Evaluation of Deficit Irrigation on Water Productivity and Yield Response of Beans Using AquaCrop in Eldoret, Kenya.

By:

Duncan Rioba Oteki

B. Eng (Hons), Grad. Eng.

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Water Engineering of the Department of Civil and Structural Engineering, Moi University

July 2015

DECLARATION

DECLARATION BY THE CANDIDATE

I hereby declare that this thesis is my original work and has not been presented for a degree in any other university. No part of this thesis may be reproduced without the prior written permission of the author and/or Moi University.

Duncan Rioba Oteki ……………………… Date: ……………………….

(TEC/PGCS/12/11)

DECLARATION BY THE SUPERVISORS

This thesis has been submitted for examination with our approval as university supervisors.

Eng. Prof. Emmanuel C. Kipkorir ………………………. Date: ……………………….

University of Eldoret, Eldoret, Kenya

Dr. Job Kosgei ………………………. Date: ……………………….

Moi University, Eldoret, Kenya

Prof. Dirk Raes………………………. Date: ……………………….

K. U. Leuven, Belgium.

DEDICATION

To my wife, Stella; my daughter, Kwamboka; my dear parents (John and Lilian), without whose love and support the completion of this work would not have been possible.

ABSTRACT

Kenya's renewable fresh water per capita is below the UN recommended benchmark of 1000 m^3/capita/year, making it a water scarce country. Over 80 percent of this freshwater is utilized in agricultural production. The increase in human population means that even more water will be channeled towards food production. Kenya predominantly depends on rain-fed agriculture for its food production; this makes the country susceptible to acute food shortages. An increase in food production needs to be coupled with an increase in crop water productivity in order to ensure the sustainability of the water resources. Beans (*Phaseolus Vulgaris L.*) are the primary source of protein for most households in Kenya. Despite this fact, there is a supply deficit dry spells. An irrigation study was carried out at Moi University. In this study, the effect of deficit irrigation as a mitigation measure to curb the shortage of beans during dry spells while ensuring sustainable use of water resources was investigated. This was carried out through modeling of water productivity (WP) and yield (Y) of beans using the FAO AquaCrop model. Field experiments were set up in a Randomized Complete Block Design (RCBD) arranged in split plots and replicated three times. Two water treatment strategies were employed (deficit irrigation, full irrigation). In the full irrigation supply, the crop was kept at 100% of irrigation requirement (T100) and data collected from these plots was used in AquaCrop model calibration. There were three levels of deficit irrigation at 80%, 60% and 50% of irrigation requirement (T80, T60, T50) these were used in model validation. The model prediction of bean yields showed a good agreement with observed values with an R^2 of 0.83, Willmott's index of agreement of 0.97 and root mean square error of 0.4014 t/ha. The T100 irrigation treatment had the highest observed Y of 4.238 t/ha with a water productivity of 1.01 kg/m^3. The T80, T60, and T50 treatments exhibited a drop in Y, 4.138, 2.254 and 1.702 t/ha respectively, and WP of 1.29, 0.92 and 0.77 kg/m^3 respectively. The highest WP, as well as the lowest yield reduction of 2.36%, was observed in the T80 treatment, this signifies water savings of up to 20% which translates to 750 m^3/ha. The highest yield reduction of 59.84% was obtained in T50 treatment, coupled with a drop in WP. Subsequently, frequency analysis was carried out on historical rainfall data of 22 years (1990-2011). The years 2007, 2002 and 2004 were obtained as the typical climatic conditions of dry, wet, and average years respectively. Deficit irrigation strategies were designed according to the level of sensitivity of the growth stages. The calibrated model was then used for simulation of Y and WP for the dry, wet and dry seasons. The results confirmed that the most water sensitive stages were at the flowering and yield formation. Consequently, irrigation schedules to relay information to stakeholders were produced. Improving water productivity is the most appropriate strategy for increasing food production for a fast growing population due to its consideration of the sustainability of water resources. Deficit irrigation results in yield reduction as observed in this study, but the amount of water saved can be used to irrigate more land or be utilized elsewhere. As a result, the high opportunity cost of water compensates for the economic loss due to reduction in yields.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

FAO	Food and Agriculture Organization of the United Nations
WP	Water Productivity
WP*	Normalized Water Productivity
Kc	Crop Coefficient
TAW	Total Available Water
FC	Field Capacity
PWP	Permanent Wilting Point
SAT	Saturation point
ET_0	Reference Evapotranspiration
HI	Harvest Index
Y	Yield
CC	Canopy Cover
B	Biomass
SWC	Soil Water Content
DAS	Days After Sowing
GOF	Goodness Of Fit
R^2	Coefficient of determination
RMSE	Root Mean Square Error
EF	Nash-Sutcliffe model efficiency coefficient
d	Willmott’s index of agreement

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my supervisors: Eng. Prof. E. C. Kipkorir, Dr. J. Kosgei for their constant guidance, constructive suggestions and encouragement throughout the study period. I would also like to thank Prof. D. Raes for introducing me to the world of *AquaCrop* and helping in the formulation of the study proposal. My fellow students played a significant role during this study at Moi University, I appreciate their assistance. Last but not least, I acknowledge all staff members at the Department of Civil and Structural Engineering, Moi University, for their continuous help throughout the study period.

I am greatly indebted to the NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY AND INNOVATION (NACOSTI) for awarding me the SCIENCE, TECHNOLOGY AND INNOVATIONS (ST&I) GRANT, which facilitated this research.

Finally, I am grateful to my wife and daughter, parents and brothers, for their constant encouragement and moral support. The help and support in different phases of the study by my friends are acknowledged.

God bless you all.

Rioba, July 2015.

Chapter 1: Introduction

1.1 Background Information

Fresh water is a finite and vulnerable resource essential to life (Solanes & Gonzalez-Villarreