc	6.00 c	13.96 d	29.76d
	60%ETc	12.13b	21.90c	38.10c
	80%ETc	13.13ab	27.56b	44.73b
	100%ETc	14.23a	31.73 a	47.86a
	R^2	0.98	0.97	0.99
	CV%	4.40	4.93	2.00
	RMSE	0.53	1.17	0.80
	Mean	11.60	23.79	40.11

Means followed by the same letter within a column a parameter are not significantly different according to Tukey,s significant difference test at $p<0.05$.

Table 4.9 Number of branches per plant for three seasons

Seasons		Weeks after planting		
1st (June – September)	Treatment	4	6	8
	40%ETc	4.00 b	5.00 c	5.00 c
	60%ETc	4.00 b	5.67bc	7.66 b
	80%ETc	4.00 b	6.33ab	7.67 b
	100%ETc	5.00 a	7.00 a	9.33 a
	R^2	1.00	0.33	0.94
	CV%	0.00	6.80	6.74
	RMSE	0.00	0.41	0.50
	Mean	4.25	6.00	7.42
2nd season (September – December 2016)	40%ETc	4.00 b	5.00 c	5.00 c
	60%ETc	4.00 b	6.33 b	7.33 b
	80%ETc	5.00a	7.00 b	8.00b
	100%ETc	5.00 a	8.00a	9.66a
	R^2	1.00	0.95	0.96
	CV%	0.00	4.38	5.44
	RMSE	0.00	0.28	0.41
	Mean	4.50	6.58	7.50
3rd season (January – April 2017)	40%ETc	4.00 b	5.00 c	5.00 c
	60%ETc	4.00 b	6.33 b	7.66 b
	80%ETc	4.66 a	7.33 b	8. 67 b
	100%ETc	5.00 a	8.00 a	10.00 a
	R^2	1.00	0.92	0.97
	CV%	0.00	6.12	5.21
	RMSE	0.00	0.41	0.41
	Mean	4.5	5.11	7.83

*Means followed by the same letter within a column and a parameter are not significantly different according to Tukey,s honestly significant difference test at $p<0.001$.

There was significant difference between treatments that received 60% and 40%ETc. generally from the result of three season there was no differences in number of branches. Finding from the result decreased irrigation level from full irrigation, decreased the number of branches.

4.2.3 Leaf area index

There were significant ($p<0.001$) differences in the leaf area index of French bean plants between all the treatments, the highest leaf area indices of (4.14, 4.31 and 4.63) were obtained from 100ETc in three season respectively, and the second highest leaf area indices were (2.58, 2.79 and 3.00) obtained from treatment 80%ETc for three season respectively, the lowest leaf area index (0.92, 1.05 and 0.94 was obtained from 40%ETc for three season respectively.as shown in table (4.10). at initial stage there was no significant differences in leaf area index because the treatments used to receive the same amount of irrigation water. There was significant differences in the rest of the crop stages.

4.2.4 Total yield

Results of total yield on response of French bean to different deficit irrigation levels presented in table 4.10. Showed that deficit irrigation affected total pod yields of French bean. High total pod yield 8680 kg ha-1 8675 kg ha-1 and 8250 kg ha-1 was obtained from high depth of water applied or 100%ETc from third second and first season respectively. The second high yield was obtained from treatment 80% ETc, 60%ETc and 40%ETc respectively. The yield increased due to increase in irrigation depth especially for third season the highest yield also due to dry season the temperature was good for beans. Therefore, yield reduction observed in the treatments that received less depth of water per season could be as a result of less soil moisture, flower drop, immature pod drop and reduction in pot number per plant. Consequently total yield reduction due to water stress is also reported by Bosland and Votava, (2000). The results indicated the differential response of the French bean to the different depth of irrigation levels in the production of total pod yield which also agreed with the previous reports of Tekele, (2009).

Table 4.10 Leaf area index/ plant for three seasons

Seasons		Weeks after planting		
1st (June – September 2016)	Treatment	4	6	8
	40%ETc	0.14c	0.33c	0.92c
	60%ETc	0.18bc	0.51bc	1.60bc
	80%ETc	0.25ab	0.77b	2.58b
	100%ETc	0.28a a	1.21a	4.14 a
2nd season (September – December 2016)	R^2	0.84	0.89	0.93
	CV%	14.13	19.72	17.39
	RMSE	0.03	0.14	0.40
	Mean	0.21	0.71	2.31
	40%ETc	0.16c	0.29c	1.05c
3rd season (January – April 2017)	60%ETc	0.19bc	0.51c	1.62b c
	80%ETc	0.24b	0.88b	2.79 b
	100%ETc	0.31a	1.27a	4.31 a
	R^2	0.89	0.95	0.92
	CV%	10.57	14.80	18.93
	RMSE	0.02	0.11	0.46
	Mean	0.23	0.74	2.44
	40%ETc	0.16c	0.31c	0.94d
	60%ETc	0.18c	0.61c	1.71c
	80%ETc	0.24b	1.10b	3.00b
	100%ETc	0.31a	1.97a	4.43a
	R^2	0.94	0.96	0.98
	CV%	8.22	15.96	9.22
	RMSE	0.02	0.16	0.24
	Mean	0.22	0.99	2.57

. *Means followed by the same letter within a column and a parameter are not significantly different according to Tukey,s honestly significant difference test at p≤0.05.

4.3 Water Use Efficiency

In order to compare the effect of irrigation levels on water use efficiency, both crop water use efficiency (CWUE) and irrigation water use efficiency (IWUE) were calculated.

4.3.1 Crop water use efficiency

The values of crop water use efficiency (CWUE) are presented in Table 4.11. The results of the irrigation water levels showed that the crop water use efficiency of French bean varied from 2.53- 3.05 kg $ha^{-1}m^3$, 2.5-3.03 kg $ha^{-1}m^3$ and 2.44- 3.03 kg $ha^{-1}m^3$ for first, second and three seasons respectively.

Maximum CWUE was obtained when 80% of ETc (3.05. 3.03 and 3.03) kg $ha^{-1}m^3$ was applied throughout the growth season for first, for three second and third season respectively. Plots which received 100%ETc throughout the growth season resulted in second largest CWUE for the three seasons. Webber et *al*., (2008) reported that, French beans had greater potential to increase water use efficiency under deficit irrigation. According to (Geerts and Raes, 2009) confirms that deficit irrigation increase water productivity for various crops. From Table 4.11, the second lowest mean value of CWUE (2.50 kg/m^3) was found when.60%ETc was imposed. The pod yield of French bean is severely affected by soil moisture stress at flowering and pod filling stages and then ultimately the crop water use efficiency. Therefore, application of adequate water during flowering and pod development was the most significant factor in bean irrigation (Simsek *et al*., 2011).

4.3.2 Irrigation water use efficiency

The calculated value of irrigation water use efficiency (IWUE) is presented in Table 4.11. IWUE as the ratio of total pod yield to the total gross irrigation water applied (Panigrahi *et al.*, 2012). The effect of irrigation levels throughout and at different growth stages on irrigation water use efficiency was significantly different. This parameter eliminates the effects of natural rainfall in order to estimate the contribution of irrigation to total yield. This is a measure of the amount of French bean obtained for every depth of irrigation water applied. From this result, it is clear seen that irrigation applied with 80% of ETc. can increases the irrigation water use efficiency with lower yield reduction (Table 4.11). Therefore, when irrigation water is plenty, the French bean can be irrigated at the level of 100% of ETc, but when the water source is scarce it can be irrigated at the lower water level (80%of ETc) taking economic conditions into consideration.

Increasing the amount of water used by the plant or increasing the growth and yield of the plant can change water use efficiency (Oweis *et al.*, 1998; Zhang *et al.*, 1998).

Table 4.11 Water use efficiency and yield response of French beans to deficit irrigation (three seasons)

Seasons	**Irrigation level**	**Net Irrigation (m^3)**	**Gross irrigation (m^3)**	**Yield (kg/ha^{-1})**	**CWUE ($kg\ ha^{-1}m^{-3}$)**	**IWUE ($kg\ ha^{-1}m^{-3}$)**
1st season (June – September 2016)	40%ETc	1194.10	1404.80	3158	2.65	2.25
	60%ETc	1792.70	2109.10	4529	2.53	2.15
	80%ETc	2388.20	2809.60	7271	3.05	2.59
	100%ETc	2985.30	3512.10	8250	2.76	2.35
2nd season (September – December 2016)	40%ETc	1228.10	1444.70	3190	2.60	2.21
	60%ETc	1842.60	2167.70	4600	2.50	2.12
	80%ETc	2456.00	2889.40	7430	3.03	2.57
	100%ETc	3070.00	3611.80	8675	2.83	2.40
3rd (January- April 2017)	40%ETc	1213.40	1427.50	3230	2.66	2.26
	60%ETc	1907.10	2243.60	4659	2.44	2.08
	80%ETc	2543.10	2991.90	7702	3.03	2.57
	100%ETc	3178.60	3739.50	8680	2.73	2.32

4.4 AquaCrop model calibration and validation

The model calibration was based on the measured crop data of all the treatments. The main calibration parameters for canopy cover include the canopy growth coefficient (CGC), the canopy decline coefficient (CDC), water stress (P-upper, P-lower unit shape factor) affecting leaf expansion and early senescence. Canopy cover per seedling was estimated based on the general knowledge of the crop characteristics by specifying row spacing and plant spacing (15×45cm), the Simulation was done for the above crop phenology's and the results were compared with the measured values. Hence, the estimated initial canopy cover for the given French bean crop was found to be 14 plants/m^2 to estimate the canopy expansion rate, phonological data (listed in Table 4.12 such as dates to emergence, maximum canopy cover, senescence and maturity were used. The model resulted fast canopy expansion and moderate canopy decline. The canopy growth coefficient (CGC) and canopy decline coefficient were 19.1%/day and 1% day, respectively. The crop parameters used for calibrating the model are presented in Tables 4.12 and 4.12.

4.4.1 User specific parameters

According to the (Hsiao *et al*., 2009) they grouped specific parameter to weather of the site, management, and crop specific parameters such as soil water characteristics, maximum rooting depth, plant density, sowing date, irrigations, and phenology all under the heading of user-specific input parameters. These parameters for the current study are presented in Table 4.13.

Table 4:12 Experimental and agronomic information used in Aqua Crop model validation

Parameter	**Value**			**Unit**
	Season one	**Season two**	**Season three**	
Planting density	14.8	14.8	14.8	Plant/m^2
Sowing date	22/6/2016	18/9/2016	4/1/2017	Day
Emergence	4/7/2016	28/9	14/1	Day
Physiological maturity	9/9/2016	15/12	24/3	Day
Harvest	31/8/2016	27/11/16	13/3/2016	Day
Maximum CC	92	92	92	%
CWP	20	20	20	g/m^2
Initial CC	0.75	0.75	0.75	%
Irrigation	299	307	318	mm
Maximum rooting depth	0.4	0.4	0.4	m

Out of all the crop parameters in Aqua Crop model, 16 of them were demonstrated or assumed to be conservative (constant). The same values of this set of 16 parameters (Table 4.13) were used in the validation reported here to further evaluate the performance and robustness of Aqua Crop model. These parameters are presumed to be applicable to a wide range of conditions and not specific for a given crop cultivar; the same parameters are used to simulate stress conditions, with stress effects manifested through the stress coefficients.

4.4.2 Green Canopy Cover, Biomass Yield

4.4.3 Green Canopy Cover

The results on green canopy cover analysis are presented in table 4.14. Water application rate had an effect on the development of canopy cover, this result also agreed with Wiedenfeld, (2000) who reported that the irrigation water level affected the growth development of sugar cane. The treatment under 100%ETc and 80%ETc had the largest canopy cover while the water stressed treatment (60 %, and 40%ETc) had the lowest canopy cover. This could be attributed to the continued water stress during the growing season for the treatments under 60 % of ETc. In addition, the treatment under 100%ETc attained maximum canopy cover earlier (55 days) than the other treatments (>65 days). This could be attributed to the increased water availability. The other treatments (60%, 40%ETc) on the other hand achieved early maximum canopy cover due to water stress. Water stress forced the crop under this treatment to attain maximum canopy cover much earlier.

Upon achieving maximum green canopy cover, within a few days, senescence was observed in all treatments influenced mainly due to the decreases of irrigation water application, The treatment under 100% and 80%ETc attained senescence later than the other three treatments because the soil have much moisture.

Table 4.13 Crop data input used in Aqua Crop to simulate French bean.

Parameter	Value	Unit or meaning
Base temperature	10	^{0}C
Cut-off temperature	27	^{0}C
CC per seeding at 90%emergence CC0	5	cm^2
Canopy growth coefficient CGC	0.14	Increase in CC relative to existing CC per GDD
Crop coefficient for transpiration at CC=100%	1.5	Full canopy transpiration relative to ETo
Decline in crop coefficient after reaching CC$^{\times}$	0.95	Decline per day due to leaf aging
Canopy decline coefficient CDC at senescence	0.033	Decrease in CC relative to CC per GDD
Water productivity	20	g(biomass)m^{-2}function of atmospheric CO_2
Leaf growth threshold p-upper	0.50	As fraction of TAW, above this leaf growth is inhibited
Leaf growth threshold p- lower	0.60	Leaf growth stops completely as this point
Leaf growth stress coefficient curve shape	3	Moderately convex curve
Stomata conductance threshold p-upper	0.50	Above these stomata begin to close
Stomata stress coefficient curve shape	3	Highly convex curve
Senescence stress coefficient curve p-upper	0.85	Above this early canopy senescence begin
Senescence stress coefficient curve shape	3	Moderately convex curve
Harvest index%	80	In the range of good crop condition

Table 4.14 Green Canopy Cover for Three seasons

	Season one (June- Sept 2016)			**Season two (Sept-Dec 2016)**			**Season three (Janu-Apr 2017)**		
	Canopy cover (mean)			**Canopy cover (mean**			**Canopy cover (mean)**		
Treat	**Obs**	**Simu**	**Dev±**	**Obs**	**Simu**	**Dev±**	**Obs**	**Simu**	**Dev±**
40%ETc	17.00	44.33	61.65	22.33	53.66	58.38	19.33	41.33	53.23
60%ETc	29.33	48.33	39.31	30.00	57.65	47.97	31.66	52.33	39.49
80%ETc	39.66	51.33	22.70	42.33	58.66	27.83	45.66	54.66	16.46
100%ETc	50.00	54.67	8.54	53.00	61.33	13.58	58.66	61.33	4.35

. The simulated above ground dry biomass agreed well with the observed biomass for T100%ETc and 80%ETc for 60% and 40%ETc there was over estimated by the model (Figure 4). There was strong relationship between the observed and simulated biomass (R2> 0.79). Table 4.14shows a deviation of the simulated pod yield and above ground biomass from their corresponding observed data. The deviation of the simulated above ground biomass from the observed data for all treatments there was an overestimation of above ground dry biomass by the model. Whereas the deviations of the simulated yield from the observed data for all the treatments shows there was as under estimation of pod yield of French bean crop by the model. Although not largely different, the pod yield was better simulated by the model when compared with the above ground biomass, which is in line with Araya, (2010).

Figure (4.1-4.12) below presents the simulation of CC for three seasons, with Aqua Crop after calibration. The observed and simulated CC development fitted well with adequate statistical values (Table 4.15) and followed standard logistic growth curve used for Aqua Crop for non-stressed conditions this results is in agreement with (Raes *et al*., 2010).

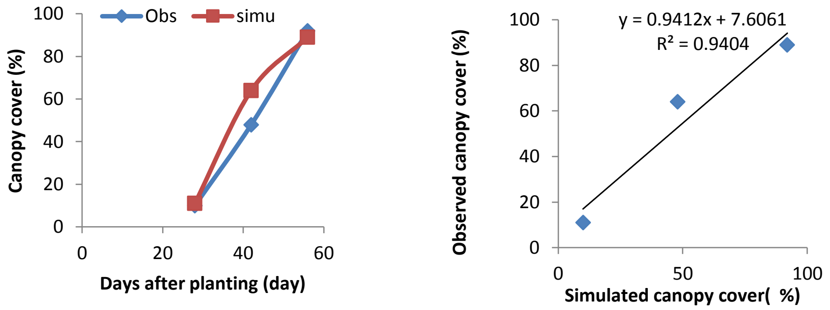

Figure 4.1 Simulation of CC for non-water stressed conditions in season one (100%ETc)

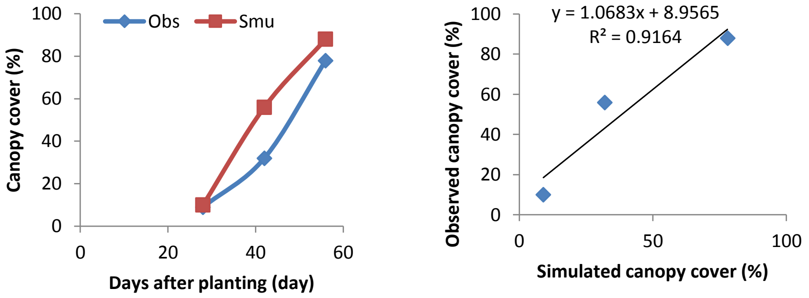

Figure 4.2 Simulation of CC for water stressed conditions season one (80%ETc)

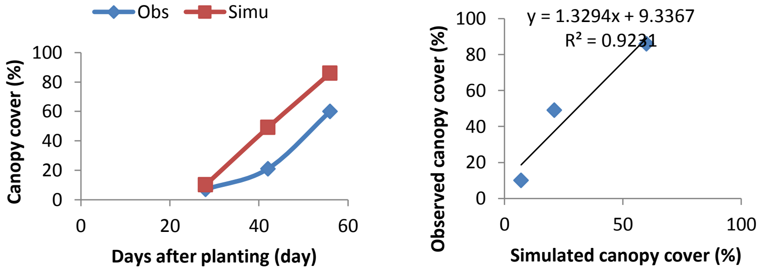

Figure 4.3 Simulation of CC for water stressed conditions season one(60%ETc)

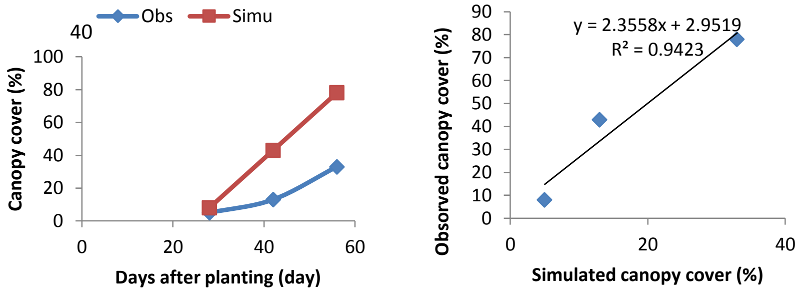

Figure 4.4 Simulation of CC for water stressed conditions season one (40%ETc)

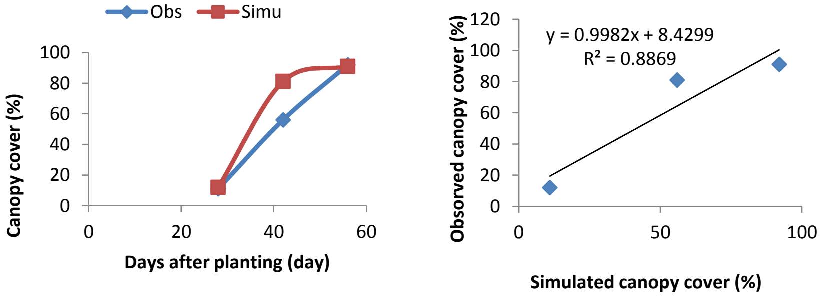

Figure 4.5 Simulation of CC for non-water stressed conditions in season two(100%ETc)

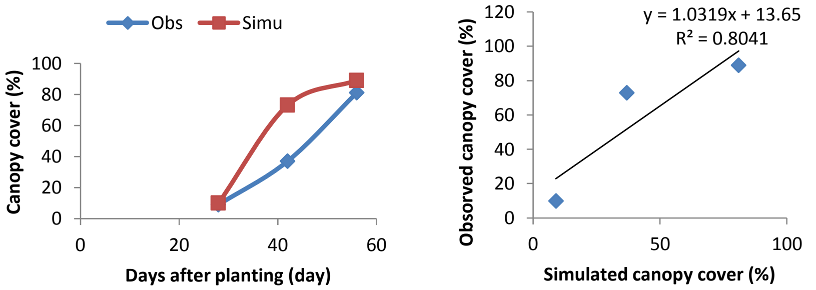

Figure 4.6 Simulation of CC for water stressed conditions season two (80%ETc)

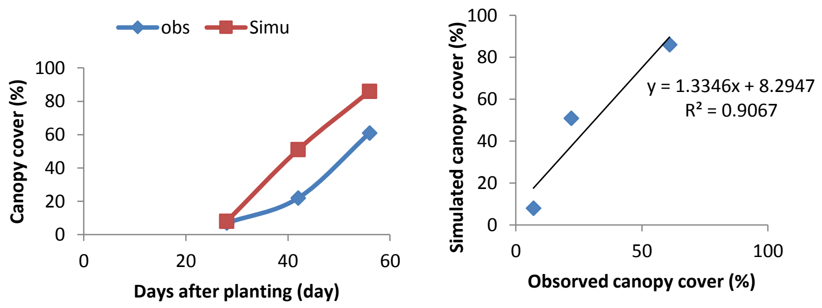

Figure 4.7 Simulation of CC for water stressed conditions season two (60%ETc)

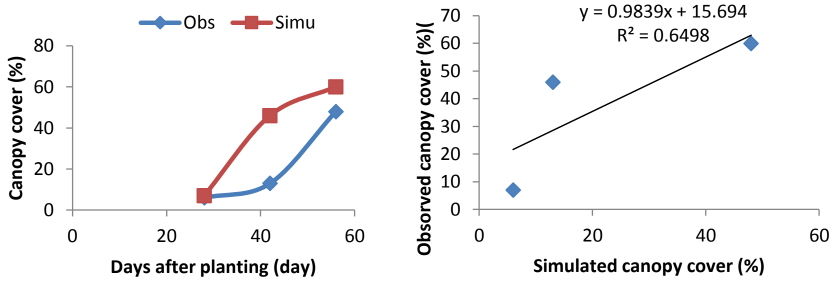

Figure 4.8 Simulation of CC for water stressed conditions season two(40%ETc)

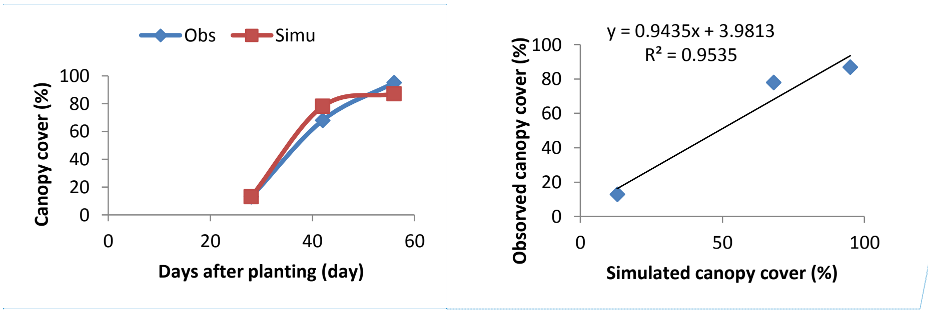

Figure 4.9Simulation of CC for non-water stressed conditions in season three(100%ETc)

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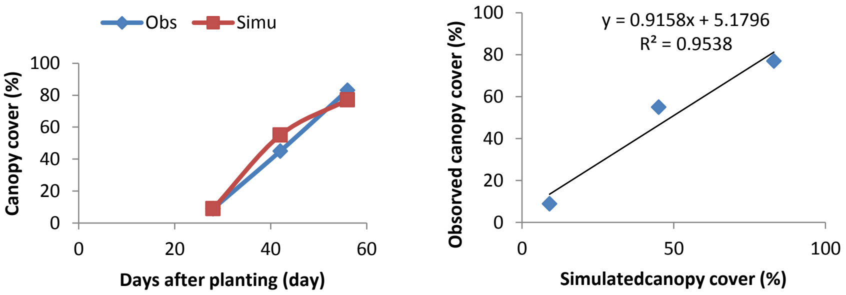

Figure 4.10 Simulation of CC for water stressed conditions season three (80%ETc)

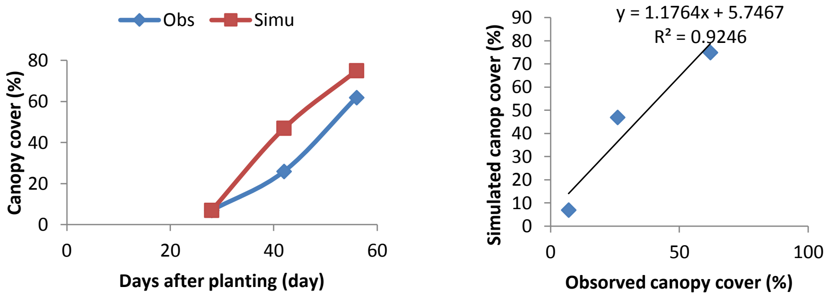

Figure 4.11Simulation of CC for water stressed conditions season three (60%ETc)

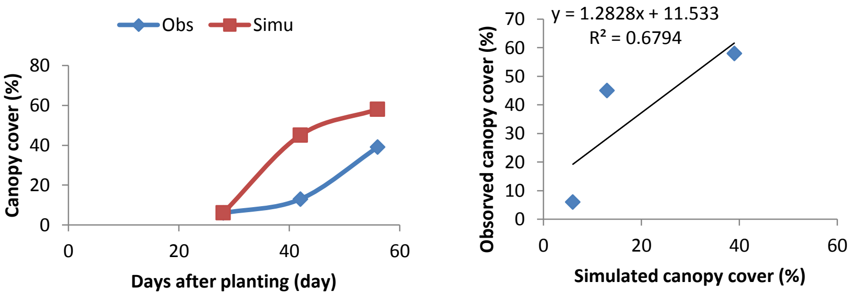

Figure 4.12 Simulation of CC for water stressed conditions season three (40%ETc)

4.4.4 Yield and biomass

As a summary of the outcome of the simulations, the simulated final biomass and pod yield of the different irrigation treatments were compared with the measured values in Table 4.15 with the deviation of the simulated value from the measured value expressed as a percentage of the measured value. When simulated final yield was compared with the measured yield, deviations ranged between 2.60 – 40.87 %. The smallest deviation recorded of 2.60 % was observed in the 100% ETc at second season and followed by 6.07 % obtained in the 80%ETc, and then largest deviation was 45.94% third season obtained under 40 % ETc. It was observed that the higher the amount of water application, the higher the accuracy in the predicted versus the measured yield. As regards biomass, the simulated values deviated from the measured by over 100% as shown in Table 5. Aqua Crop model did not compare the pod yield well with the measured yield in all the treatments under water stress.

The 100%ETc irrigation treatment had the highest yield as compared to the other treatments due to lack of water stress. (Steduto *et al*., 2009) explains that solar radiation is the driving force between biomass production and transpiration. Plants need to satisfy the evapotranspiration demand of the atmosphere. In order to capture carbon dioxide, stomata need to be open for evaporation to take place. If there is water stress, stomata close thus reducing the rate of photosynthesis and consequently transpiration is reduced thus ultimately affecting the yield. The 80, T60 and 40%ETc irrigation treatments had lower yields because of the reduced evaporation rate due to the closure of stomata, which retarded growth.

4.4.5 Validation

Results on the comparison of predicted canopy cover (CC) with measured CC are shown in Table 4.15. The results show the differences in the green canopy cover due to treatment effect. This was due to the higher amount of water transpired by the crop and increased vegetative growth. The results showed that the model over predicted green canopy cover in all the treatments and the over prediction increased with a decrease in water application rate. This may be attributed to the fact that the model predicts well under no water stress conditions. Consequently, green canopy cover with 100 % of ETc had values close to those of predicted green canopy cover. The deficit irrigated treatments of 60 %, and 40%ETc, produced lower green canopy cover values compared with the predicted green canopy cover. For the deficit irrigated treatment of 60 % of ETc, the model predicted well only during the initial growing period of the crop from 35 days after planting. Thereafter, the model did not predict well because as the crop progressed in growth, the demand for water increased while water supply was inadequate to meet crop water requirements. In addition, treatments under 80 % of ETc had a good prediction of crop growth during the initial growth stage (<40 days after planting), however, Aqua Crop over predicted the green canopy cover.

The treatment under 80 % of ETc showed the good prediction of canopy cover during the first 50 days after planting. Conversely, the 100 % of ETc showed good agreement in the prediction for most of the growing season up to about 61 days after transplanting. Water stress during most of the growing period was negligible.

Table 4.16 showed the model efficiency M (E) and root mean square error (RMSE), Deviation (Dev. %) and correlation of regression (R^2) was used to evaluate the model performance. These parameters showed good to moderate performance for the pod yield (E=0.95-0.98) for three seasons RMSE ranged between (0.85-2.15), R^2 ranged between (0.95 -0.98) according to the validation results. The calculated model efficiency ME was close to one that is the more robust the model. Good to moderate RMSE values indicate the good performance of the model. However, the model performs well to poor for more stress treatments for canopy cover. The observed and simulated yield and biomass for all the irrigation treatments are presented in Table 4.15.The model prediction of French bean yield showed a good agreement with observed values with an R^2 of 0.96, 0.97 and 0.99 for three seasons. (Fig.4.10). The Willmott's index of agreement was 0.90, 0.92 and 0.98 for three seasons and root mean square error was 0.98, 2.51and 2.75for three seasons.

Table 4.15 Observed and simulated yield and biomass for first second and third season

Seasons	**Treatment**	**Yield**		**Dev(±)**	**Above ground biomass**		**Dev(±)**
		Observed	**Simulated**		**Observed**	**Simulated**	
1st season (June – Sept 2016)	40%ETc	3158	4381	27.91	5831	6578	11.35
	60%ETc	4529	6388	29.10	8401	9516	11.71
	80%ETc	7271	8548	14.93	9861	10772	8.45
	100%ETc	8250	8898	7.28	10312	11151	7.52
2nd season (Sept – Dec 2016)	40%ETc	3190	5395	40.87	6743	7222	6.63
	60%ETc	4600	6698	31.32	8230	8836	5.83
	80%ETc	7430	8399	11.53	10490	11103	5.52
	100%ETc	8675	8907	2.60	11122	11228	0.94
3rd season (Jan – April 2017)	40%ETc	3230	4194	22.98	6830	4680	-45.94
	60%ETc	4659	5838	20.19	8900	6685	-33.13
	80%ETc	7702	7261	-6.07	10540	8358	-26.10
	100%ETc	8680	8944	2.95	11331	10280	-10.22

Table 4.16 Statistical indices derived for evaluating the performance of Aqua crop in predicting yield biomass and canopy cover.

Season	**Statistical index**	**Dev. (%)**	**RMSE**	**E**	**R^2**
1st (June-Sept 2016)	Yield (mean)	17.77	2.51	0.92	0.96
	Biomass (mean)	9.51	2.07	0.98	0.95
	CC 40% ETC	61.60	47.34	-4.81	0.94
	CC 60%ETc	39.31	32.90	0.24	0.92
	CC 80%ETc	22.72	20.21	0.81	0.91
	CC100%ETc	8.53	8.08	0.98	0.94
2nd (Sept – Dec 2016)	Yield	18.70	2.75	0.90	0.98
	Biomass	4.69	1.04	0.99	0.97
	CC40%ETc	58.00	53.99	-3.42	0.64
	CC 60%ETc	47.97	47.67	-0.91	0.90
	CC80%ETc	27.84	28.14	0.66	0.80
	CC100%ETc	13.58	14.34	0.94	0.96
3rd (Janu – April 2017)	Yield	7.49	0.98	0.98	0.95
	Biomass	-25	4.36	0.92	0.96
	CC40%ETc	46.78	29.29	-0.73	0.67
	CC60%ETc	26.35	19.33	0.71	0.92
	CC80%ETc	2.85	2.29	0.99	0.95
	CC100%ETc	1.29	1.15	0.99	0.95

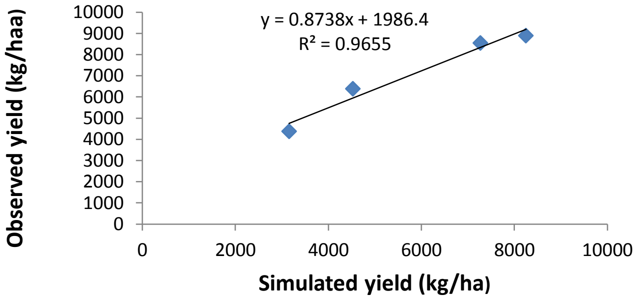

Figure 4:13 Observed and simulated yield first season

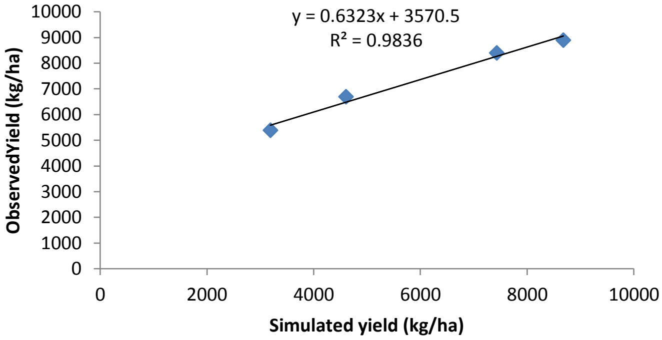

Figure 4:14 Observed and simulated yield second season

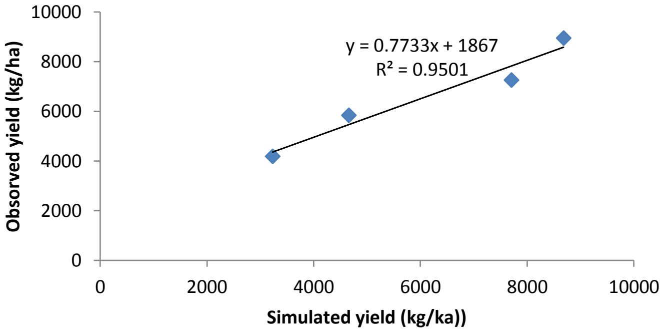

Figure 4:15Observed and simulated yield third season

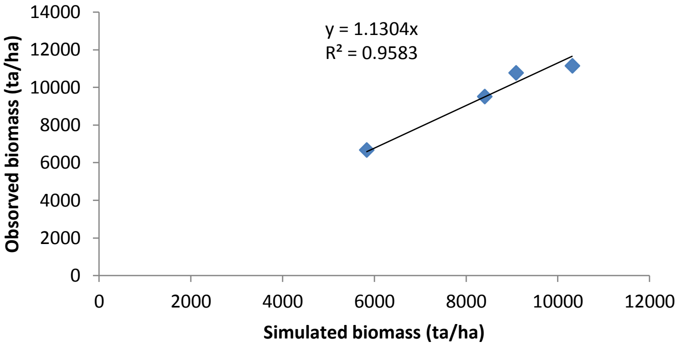

Figure 4:16 Observed and simulated biomass first season

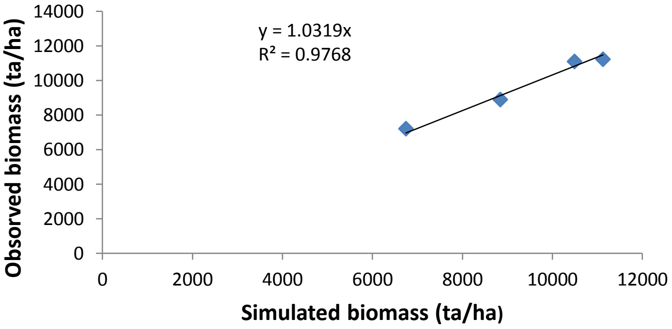

Figure 4:17 Observed and simulated biomass second season

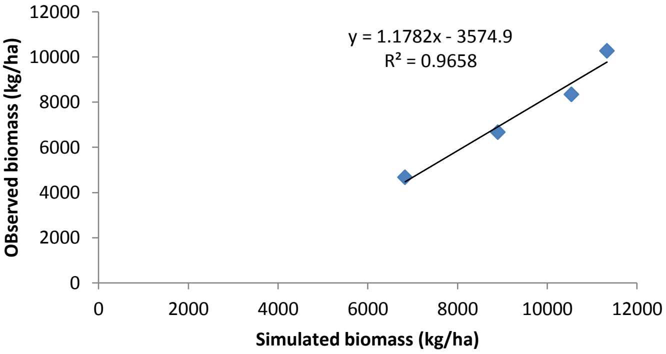

Figure 4:18 Observed and simulated biomass second season

4.5 Crop-water-production functions

CWPFs show the rate of transformation of production functions to yield. The mathematical functions of ETc and yield that better fit the production obtained with the water volume received (Mao *et al*., 2003). It is noted that there is no CWPF universally applicable to all crops, growing seasons and climatic zones. There is a need to establish the CWPFs using Aqua Crop model. The coefficient of determination of the regressed equation was 0.97, which shows good correlation between applied water and yield. The good relationship obtained in this study between crop performance and seasonal irrigation water demonstrates that, accurate estimates of water requirement on a seasonal basis can be valuable in irrigation management decisions and scheduling. The maximum yield (9540 kg ha-1) was obtained when the optimal gross irrigation water depth was 4478.67 m3/ha (average of three seasons).

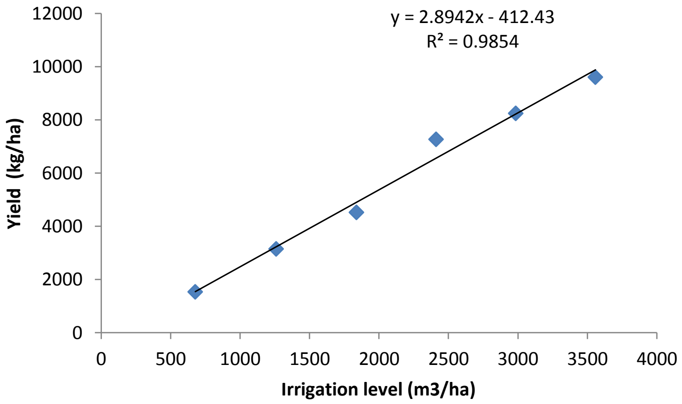

Figure 4:19 Yield and irrigation water applied for first season

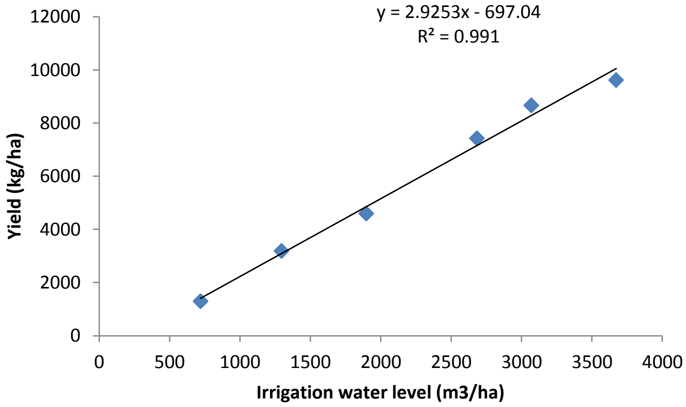

Figure 4:20 Yield and irrigation water applied for second season

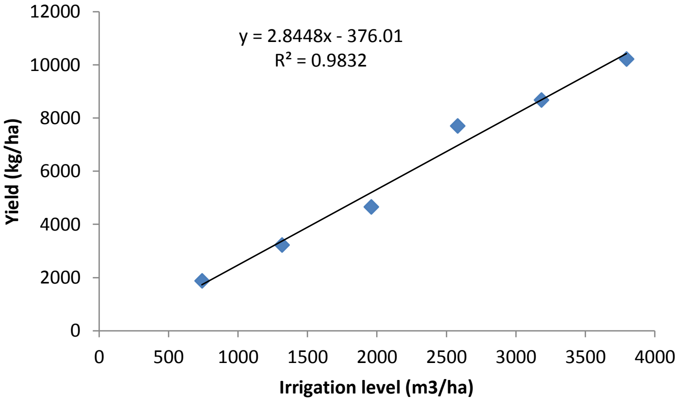

Figure 4:21Yield and irrigation water applied for third season

4.5.1 Yield – Water Relationship

The relationship between yield (kg ha-1) and the depth of irrigation water for each treatment in the three seasons is presented in Table (16). The average yield under deficit irrigation is about 7250, kg ha-1. One also should notice that treatment 80% ETc that received 241 mm irrigation water throughout the growing season produced 7201 kg ha-1. The yield reduction in 80% ETc was much less than those observed in the treatment 60% to 40% and 20% ETc had shown the yield reduction of 45.61, 61.81 and 80.72%, respectively as compared to the 80% ETc treatment resulted in yield reduction of 12.73 respectively.

From the above result it can be observed that the yield reduction is lower if the crop is 20 and 40% deficit rather than 60 and 80% deficit the crop throughout the growing season. Similarly, Ngouajio *et al*., 2008) was reported that 34% less water supply resulted in yield reduction of 42% and 20% less water resulted in yield reduction of 27% .

Table 4.17 Yield reduction and water saved for all the seasons

Seasons	Treatment	Irrigation water m^3	Yield (t/ha)	Yield reduction %	Water saved %
1st (June – September 2016)	20%ETc	676.70	1546	81.26	80
	40%ETc	1259.20	3158	61.17	60
	60%ETc	1838.10	4529	45.21	40
	80%ETc	2411.40	7271	11.86	20
	100%ETc	2984.50	8250	0.00	0.0
	120%ETc	3557.60	9608	-16.46	+20
2nd (September – December 2016)	20%ETc	718.70	1304	84.96	80
	40%ETc	1295.20	3190	63.22	60
	60%ETc	1896.80	4600	46.97	40
	80%ETc	2682.60	7430	14.35	20
	100%ETc	3070.00	8675	0.00	0.0
	120%ETc	3672.00	9628	-10.98	+20
3rd (January – April 2017)	20%ETc	740.00	1875	78.38	80
	40%ETc	1317.40	3230	62.78	60
	60%ETc	1959.20	4659	46.32	40
	80%ETc	2580.40	7702	11.26	20
	100%ETc	3184.20	8680	0.00	0.00
	120%ETc	3795.20	10220	-17.74	+20

This consistent decrease in the pod yield production with the decrease for water could be explained by the fact that when full crop water requirement is not met, water deficit in the plant causes stomata closure for the plant to save water, but at the expense of photosynthesis and biomass production Kassam and Smith, (2001).

4.5.2 Yield Response Factors

The yield response factor (ky) was derived from the relationship of relative yield reduction (1-Ya/Ym) and relative evapotranspiration deficits (1-ETa/ETm) for the whole growing period and are given in Table 11. According to this relationship, water stress throughout the growth stage, 80% ETc had limited effect on French bean .Observed yield response factors (ky) for French bean ranged between 0.5 and 1.33, the lowest and highest being for 80% and 60% ETc irrigation levels, respectively Table 17. Deficit irrigations level, 80% ETc of the full irrigation in this experiment is therefore useful in saving irrigation water.

Table 4:18 Yield response factor of deficit irrigated French bean

Seasons	Treatment	Yield (kg/ha)	Net Irrigation (mm)	1-Ya/Ym	I- ETa/ETm	ky
1st (June – September 2016)	20% ETc	1546	67.67	0.81	0.77	1.05
	40%ETc	3158	125.92	0.61	0.57	1.07
	60%ETc	4529	183.81	0.45	0.54	0.83
	80%ETc	7271	241.14	0.13	.0.39	0.33
	100%ETc	8250	298.45	-	-	-
	120%ETc	8608	355.76	-0.04	-0.19	0.21
2nd (September – December 2016)	20% ETc	1304	71.87	0.85	0.77	1.10
	40%ETc	3190	129.52	0.63	0.58	1.08
	60%ETc	4600	189.68	0.47	0.38	1.23
	80%ETc	7430	268.26	0.12	0.13	0.92
	100%ETc	8675	307.00	-	-	-
	120%ETc	9628	367.00	-0.11	-0.19	0.58
3rd (January – April 2017)	20% ETc	1575	74.00	0.82	0.77	1.06
	40%ETc	3230	131.74	0.63	0.59	1.07
	60%ETc	4659	195.92	0.46	0.38	1.21
	80%ETc	7702	258.04	0.11	0.19	0.58
	100%ETc	8680	318.42	-	-	-
	120%ETc	10220	379.52	-0.17	0.19	0.89

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The purpose of the current study was to determine the effectiveness of adopting efficient economical irrigation water application techniques and developing water management technologies, which can be used in combination with Aquacrop model to maximize the benefits of irrigation while improving water use efficiency. It was based on the application of four different level of water application using drip irrigation system for French beans crop in Njoro Nakuru County – Kenya. These works were out lined in section (i), (ii), (iii), (iv) below.

i) Objective 1: To determine the effectiveness of deficit irrigation on crop performance

It is concluded that growth parameters (plant height, number of branches and leaf area index) were significantly ($P < 0.001$) influenced by deficit irrigation levels. Number of branches and highest plant height were observed from full irrigation followed by 80% ETc irrigation levels. In this study 40% ETc deficit irrigation levels had shorter plant height, less number of branches, smaller leaf area index and lower yield.

ii) Objective 2: To determine the water use efficiency of French beans under deficit irrigation.

It is concluded that the irrigation water use efficiency and crop water use efficiency obtained from 80%ETc irrigation levels were relatively higher than the 100%, 120%, 60% and 20% ETc deficit irrigation levels.

iii) Objective 3: To calibrate and validate Aqua Crop model for simulation of the yield of French bean.

It is concluded that Aqua Crop predicted good, the cumulative green canopy cover and cumulative biomass production in the 100%ETc and predicted total biomass acceptable to poor under the 80% ETc treatments.

It is concluded that Aqua Crop model was, however, less satisfactory in predicting yields in severely water stressed treatments (40%ETc). This needs further studies to consider different French bean genotypes with different climatic conditions.

iv) Objective 4: To determine the crop water production function for French beans using irrigation scheduling.

It is concluded that it is better to irrigate French bean either with 100% ETc during the time when water is available/ rain fall is abundant or application of 80% ETc during water scarcity periods.

5.2 Recommendations:

The present research focused on the effectiveness of deficit irrigation on crop growth of French bean, to find out the best water use efficiency under deficit irrigation and to test the ability of AquaCrop Model to simulate yield and growth of French bean under condition in Njoro Nakuru County, Kenya. From the present research findings it is recommended that more research should be conducted in the following areas:

i) Evaluation of crop yield response to water stress of different French bean growth stages.
ii) Effectiveness of deficit irrigation on French bean yield quality and nutrient.
iii) Application of Aqua Crop model for simulating yield of French bean under deficit irrigation of different crop stages and different regions.

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APPENDIX

Appendix A.1 Historical ETo (2001-2015) using ETo calculator penmen Montieth methods

Years	Jan	Feb	March	Apr	May	Jun	Jul	Agus	Sep	Octo	Nov	Dec
2001	4.3	4.32	4.29	4.25	4.27	4.1	4.0	4.12	4.2	4.22	4.15	4.17
2002	4.27	4.33	4.32	4.33	4.25	4.15	4.14	4.18	4.22	4.28	4.25	4.25
2003	4.19	4.40	4.43	4.39	4.27	4.17	4.09	4.07	4.20	4.20	4.19	4.16
2004	4.24	4.32	4.40	4.33	4.20	4.06	4.06	4.14	4.23	4.19	4.18	4.23
2005	4.32	4.40	4.47	4.42	4.30	4.17	4.08	4.12	4.18	4.25	4.21	4.25
2006	4.27	4.41	4.39	4.31	4.29	4.25	4.17	4.14	4.20	4.32	4.22	4.24
2007	4.27	4.44	4.34	4.30	4.37	4.22	4.14	4.18	4.17	4.16	4.14	4.17
2008	4.22	4.29	4.49	4.25	4.24	4.34	4.11	4.15	4.28	4.22	4.32	4.27
2009	4.29	4.39	4.53	4.44	4.37	4.25	4.06	4.25	4.40	4.35	4.29	4.32
2010	4.29	4.47	4.35	4.40	4.33	4.20	4.18	4.49	4.19	4.32	4.17	428
2011	4.28	4.37	4.42	4.37	4.32	4.28	4.15	4.13	4.19	4.19	4.25	4.22
2012	4.18	4.27	4.40	4.42	4.28	4.19	4.13	4.15	4.22	4.30	4.24	4.23
2013	4.22	4.34	4.50	4.49	4.30	4.24	4.18	4.14	4.30	4.33	4.27	4.20
2014	4.38	4.32	4.40	4.34	4.34	4.25	4.20	4.23	4.23	4.35	4.32	4.28
2015	4.35	4.49	4.49	4.48	4.42	4.32	4.28	428	4.39	4.43	4.43	4.29
Total	64.07	65.56	69.83	65.52	68.74	58.1	61.92	62.77	63.6	64.17	76.3	63.47
Aver	**4.3**	**4.4**	**4.7**	**4.4**	**4.6**	**3.9**	**4.1**	**4.2**	**4.3**	**4.3**	**4.2**	**4.2**

Appendix A.2 Amount of irrigation water applied during the first season

Date	ETc	Growth stage	Interval	Irrigation Treatments					
				100%	80%	60%	40%	20%	120%
22-Jun	1.95	Initial	2	3.90	3.9	3.90	3.90	3.90	3.90
24-Jun	1.95	Initial	2	3.90	3.9	3.90	3.90	3.90	3.90
26-Jun	1.95	Initial	2	3.90	3.9	3.90	3.90	3.90	3.90
28-Jun	1.95	Initial	2	3.90	3.12	2.32	1.56	0.78	4.68
30-Jun	1.95	Initial	2	4.00	3.2	2.40	1.60	0.80	4.8
02-Jul	2.05	Initial	2	4.10	3.28	2.46	1.56	0.82	4.92
04-Jul	2.05	Initial	2	4.10	3.28	2.46	1.56	0.82	4.92
06-Jul	2.05	Initial	2	4.10	3.28	2.46	1.56	0.82	4.92
08-Jul	2.05	Initial	2	4.10	3.28	2.46	1.56	0.82	4.92
10-Jul	2.05	Initial	2	4.10	3.28	2.46	1.56	0.82	4.92
12-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
14-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
16-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
18-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
20-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
22-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
24-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
26-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
28-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
30-Jul	3.08	Deve	2	6.16	4.93	3.70	2.46	1.23	7.39
01-Aug	3.15	Deve	2	6.30	5.04	3.78	2.52	1.26	7.56
03-Aug	3.15	Deve	2	6.30	5.04	3.78	2.52	1.26	7.56
05-Aug	3.15	Deve	2	6.30	5.04	3.78	2.52	1.26	7.56
07-Aug	3.15	Deve	2	6.30	5.04	3.78	2.52	1.26	7.56
09-Aug	3.15	Deve	2	6.30	5.04	3.78	2.52	1.26	7.56
11-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.26	11.59
13-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.26	11.59
15-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.93	11.59
17-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.93	11.59
19-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.93	11.59
21-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.93	11.59
23-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.93	11.59
25-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.93	11.59
27-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.93	11.59
29-Aug	4.83	Mid	2	9.66	7.73	5.80	3.86	1.93	11.59
31-Aug	4.83	Mid	2	9.78	7.82	5.87	3.91	1.96	11.74
02-Sep	4.95	Mid	2	9.90	7.92	5.94	3.96	1.98	11.88
04-Sep	4.95	Mid	2	9.90	7.92	5.94	3.96	1.98	11.88

06-Sep	4.95	Mid	2	9.90	7.92	5.94	3.96	1.98	11.88
08-Sep	4.95	Mid	2	9.90	7.92	5.94	3.96	1.98	11.88
10-Sep	4.95	Late	2	7.70	6.16	4.62	3.08	1.54	9.24
12-Sep	3.87	Late	2	7.70	6.16	4.62	3.08	1.54	9.24
14-Sep	3.87	Late	1	3.87	3.1	2.32	1.55	0.77	4.64
Total			85	298.45	241.14	183.81	125.92	67.67	355.76

Appendix A.3 Amount of irrigation water applied during the second season

Date	**ETc**	**Growth stage**	**Interval**	**Irrigation Treatments**					
				100%	**80%**	**60%**	**40%**	**20%**	**120%**
18/9/016	2.15	Initial	2	4.30	4.30	4.30	4.30	4.30	4.30
20-Sep	2.15	Initial	2	4.30	4.30	4.30	4.30	4.30	4.30
22-Sep	2.15	Initial	2	4.30	4.30	4.30	4.30	4.30	4.30
24-Sep	2.15	Initial	2	4.30	4.30	4.30	4.30	4.30	4.30
26-Sep	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
28-Sep	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
30-Sep	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
02-Oct	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
04-Oct	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
06-Oct	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
08-Oct	2.69	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
10-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
12-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
14-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
16-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
18-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
20-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
22-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
24-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
26-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
28-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
30-Oct	3.23	Deve	2	6.46	5.17	3.88	2.58	1.30	7.87
01-Nov	3.15	Deve	2	6.30	5.04	3.78	2.52	1.30	7.56
03-Nov	3.15	Deve	2	6.30	5.04	3.78	2.52	1.30	7.56
05-Nov	3.15	Deve	2	6.30	5.04	3.78	2.52	1.30	7.56
07-Nov	3.99	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
09-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
11-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59

13-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
15-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
17-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
19-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
21-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
23-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
25-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
27-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
29-Nov	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
01-Dec	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
03-Dec	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
05-Dec	4.83	Mid	2	9.66	7.73	5.80	3.80	1.93	11.59
07-Dec	4.83	Late	2	7.56	6.05	4.54	1.51	1.50	9.07
09-Dec	3.78	Lat	2	7.56	6.05	4.54	1.51	1.50	9.07
11-Dec	3.78	Lat	2	7.56	6.05	4.54	1.51	1.50	9.07
	153.17		86	307	248.24	189.48	124.99	71.87	367.2

Appendix A.4 Amount of irrigation water applied during the third season

Date	**ETc**	**Growth stage**	**Interval**	**Irrigation Treatments**					
				100%	**80%**	**60%**	**40%**	**20%**	**120%**
4/1/017	2.15	Initial	2	4.30	4.30	4.30	4.30	4.30	4.30
06-Jan	2.15	Initial	2	4.30	4.30	4.30	4.30	4.30	4.30
08-Jan	2.15	Initial	2	4.30	4.30	4.30	4.30	4.30	4.30
10-Jan	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
12-Jan	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
14-Jan	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
16-Jan	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
18-Jan	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
20-Jan	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
22-Jan	2.15	Initial	2	4.30	3.44	2.58	1.72	0.86	5.16
24-Jan	2.15	Deve	2	6.50	5.20	3.90	2.60	1.30	7.80
26-Jan	3.23	Deve	2	6.50	5.20	3.90	2.60	1.30	7.80
28-Jan	3.23	Deve	2	6.50	5.20	3.90	2.60	1.32	7.80
30-Jan	3.23	Deve	2	6.50	5.20	3.90	2.60	1.32	7.80
01-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
03-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
05-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
07-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92

09-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
11-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
13-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
15-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
17-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
21-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
23-Feb	3.3	Deve	2	6.60	5.28	3.96	2.64	1.32	7.92
25-Feb	5.06	Mid	2	10.10	8.08	6.06	4.04	2.02	12.12
27-Feb	5.06	Mid	2	10.10	8.08	6.06	4.04	2.02	12.12
01-Mar	5.06	Mid	2	10.10	8.8	6.06	4.04	2.02	12.12
03-Mar	5.41	Mid	2	10.80	8.64	6.06	4.04	2.16	12.96
05-Mar	5.41	Mid	2	10.80	8.64	6.60	4.04	2.16	12.96
07-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
09-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
11-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
13-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
15-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
17-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
19-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
21-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
23-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
25-Mar	5.41	Mid	2	10.80	8.64	6.48	4.04	2.16	12.96
27-Mar	4.23	Mid	2	8.46	6.77	5.08	3.38	1.69	10.15
29-Mar	4.23	Mid	2	8.46	6.77	5.08	3.38	1.69	10.15
Total	158.2		84	318.42	258.04	195.92	131.74	74.04	379.52

Appendix A.5 SAS output number of branches season one

```
Dependent Variable: Number of branches (8 week)

                              Sum of
    Source            DF      Squares        Mean Square   F Value   Pr > F

    Model              3      28.91666667    9.63888889    38.56     <.0001

    Error              8       2.00000000     0.25000000

    Corrected Total   11      30.91666667

              R-Square    Coeff Var    Root MSE    Nb8w Mean

              0.935310     6.741573    0.500000     7.416667
```

Appendix A.6 SAS output plant height season one

Dependent Variable: Plant height (8 wee)

```
                              Sum of
Source              DF       Squares      Mean Square   F Value   Pr > F
Model                3    351.4025000    117.1341667    112.90   <.0001
Error                8      8.3000000      1.0375000
Corrected Total     11    359.7025000
          R-Square    Coeff Var    Root MSE    Ph8w Mean
          0.976925     2.736273    1.018577     37.22500
```

Appendix A.7 SAS output leaf area index season one

Dependent Variable: LAI (8week)

```
                              Sum of
Source              DF       Squares      Mean Square   F Value   Pr > F
Model                3    17.55163333     5.85054444     36.20   <.0001
Error                8     1.29293333     0.16161667
Corrected Total     11    18.84456667
          R-Square    Coeff Var    Root MSE    LAI8w Mean
          0.931390     17.39073    0.402016     2.311667
```

Appendix 4.8 SAS output number of branches seasons two

Dependent Variable: Number of branches (8 week)

```
                              Sum of
Source              DF      Squares       Mean Square    F Value   Pr > F
Model                3    33.66666667    11.22222222     67.33   <.0001
Error                8     1.33333333     0.16666667
Corrected Total     11    35.00000000
          R-Square    Coeff Var    Root MSE    Nb8w Mean
          0.961905     5.443311    0.408248     7.500000
```

Appendix A.9 SAS output plant height season two

```
Dependent Variable: Plant height (8 week)                        Sum of
     Source               DF       Squares        Mean Square    F Value   Pr > F
     Model                 3     502.0625000     167.3541667      85.90    <.0001
     Error                 8     15.5866667       1.9483333
     Corrected Total      11     517.6491667
                R-Square    Coeff Var     Root MSE     Ph8w Mean
                0.969890     3.776759     1.395827     36.95833
```

Appendix A.10 SAS output leaf area index season two

```
Dependent Variable: LAI (8week)
                                        Sum of
     Source               DF       Squares       Mean Square    F Value   Pr > F
     Model                 3     18.71353333     6.23784444      29.16    0.0001
     Error                 8     1.71133333      0.21391667
     Corrected Total      11     20.42486667
                R-Square    Coeff Var     Root MSE    LAI8w Mean
                0.916213    18.92952      0.462511     2.443333
```

Appendix A.11 SAS output number of branches season three

```
Dependent Variable: Number of branches (8week)
                                       Sum of
     Source               DF       Squares        Mean Square    F Value   Pr > F
     Model                 3     40.33333333     13.44444444      80.67    <.0001
     Error                 8      1.33333333      0.16666667
     Corrected Total      11     41.66666667
                R-Square    Coeff Var     Root MSE     Nb8w Mean
                0.968000     5.211680     0.408248     7.833333
```

Appendix A.12 SAS output plant height season three

```
Dependent Variable: Plant height (8 week)
                              Sum of
  Source            DF       Squares      Mean Square     F Value   Pr > F
  Model              3    577.6966667    192.5655556      298.55   <.0001
  Error              8      5.1600000      0.6450000
  Corrected Total   11    582.8566667
          R-Square    Coeff Var     Root MSE    Ph8w Mean
          0.991147     2.001958     0.803119     40.11667
```

Appendix A.13 SAS output leaf area index season three

```
Dependent Variable: LAI (8 week)
                              Sum of
  Source            DF       Squares      Mean Square   F Value   Pr > F
  Model              3    23.53169167     7.84389722    137.55   <.0001
  Error              8     0.45620000     0.05702500
  Corrected Total   11    23.98789167
          R-Square    Coeff Var     Root MSE   LAI8w Mean
          0.980982     9.276753     0.238799     2.574167
```

Appendix A.14 French beans parameters used to calibrate AquaCrop model

```
french beans source variety
     4.0       : AquaCrop Version (June 2012)
     1         : File not protected
     2         : fruit/grain producing crop
     1         : Crop is sown
     0         : Determination of crop cycle : by growing degree-days
     1         : Soil water depletion factors (p) are adjusted by ETo
    10.0       : Base temperature (°C) below which crop development
does not progress
    27.0       : Upper temperature (°C) above which crop development no
longer increases with an increase in temperature
   647         : Total length of crop cycle in growing degree-days
     0.20      : Soil water depletion factor for canopy expansion (p-
exp) - Upper threshold
     0.60      : Soil water depletion factor for canopy expansion (p-
exp) - Lower threshold
     3.0       : Shape factor for water stress coefficient for canopy
expansion (0.0 = straight line)
     0.50      : Soil water depletion fraction for stomatal control (p
- sto) - Upper threshold
```

```
     3.6       : Shape factor for water stress coefficient for stomatal
control (0.0 = straight line)
     0.70      : Soil water depletion factor for canopy senescence (p -
sen) - Upper threshold
     3.0       : Shape factor for water stress coefficient for canopy
senescence (0.0 = straight line)
     0         : Sum(ETo) during stress period to be exceeded before
senescence is triggered
     0.90      : Soil water depletion factor for pollination (p - pol)
- Upper threshold
     5         : Vol% for Anaerobiotic point (* (SAT - [vol%]) at which
deficient aeration occurs *)
    50         : Considered soil fertility/salinity stress for
calibration of stress response (%)
    25.00      : Response of canopy expansion is not considered
    25.00      : Response of maximum canopy cover is not considered
    25.00      : Response of crop Water Productivity is not considered
    25.00      : Response of decline of canopy cover is not considered
    25.00      : Response of stomatal closure is not considered
     8         : Minimum air temperature below which pollination starts
to fail (cold stress) (˚C)
    40         : Maximum air temperature above which pollination starts
to fail (heat stress) (˚C)
    -9.0       : Cold (air temperature) stress on production of above
ground biomass not considered
    -9         : Electrical Conductivity of soil saturation extract at
which crop starts to be affected by soil salinity (dS/m)
    -9         : Electrical Conductivity of soil saturation extract at
which crop can no longer grow (dS/m)
     3.0       : Shape factor for soil salinity stress coefficient
(coefficient > 0: convex)
     0.95      : Crop coefficient when canopy is complete but prior to
senescence (KcTr,x)
     0.150     : Decline of crop coefficient (%/day) as a result of
ageing, nitrogen deficiency, etc.
     0.20      : Minimum effective rooting depth (m)
     0.40      : Maximum effective rooting depth (m)
    12         : Shape factor describing root zone expansion
     0.059     : Maximum root water extraction (m3water/m3soil.day) in
top quarter of root zone
     0.016     : Maximum root water extraction (m3water/m3soil.day) in
bottom quarter of root zone
    90         : Effect of canopy cover in reducing soil evaporation in
late season stage
     5.00      : Soil surface covered by an individual seedling at 90 %
emergence (cm2)
   148148      : Number of plants per hectare
     0.14632   : Canopy growth coefficient (CGC): Increase in canopy
cover (fraction soil cover per day)
    -9         : Maximum decrease of Canopy Growth Coefficient in and
between seasons - Not Applicable
    -9         : Number of seasons at which maximum decrease of Canopy
Growth Coefficient is reached - Not Applicable
    -9.0       : Shape factor for decrease Canopy Growth Coefficient -
Not Applicable
     0.92      : Maximum canopy cover (CCx) in fraction soil cover
     0.03315   : Canopy decline coefficient (CDC): Decrease in canopy
cover (in fraction per day)
```

```
    12         : Calendar Days: from sowing to emergence
    51         : Calendar Days: from sowing to maximum rooting depth
    71         : Calendar Days: from sowing to start senescence
    98         : Calendar Days: from sowing to maturity (length of crop
cycle)
    51         : Calendar Days: from sowing to flowering
    30         : Length of the flowering stage (days)
     1         : Crop determinancy linked with flowering
    50         : Excess of potential fruits (%)
    41         : Building up of Harvest Index starting at flowering
(days)
    20.0       : Water Productivity normalized for ETo and CO2 (WP*)
(gram/m2)
   100         : Water Productivity normalized for ETo and CO2 during
yield formation (as % WP*)
    50         : Crop performance under elevated atmospheric CO2
concentration (%)
    80         : Reference Harvest Index (HIo) (%)
    10         : Possible increase (%) of HI due to water stress before
flowering
    10.0       : Coefficient describing positive impact on HI of
restricted vegetative growth during yield formation
     8.0       : Coefficient describing negative impact on HI of
stomatal closure during yield formation
    15         : Allowable maximum increase (%) of specified HI
    70         : GDDays: from sowing to emergence
   314         : GDDays: from sowing to maximum rooting depth
   468         : GDDays: from sowing to start senescence
   647         : GDDays: from sowing to maturity (length of crop cycle)
   306         : GDDays: from sowing to flowering
   214         : Length of the flowering stage (growing degree days)
     0.022539  : CGC for GGDays: Increase in canopy cover (in fraction
soil cover per growing-degree day)
     0.005186  : CDC for GGDays: Decrease in canopy cover (in fraction
per growing-degree day)
   286         : GDDays: building-up of Harvest Index during yield
formation
```

Appendix A. 15 Project Run out put 100%ETc season one
AquaCrop 4.0 (June 2012) - Output created on (date): 11/09/2018   at (time): 13:36:17

```
Simulation run

  RunNr    Day1   Month1    Year1    Rain     ETo      GD     CO2      Irri    Infilt  Runoff    Drain  Upflow

                                                 mm       mm    °C.day    ppm     mm      mm        mm        mm        mm

      1        22        6           2016      0       378       651      401.57   306      306       0           77        0


E     E/Ex      Tr   Tr/Trx    SaltIn   SaltOut    SaltUp   SaltProf    Cycle   SaltStr   FertStr  TempStr   ExpStr

mm       %    mm       %    ton/ha    ton/ha    ton/ha    ton/ha      days        %        %           %           %

52       95      212       96   0.196     0.061       0.000      0.134         86       0         0           0           0


StoStr  BioMass  Brelative   HI     Yield      WPet          DayN    MonthN    YearN

 %        ton/ha         %          %       ton/ha    kg/m3

3          11.151        96       79.8       8.898      3.37           27          9            2016
```

Appendix A.16 Project Run out put 80%ETc season one
AquaCrop 4.0 (June 2012) - Output created on (date) : 11/09/2018   at (time) : 14:36:14

```
Simulation run

  RunNr    Day1   Month1    Year1    Rain     ETo      GD     CO2      Irri   Infilt   Runoff    Drain   Upflow
                                                 mm       mm    °C.day    ppm    mm       mm       mm        mm     mm
      1        22       6             2016       0     378        651    401.57    254      254       0         37        0

E     E/Ex        Tr   Tr/Trx    SaltIn   SaltOut    SaltUp   SaltProf   Cycle   SaltStr   FertStr   TempStr   ExpStr
mm     %       mm       %     ton/ha    ton/ha    ton/ha   ton/ha      days       %          %        %             %
50      93      204       93    0.163     0.017     0.000       0.145          86       0           0            0           0

StoStr   BioMass   Brelative   HI    Yield     WPet      DayN   MonthN    YearN
%           ton/ha         %            %      ton/ha    kg/m3
6          10.772          93          79.4    8.548      3.36          27        9             2016
```

Appendix A.17 Project Run out put 60%ETc season one

```
AquaCrop 4.0 (June 2012) - Output created on (date) : 11/09/2018   at (time) : 14:43:39
Simulation run

   RunNr    Day1   Month1   Year1    Rain     ETo     GD     CO2      Irri   Infilt  Runoff   Drain   Upflow
                                      mm       mm    °C.day   ppm     mm     mm       mm       mm       mm
     1       22       6       2016     0       378     651    401.57   181    181      0       19       0

E    E/Ex     Tr   Tr/Trx   SaltIn  SaltOut   SaltUp  SaltProf    Cycle  SaltStr  FertStr TempStr  ExpStr
mm      %    mm      %     ton/ha   ton/ha   ton/ha   ton/ha      days     %        %       %       %
48     90    153     70     0.116    0.003    0.000    0.113       86      0        0       0        4

StoStr  BioMass  Brelative  HI    Yield     WPet    DayN  MonthN   YearN
%        ton/ha      %       %    ton/ha   kg/m3
 21      8.401       73     76.0   6.388    3.17     27      9       2016
```

Appendix A.18 Project Run out put 40%ETc season one

```
AquaCrop 4.0 (June 2012) - Output created on (date) : 04/09/2018   at (time) : 11:54:19
Simulation run

   RunNr    Day1   Month1   Year1    Rain     ETo     GD     CO2      Irri   Infilt  Runoff   Drain   Upflow
                                      mm       mm    °C.day   ppm     mm     mm       mm       mm       mm
     1       22       6       2016     0       378     651    401.57   135    135      0       10       0

E    E/Ex     Tr   Tr/Trx   SaltIn  SaltOut   SaltUp  SaltProf    Cycle  SaltStr  FertStr  TempStr  ExpStr
mm     %     mm      %     ton/ha   ton/ha   ton/ha   ton/ha      days     %       %         %        %
46     87    119     57     0.086    0.001    0.000    0.086       86      0       0         0        23

StoStr  BioMass  Brelative  HI    Yield    WPet     DayN  MonthN   YearN
  %       ton/ha     %       %    ton/ha   kg/m3
  30      6.578      58     66.6   4.381    2.65     27      9       2016
```

Appendix A. 19 Project Run out put 100%ETc season two

```
AquaCrop 4.0 (June 2012) - Output created on (date) : 11/09/2018   at (time) : 15:18:11
Simulation run

   RunNr    Day1   Month1    Year1     Rain     ETo      GD     CO2      Irri     Infilt   Runoff    Drain   Upflow
                                        mm       mm   °C.day   ppm      mm       mm     mm        mm       mm
      1      18        9             2016       0        327       652     401.57   288      288      0         74         0
E    E/Ex      Tr   Tr/Trx    SaltIn   SaltOut    SaltUp   SaltProf     Cycle   SaltStr  FertStr  TempStr   ExpStr
mm   %      mm    %      ton/ha    ton/ha    ton/ha    ton/ha      days      %        %           %          %
46    93      187     100    0.184    0.083    0.000    0.101        79        0         0            0         0

StoStr   BioMass   Brelative   HI      Yield      WPet      DayN   MonthN    YearN
%          ton/ha       %            %      ton/ha    kg/m3
 0         11.129     100        80.0    8.907      3.83        15        12         2016
```

Appendix A.20 Project Run out put 80%ETc season two

```
AquaCrop 4.0 (June 2012) - Output created on (date) : 11/09/2018   at (time) : 15:34:21
Simulation run

   RunNr    Day1   Month1    Year1     Rain     ETo      GD     CO2      Irri   Infilt   Runoff    Drain   Upflow
                                        mm       mm   °C.day   ppm     mm  mm     mm        mm       mm
     1         18         9         2016       0        327       652   401.57   254   254       0           34       0

E    E/Ex      Tr   Tr/Trx    SaltIn   SaltOut    SaltUp   SaltProf     Cycle   SaltStr    FertStr  TempStr   ExpStr
mm   %      mm      %     ton/ha    ton/ha    ton/ha    ton/ha      days      %           %           %          %
47    93      186      100    0.163    0.036     0.000        0.126       79        0           0           0         3

StoStr   BioMass   Brelative   HI     Yield     WPet     DayN   MonthN    YearN
%         ton/ha          %          %     ton/ha    kg/m3
 0          11.103       100        75.7    8.401      3.61        15        12        2016
```

Appendix A.21 Project Run out put 60%ETc season two

```
AquaCrop 4.0 (June 2012) - Output created on (date) : 04/09/2018   at (time) : 18:42:08
Simulation run

   RunNr    Day1   Month1   Year1    Rain     ETo      GD     CO2      Irri  Infilt  Runoff   Drain  Upflow
                                      mm       mm    °C.day  ppm     mm   mm      mm      mm      mm
      1       18        9       2016     0       327     652    401.57  168   168      0        12       0

E    E/Ex     Tr   Tr/Trx   SaltIn  SaltOut   SaltUp  SaltProf   Cycle  SaltStr  FertStr  TempStr  ExpStr
mm    %       mm   %       ton/ha   ton/ha   ton/ha   ton/ha   days     %         %          %         %
43     89     150    81    0.108      0.001      0.000     0.106      79       0          0            0      17

StoStr  BioMass  Brelative  HI    Yield    WPet    DayN  MonthN   YearN
   %    ton/ha        %        %    ton/ha   kg/m3
   15    8.899         80       75.3   6.698   3.46       15       12        2016
```

Appendix A.22 Project Run out put 40%ETc season two

```
AquaCrop 4.0 (June 2012) - Output created on (date) : 04/09/2018   at (time) : 18:52:59
Simulation run

   RunNr    Day1   Month1   Year1    Rain     ETo      GD    CO2     Irri  Infilt  Runoff   Drain  Upflow
                                      mm       mm    °C.day  ppm    mm   mm    mm        mm      mm
      1       18         9        2016     0       327     652     401.57  135   135    0          6         0

E    E/Ex      Tr  Tr/Trx   SaltIn  SaltOut   SaltUp  SaltProf   Cycle  SaltStr  FertStr  TempStr  ExpStr
mm   %        mm   %        ton/ha   ton/ha   ton/ha  ton/ha      days     %         %          %         %
42    89       123   69      0.086     0.000      0.000    0.086       79       0          0            0        29

StoStr  BioMass  Brelative  HI    Yield    WPet    DayN  MonthN   YearN
   %      ton/ha         %        %     ton/ha   kg/m3
   25     7.222           65       74.7    5.395    3.28       15         12       2016
```

Appendix A .23 Project Run out put 100%ETc season three

AquaCrop 4.0 (June 2012) - Output created on (date) : 16/09/2018   at (time) : 12:22:55

Simulation run

```
   RunNr    Day1   Month1   Year1    Rain     ETo      GD     CO2      Irri   Infilt   Runoff    Drain   Upflow
                                      mm       mm    °C.day    ppm    mm    mm      mm        mm       mm
      1        4        1       2017      0      420      656     403.57   297   297     0         19       0

E    E/Ex      Tr   Tr/Trx    SaltIn   SaltOut    SaltUp   SaltProf     Cycle   SaltStr   FertStr   TempStr   ExpStr
mm    %       mm     %      ton/ha   ton/ha    ton/ha    ton/ha       days       %          %            %           %
62     90     222    99     0.190    0.004      0.000     0.186          70        0           0            0           9

StoStr   BioMass   Brelative   HI     Yield     WPet      DayN   MonthN    YearN
  %        ton/ha       %          %     ton/ha    kg/m3
  1        10.280       98       87.0    8.944      3.16       24         3         2017
```

Appendix A.24 AquaCrop 4.0 (June 2012) - Output created on (date) : 16/09/2018   at (time) : 12:40:23

Simulation run

```
   RunNr    Day1   Month1   Year1    Rain     ETo      GD     CO2      Irri    Infilt   Runoff    Drain   Upflow
                                       mm       mm    °C.day    ppm     mm    mm      mm        mm       mm
      1          4        1        2017      0       420      656     403.57   238   238     0          15        0

E    E/Ex      Tr   Tr/Trx    SaltIn   SaltOut    SaltUp   SaltProf    Cycle   SaltStr  FertStr  TempStr   ExpStr
mm   %        mm    %        ton/ha    ton/ha    ton/ha    ton/ha    days       %         %            %          %
61    89      182    87      0.152     0.002      0.000     0.150       70         0         0            0          30

StoStr  BioMass  Brelative   HI     Yield     WPet      DayN   MonthN    YearN
  %        ton/ha      %         %     ton/ha   kg/m3
  10       8.358       80       86.9   7.261    3.00       24        3          2017
```

Appendix A.25 Project Run out put 60%ETc season three
AquaCrop 4.0 (June 2012) - Output created on (date) : 16/09/2018   at (time) : 12:52:38
Simulation run

```
   RunNr    Day1   Month1   Year1    Rain     ETo      GD     CO2      Irri    Infilt   Runoff    Drain   Upflow
                                      mm      mm     °C.day   ppm     mm     mm       mm       mm       mm
     1         4        1         2017      0       420      656     403.57   180     180     0          5          0

E    E/Ex      Tr    Tr/Trx    SaltIn   SaltOut    SaltUp   SaltProf    Cycle   SaltStr   FertStr   TempStr   ExpStr
mm   %       mm      %       ton/ha    ton/ha    ton/ha     ton/ha      days      %          %            %          %
58    89      145     70       0.115    0.000      0.000    0.115        70       0          0            0         32

StoStr   BioMass  Brelative   HI      Yield      WPet     DayN   MonthN    YearN
%         ton/ha           %          %      ton/ha    kg/m3
 22       6.685            64        87.3   5.838      2.89        24          3          2017
```

Appendix A.26 Project Run out put 40%ETc season three
AquaCrop 4.0 (June 2012) - Output created on (date) : 16/09/2018   at (time) : 12:59:12
Simulation run

```
   RunNr    Day1   Month1   Year1    Rain     ETo      GD      CO2     Irri    Infilt   Runoff    Drain   Upflow
                                      mm      mm     °C.day  ppm      mm     mm       mm       mm       mm
      1          4        1        2017       0        420     656     403.57   129   129       0          4          0
E    E/Ex      Tr     Tr/Trx    SaltIn   SaltOut    SaltUp   SaltProf    Cycle   SaltStr   FertStr  TempStr   ExpStr
mm    %      mm       %        ton/ha   ton/ha    ton/ha   ton/ha       days      %           %          %           %
 55    74     101      58        0.083    0.000     0.000    0.083         70        0           0          0          40
StoStr   BioMass   Brelative   HI      Yield      WPet      DayN   MonthN    YearN
%          ton/ha        %           %       ton/ha    kg/m3
 31       4.680          45          89.6    4.194    2.70         24          3          2017
```

Legend

RunNr	Number simulation run
Day1	Start day of simulation run
Month1	Start month of simulation run
Year1	Start year of simulation run
Rain	Rainfall
ETo	Reference evapotranspiration
GD	Growing degrees
CO2	Atmospheric CO2 concentration
Irri	Water applied by irrigation OR Net irrigation requirement

Infilt	Infiltrated water in soil profile
Runoff	Water lost by surface runoff
Drain	Water drained out of the soil profile
Upflow	Water moved upward by capillary rise
E	Soil evaporation
E/Ex	Relative soil evaporation (100 E/Ex)
Tr	Crop transpiration
Tr/Trx	Relative crop transpiration (100 Tr/Trx)
SaltIn	Salt infiltrated in the soil profile
SaltOut	Salt drained out of the soil profile
SaltUp	Salt moved upward by capillary rise from groundwater table
SaltProf	Salt stored in the soil profile
Cycle	Length of crop cycle: from germination to maturity (or early senescence)
SaltStr	Average soil salinity stress
FertStr	Average soil fertility stress
TempStr	Average temperature stress (affecting biomass)
ExpStr	Average leaf expansion stress
StoStr	Average stomatal stress
Biomass	Cumulative biomass produced
Brelative	Relative biomass (Reference: no water, no soil fertility, no soil salinity stress)
HI	Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress
Yield	Yield (HI x Biomass)
WPet	ET Water Productivity for yield part (kg yield produced per m3 water evapotranspired)
DayN	End day of simulation run
MonthN	End month of simulation run
YearN	End year of simulation run

Appendix A.27 Table showed the weather data used to calibrate Aqua Crop model June 2016

Date	**Max Temp C**	**Min Temp C**	**Rainfall mm/day**	**ETo mm/day**
01-Jun-16	24.8	9.0	0.0	4.0
02-Jun-16	24.8	9.5	0.0	4.5
03-Jun-16	25.0	9.8	0.0	45.0
04-Jun-16	24.7	9.6	0.0	5.0
05-Jun-16	24.9	9.5	0.0	5.0
06-Jun-16	25.1	9.2	8.2	5.2
07-Jun-16	23.6	9.7	0.0	5.0
08-Jun-16	24.9	9.5	0.0	5.0
09-Jun-16	24.5	10.0	0.0	5.5
10-Jun-16	25.0	10.0	0.0	5.0
11-Jun-16	24.7	9.8	0.0	5.5
12-Jun-16	24.8	9.6	0.0	6.5
13-Jun-16	25.0	9.3	0.0	6.0
14-Jun-16	24.6	9.5	0.0	5.0
15-Jun-16	24.7	9.9	0.0	4.5
16-Jun-16	23.2	9.3	0.0	3.5
17-Jun-16	23.0	13.0	0.0	3.0
18-Jun-16	23.6	10.0	0.0	4.0
19-Jun-16	23.8	9.6	8.0	4.0
20-Jun-16	24.2	9.0	0.0	4.8
21-Jun-16	21.2	13.0	7.8	2.4
22-Jun-16	21.5	12.8	16.4	2.8
23-Jun-16	19.0	12.8	37.8	1.5
24-Jun-16	20.7	12.0	2.0	1.5
25-Jun-16	20.9	9.6	13.5	2.4
26-Jun-16	21.2	8.5	4.4	3.5
27-Jun-16	21.6	7.9	0.0	4.0
28-Jun-16	21.8	9.9	0.1	3.6
29-Jun-16	22.0	11.0	0.0	3.5
30-Jun-16	23.0	11.0	1.9	1.9

Appendix A.28 Table showed the weather data used to calibrate Aqua Crop model July 2016

Date	Max Temp (C)	Min Temp (C)	Rainfall (mm/day)	ETo (mm/day)
01-Jul-16	23.5	8.0	0.7	5.7
02-Jul-16	23.4	9.5	14	4.5
03-Jul-16	23.5	10.0	43	5.0
04-Jul-16	24.0	10.5	0.0	4.0
05-Jul-16	22.5	11.9	0.0	3.0
06-Jul-16	23.0	12.0	6.0	1.0
07-Jul-16	23.2	12.2	11.2	4.2
08-Jul-16	23.0	12.5	7.8	1.8
09-Jul-16	20.5	12.7	0.5	3.5
10-Jul-16	21.4	11.2	1.6	3.1
11-Jul-16	22.5	10.7	0.0	4.0
12-Jul-16	22.0	12.0	0.0	2.0
13-Jul-16	18.0	11.0	0.0	2.0
14-Jul-16	21.5	9.0	1.2	3.2
15-Jul-16	20.0	9.0	1.4	3.9
16-Jul-16	20.0	10.5	0.0	3.5
17-Jul-16	21.0	10.0	15.5	4.5
18-Jul-16	24.0	9.5	4.4	2.9
19-Jul-16	22.0	8.5	0.7	2.7
20-Jul-16	22.5	11.0	7.6	4.6
21-Jul-16	23.0	10.0	10.9	3.4
22-Jul-16	22.5	11.5	3.3	2.3
23-Jul-16	21.5	9.3	1.2	4.2
24-Jul-16	21.5	9.0	0.0	3.5
25-Jul-16	21.0	11.0	0.0	2.5
26-Jul-16	22.0	8.0	0.0	3.0
27-Jul-16	20.5	9.0	16	5.0
28-Jul-16	21.0	12.5	9.7	4.7
29-Jul-16	20.0	10.0	0.0	3.0
30-Jul-16	23.5	9.5	7.6	3.6
31-Jul-16	23.8	11.0	1.5	4.0

Appendix A.29 Table showed the weather data used to calibrate Aqua Crop model August 2016

Date	Max Temp (C)	Min Temp (C)	Rainfall (mm/day)	ETo (mm/day)
01-Aug-16	19.0	9.0	1.9	3.9
02-Aug-16	22.2	9.1	1.2	2.7
03-Aug-16	24.0	12.0	4.8	3.3
04-Aug-16	24.5	14.0	0.0	3.0
05-Aug-16	23.0	13.5	10.8	1.8
06-Aug-16	24.5	11.5	0.0;	3.0
07-Aug-16	23.5	10.0	0.0	3.5
08-Agu-16	20.5	13.0	24.0	4.0
09-Agu-16	20.6	8.0	0.0	3.0
10-Agu-16	21.0	12.0	4.0	3.0
11-Agu-16	25.5	12.3	0.0	3.5
12-Agu-16	25.2	12.0	2.3	2.3
13-Agu-16	24.5	14.0	9.6	2.6
14-Agu-16	24.5	12.5	0.0	4.0
15-Agu-16	23.0	14.5	4.0	3.5
16-Agu-16	25.5	13.5	5.8	8.0
17-Agu-16	23.0	13.0	0.0	4.0
18-Agu-16	23.6	15.0	0.0	3.0
19-Agu-16	26.0	13.0	0.0	4.0
20-Agu-16	24.0	10.0	19.2	3.2
21-Agu-16	23.5	12.5	0.0	3.5
22-Agu-16	24.0	14.0	0.0	4.0
23-Agu-16	24.5	15.0	16.5	3.0
24-Agu-16	22.5	14.5	4.0	2.0
25-Agu-16	23.0	12.5	0.0	4.0
26-Aug-16	23.0	10.5	0.0	3.0
27-Aug-16	23.0	9.5	0.0	4.0
28-Aug-16	22.9	8.5	0.0	4.0
29-Aug-16	24.0	7.5	0.0	4.5
30-Aug-16	23.0	9.2	0.0	4.5
31-Aug-16	23.6	10.5	3.0	2.5

Appendix A.30 Table showed the weather data used to calibrate Aqua Crop model September 2016

Date	Max Temp (C)	Min Temp (C)	Rainfall (mm/day)	ETo (mm/day)
01-Sep-16	22.7	9.0	0.0	3.5
02-Sep-16	21.8	6.0	0.0	3.5
03-Sep-16	23.3	7.2	0.0	4.0
04-Sep-16	23.6	7.5	0.0	4.0
05-Sep-16	24.4	7.7	7.5	3.5
06-Sep-16	24.2	8.6	0.6	4.0
07-Sep-16	24.7	7.4	0.0	4.1
08-Sep-16	26.5	8.0	0.0	5.0
09-Sep-16	24.6	8.5	0.0	4.0
10-Sep-16	26.0	8.4	0.0	4.5
11-Sep-16	25.5	8.2	0.0	4.5
12-Sep-16	25.8	8.0	0.0	5.0
13-Sep-16	26.1	7.9	0.0	5.0
14-Sep-16	26.2	10.5	1.2	4.5
15-Sep-16	25.6	10.0	7.4	4.2
16-Sep-16	25.2	9.5	1.7	2.9
17-Sep-16	24.5	9.5	1.2	4.7
18-Sep-16	25.1	9.2	0.0	4.7
19-Sep-16	25.4	9.7	0.0	4.0
20-Sep-16	24.6	10.0	3.4	4.0
21-Sep-16	23.8	10.4	10.6	4.4
22-Sep-16	23.7	12.5	0.0	4.6
23-Sep-16	23.1	9.4	0.5	3.0
24-Sep-16	25.0	9.6	6.0	4.0
25-Sep-16	24.2	9.9	35.0	4.0
26-Sep-16	25.0	10.7	0.3	4.5
27-Sep-16	23.9	10.5	17.8	3.8
28-Sep-16	24.2	11.4	7.8	5.3
29-Sep-16	24.6	10.4	0.0	4.3
30-Sep-16	24.9	10.2	0.0	4.0

Appendix A.31 Table showed the weather data used to calibrate Aqua Crop model October 2016

Date	**Max Temp (C)**	**Min Temp (C)**	**Rainfall (mm/day)**	**ETo (mm/day)**
01-Oct-16	25.0	11.5	0.0	3.5
02-Oct-16	25.2	11.0	15.0	4.0
03-Oct-16	25.7	10.5	18.3	4.3
04-Oct-16	24.5	13.4	14.7	4.7
05-Oct-16	22.8	10.7	8.8	2.8
06-Oct-16	23.0	11.0	2.8	2.3
07-Oct-16	23.6	10.0	2.0	4.0
08-Oct-16	25.1	10.2	0.0	4.0
09-Oct-16	25.3	10.1	0.0	4.0
10-Oct-16	25.6	10.0	0.0	5.0
11-Oct-16	26.5	9.6	0.0	4.5
12-Oct-16	24.8	9.0	0.3	4.3
13-Oct-16	26.0	9.5	0.0	4.5
14-Oct-16	25.5	9.2	0.0	5.0
15-Oct-16	25.6	9.3	0.0	4.5
16-Oct-16	25.6	9.4	0.0	5.0
17-Oct-16	25.8	9.5	0.7	4.2
18-Oct-16	25.6	11.4	0.0	4.5
19-Oct-16	26.0	11.5	0.5	3.5
20-Oct-16	27.0	10.0	0.0	3.5
21-Oct-16	27.1	9.0	0.0	4.5
22-Oct-16	25.5	9.5	0.0	5.0
23-Oct-16	25.7	9.6	0.0	4.5
24-Oct-16	25.5	10.0	0.0	3.5
25-Oct-16	25.5	11.7	0.0	3.5
26-Oct-16	24.5	11.7	0.0	4.0
27-Oct-16	25.0	9.1	0.0	4.0
28-Oct-16	24.0	10.4	0.0	3.5
29-Oct-16	24.4	10.0	0.0	3.1
30-Oct-16	25.9	9.5	0.0	3.5
31-Oct-16	25.5	9.4	0.0	3.0

Appendix A.32 Table showed the weather data used to calibrate Aqua Crop model November 2016

Date	Max Temp (C)	Mini Temp (C)	Rainfall (mm/day)	ETo (mm/day)
01-Nov-16	25.7	11.2	0.0	4.0
02-Nov-16	25.2	10.6	0.0	4.0
03-Nov-16	23.2	12.4	1.9	2.5
04-Nov-16	22.2	11.2	0.0	1.4
05-Nov-16	24.1	10.6	2.4	3.0
06-Nov-16	24.0	10.0	0.0	3.4
07-Nov-16	24.2	9.7	0.0	3.0
08-Nov-16	25.0	10.9	0.0	4.0
09-Nov-16	23.5	10.4	6.0	3.5
10-Nov-16	23.0	11.0	3.0	3.1
11-Nov-16	21.1	11.0	0.0	2.0
12-Nov-16	23.0	10.5	0.0	3.5
13-Nov-16	23.5	9.0	0.0	4.0
14-Nov-16	24.6	10.4	0.0	4.5
15-Nov-16	23.4	10.0	0.0	3.5
16-Nov-16	21.4	10.2	0.2	2.0
17-Nov-16	22.5	10.0	3.3	1.7
18-Nov-16	22.7	10.3	0.5	1.3
19-Nov-16	21.4	10.5	14.0	2.5
20-Nov-16	21.8	10.4	0.0	3.5
21-Nov-16	22.2	12.5	0.8	3.5
22-Nov-16	22.0	10.7	2.6	2.8
23-Nov-16	18.5	13.4	1.0	0.6
24-Nov-16	23.7	11.0	0.0	3.0
25-Nov-16	24.0	12.0	4.5	3.5
26-Nov-16	25.0	11.2	6.0	3.0
27-Nov-16	24.9	10.5	4.5	3.1
28-Nov-16	25.4	11.7	13.0	3.0
29-Nov-16	24.7	9.5	11.5	5.0
30-Nov-16	24.0	10.0	0.0	3.5

Appendix A.33 Table showed the weather data used to calibrate Aqua Crop model December 2016

Date	Max Temp (C)	Min Temp(C)	Rainfall (mm/day)	ETo (mm/day)
01-Dec-16	24.5	12.4	0.0	4.0
02-Dec-16	24.6	10.6	0.0	3.5
03-Dec-16	24.0	10.8	0.0	4.0
04-Dec-16	23.5	11.0	0.0	3.0
05-Dec-16	24.2	10.0	1.5	4.0
06-Dec-16	23.2	8.0	0.0	4.5
07-Dec-16	23.0	8.5	0.0	5.0
08-Dec-16	25.1	10.0	0.0	4.0
09-Dec-16	24.2	9.8	0.0	4.5
10-Dec-16	24.3	9.5	0.0	5.0
11-Dec-16	24.2	10.2	0.0	4.5
12-Dec-16	24.0	9.9	0.0	4.0
13-Dec-16	24.5	9.7	2.1	4.1
14-Dec-16	22.7	7.5	0.0	4.0
15-Dec-16	23.2	8.4	0.0	4.5
16-Dec-16	24.5	9.5	0.0	5.0
17-Dec-16	24.7	9.0	0.0	5.5
18-Dec-16	25.0	8.0	0.0	6.0
19-Dec-16	25.1	7.7	0.0	6.0
20-Dec-16	24.5	7.5	0.0	4.5
21-Dec-16	24.0	9.2	0.0	4.5
22-Dec-16	24.0	10.5	0.0	3.5
23-Dec-16	23.0	10.2	0.0	3.5
24-Dec-16	25.0	9.8	0.0	4.0
25-Dec-16	25.1	9.6	0.0	4.5
26-Dec-16	25.2	9.3	0.0	4.5
27-Dec-16	25.0	9.0	0.0	4.0
28-Dec-16	25.4	8.7	0.0	4.5
29-Dec-16	26.1	11.9	0.0	4.0
30-Dec-16	24.5	12.9	0.0	3.5
31-Dec-16	24.2	12.4	0.0	4.0

Appendix A.34 Table showed the weather data used to calibrate Aqua Crop model January 2017

Date	Max temp C	Min Temp C	Rainfall mm/day	ETo mm/day
01/01/2017	24.3	8.5	0.0	4.0
02/01/2017	24.8	9.0	0.0	3.5
03/01/2017	25.2	9.3	0.0	4.0
04/01/2017	25.8	8.0	0.0	5.5
05/01/2017	25.6	7.5	0.0	5.5
06/01/2017	25.5	8.4	0.0	5.0
07/01/2017	26.0	8.5	0.0	5.0
08/01/2017	26.1	8.6	0.0	5.5
09/01/2017	26.2	8.7	0.0	5.0
10/01/2017	26.5	9.0	0.0	5.0
11/01/2017	26.0	8.0	0.0	5.5
12/01/2017	26.0	7.0	0.0	5.5
13/01/2017	25.0	7.7	0.0	5.5
14/01/2017	25.4	8.2	0.0	5.0
15/01/2017	25.9	8.5	0.0	5.5
16/01/2017	26.6	8.9	0.0	6.0
17/01/2017	26.4	7.2	0.0	6.0
18/01/2017	25.6	7.9	0.0	6.0
19/01/2017	26.7	8.6	0.0	5.5
20/01/2017	26.3	10.0	0.0	5.0
21/01/2017	25.8	9.0	0.0	5.5
22/01/2017	26.0	8.5	0.0	6.0
23/01/2017	26.4	8.0	0.0	5.5
24/01/2017	27.2	7.2	0.0	6.0
25/01/2017	26.2	9.5	0.0	6.0
26/01/2017	27.0	10.0	0.0	6.0
27/01/2017	27.2	10.0	0.0	6.0
28/01/2017	26.2	10.1	0.0	5.5
29/01/2017	26.4	10.2	0.0	6.0
30/01/2017	26.3	10.4	0.0	5.0
31/01/2017	26.6	10.5	3.0	5.5

Appendix A.35 Table showed the weather data used to calibrate Aqua Crop model February 2017

Date	**Max Temp (C)**	**Min Temp (C)**	**Rainfall (mm/day)**	**ETo (mm/day)**
01/02/2017	25.6	11.6	0.7	3.7
02/02/2017	27.0	10.5	2.2	4.7
03/02/2017	26.0	9.0	0.0	5.0
04/02/2017	26.8	9.2	0.2	4.2
05/02/2017	26.5	9.6	0.0	5.0
06/02/2017	27.0	9.5	0.0	5.5
07/02/2017	26.7	9.0	0.0	6.0
08/02/2017	27.7	10.8	0.0	5.5
09/02/2017	27.8	9.7	0.0	6.5
10/02/2017	27.9	8.7	0.0	6.5
11/02/2017	28.4	8.8	0.0	6.5
12/02/2017	28.5	9.0	0.0	6.5
13/02/2017	28.6	9.2	0.0	6.0
14/02/2017	28.8	9.5	0.0	7.0
15/02/2017	29.2	9.7	0.9	6.9
16/02/2017	26.0	10.5	0.0	7.5
17/02/2017	24.0	10.4	0.0	5.0
18/02/2017	25.0	11.5	4.5	5.0
19/02/2017	26.5	10.5	0.0	5.5
20/02/2017	27.0	10.0	0.0	6.0
21/02/2017	26.0	10.4	12.0	5.0
22/02/2017	24.0	11.0	0.0	5.0
23/02/2017	26.2	11.2	0.0	4.5
24/02/2017	26.6	14.5	0.0	4.5
25/02/2017	26.8	13.0	0.0	5.0
26/02/2017	27.2	12.0	2.0	5.0
27/02/2017	27.0	10.5	9.5	4.5
28/02/2017	27.0	11.5	0.0	5.0

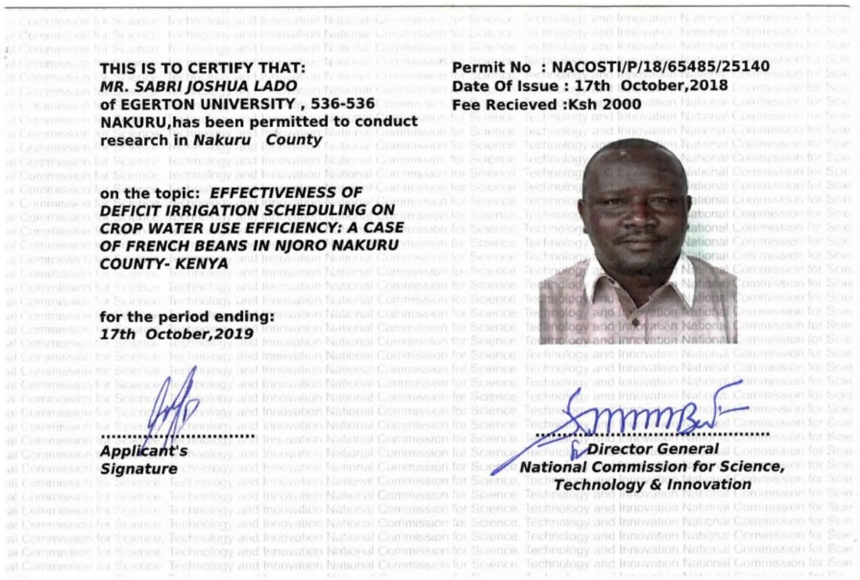
Appendix A.36Table showed the weather data used to calibrate Aqua Crop model March 2017

Date	**Max Temp (C)**	**Min Temp (C)**	**Rainfall (mm/day)**	**ETo (mm/day)**
01/03/2017	26.0	10.2	0.0	4.5
02/03/2017	25.0	9.5	0.0	4.5
03/03/2017	27.0	11.0	0.0	5.0
04/03/2017	26.2	10.0	1.6	5.6
05/03/2017	26.7	10.5	0.0	5.0
06/03/2017	27.5	11.0	0.0	5.5
07/03/2017	28.0	11.2	0.0	6.0
08/03/2017	28.0	10.0	0.0	6.0
09/03/2017	28.5	10.5	0.0	6.5
10/03/2017	28.0	11.9	0.0	6.0
11/03/2017	28.5	9.9	0.0	6.5
12/03/2017	28.8	9.8	0.0	7.0
13/03/2017	29.0	9.9	0.0	6.5
14/03/2017	29.4	11.0	0.0	7.0
15/03/2017	28.8	12.0	0.0	6.0
16/03/2017	28.0	11.4	0.0	6.0
17/03/2017	27.7	11.5	0.0	5.0
18/03/2017	28.5	12.0	2.3	5.3
19/03/2017	28.6	11.0	0.0	6.5
20/03/2017	28.7	10.5	0.0	6.5
21/03/2017	28.5	11.0	0.0	7.0
22/03/2017	27.5	12.0	0.0	5.5
23/03/2017	28.2	11.5	0.0	5.0
24/03/2017	28.5	11.0	1.0	4.5
25/03/2017	29.0	11.2	0.0	4.5
26/03/2017	28.8	11.5	5.7	5.2
27/03/2017	29.0	11.9	0.0	4.0
28/03/2017	25.2	12.0	23.4	3.9
29/03/2017	27.5	11.2	0.2	4.2
30/03/2017	26.2	11.5	2.9	3.9
31/03/2017	26.4	9.9	0.0	5.0

Appendix C list of published and acceptance article

S.No	Description of the published article
1	Sabri, J .Lado , Prof Japheth Onyando, Dr. Anthony Karanja. Calibration and Validation of Aqua Crop Model For Full and Deficit Irrigation of French Bean in Njoro Nakuru- Kenya- International Journal of Science and Research (IJSR) 2017
2	Sabri Joshua Lado, Dr. Anthony Karanja. Prof. Japheth Onyando. Effect of Deficit Irrigation on Yield –Water Relation of French Bean in Rift Valley-Njoro Nakuru County- Kenya. Journal of Agriculture and Veterinary Science (JOSR-IAVS) 2017
3	Sabri Joshua Lado, Dr. Anthony Karanja. Prof. Japheth. O.Onyando Effectiveness of Deficit Irrigation Scheduling on Water Use Efficiency, Growth and Yield Response of French Bean Crop in Njoro Nakuru County-Kenya International Journal of Science and Research (IJSR) 2017 (Acceptance)

Appendix D some pictures from field experiment



THIS IS TO CERTIFY THAT:
MR. SABRI JOSHUA LADO
of EGERTON UNIVERSITY , 536-536
NAKURU,has been permitted to conduct
research in *Nakuru County*

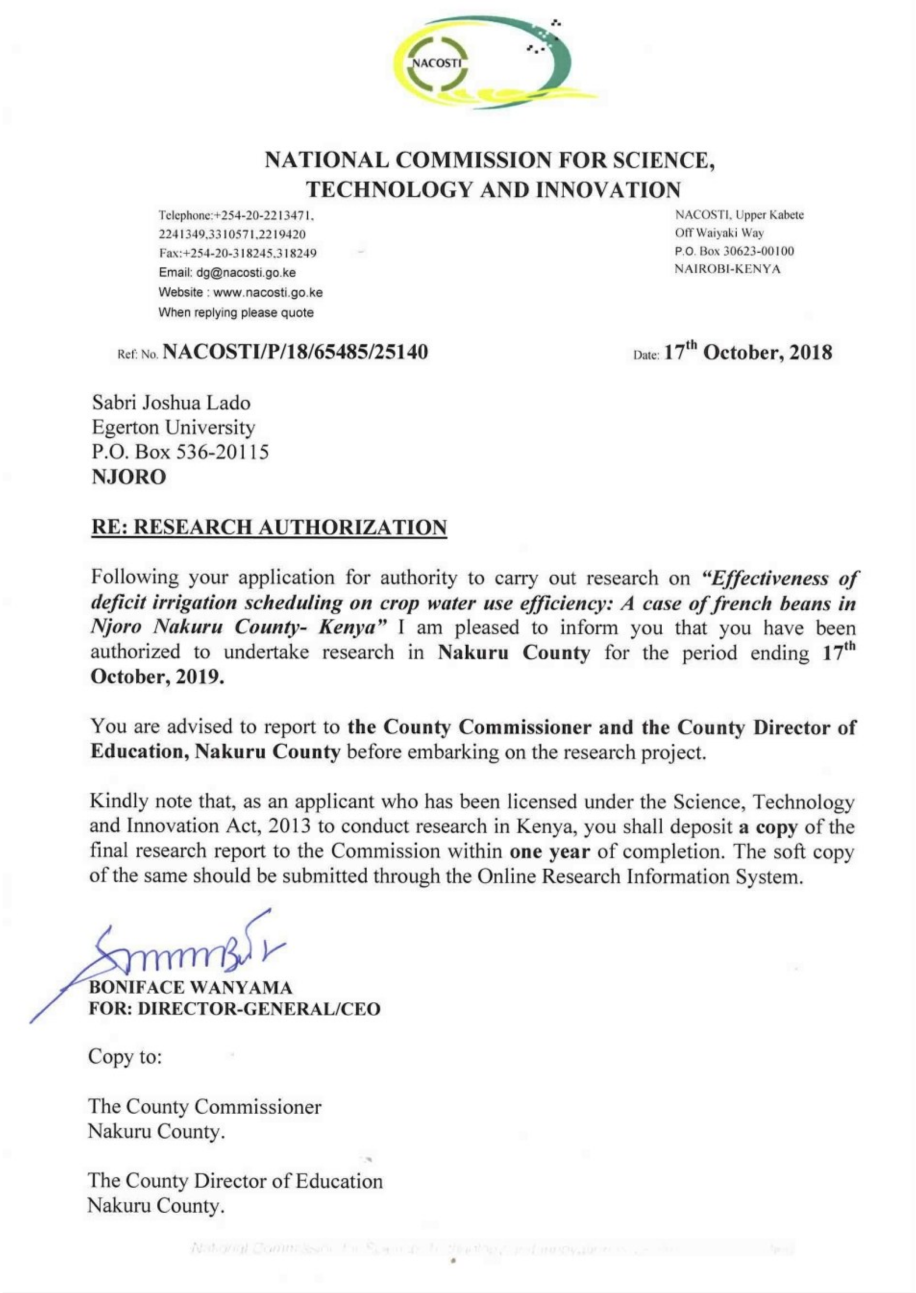
on the topic: *EFFECTIVENESS OF DEFICIT IRRIGATION SCHEDULING ON CROP WATER USE EFFICIENCY: A CASE OF FRENCH BEANS IN NJORO NAKURU COUNTY- KENYA*

for the period ending:
17th October,2019

Permit No : NACOSTI/P/18/65485/25140
Date Of Issue : 17th October,2018
Fee Recieved :Ksh 2000

....
Applicant's Signature

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



**NATIONAL COMMISSION FOR SCIENCE,
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Telephone:+254-20-2213471,
2241349,3310571,2219420
Fax:+254-20-318245,318249
Email: dg@nacosti.go.ke
Website : www.nacosti.go.ke
When replying please quote

NACOSTI, Upper Kabete
Off Waiyaki Way
P.O. Box 30623-00100
NAIROBI-KENYA

Ref: No. **NACOSTI/P/18/65485/25140**

Date: **17th October, 2018**

Sabri Joshua Lado
Egerton University
P.O. Box 536-20115
NJORO

RE: RESEARCH AUTHORIZATION

Following your application for authority to carry out research on ***"Effectiveness of deficit irrigation scheduling on crop water use efficiency: A case of french beans in Njoro Nakuru County- Kenya"*** I am pleased to inform you that you have been authorized to undertake research in **Nakuru County** for the period ending **17th October, 2019.**

You are advised to report to **the County Commissioner and the County Director of Education, Nakuru County** before embarking on the research project.

Kindly note that, as an applicant who has been licensed under the Science, Technology and Innovation Act, 2013 to conduct research in Kenya, you shall deposit **a copy** of the final research report to the Commission within **one year** of completion. The soft copy of the same should be submitted through the Online Research Information System.

BONIFACE WANYAMA
FOR: DIRECTOR-GENERAL/CEO

Copy to:

The County Commissioner
Nakuru County.

The County Director of Education
Nakuru County.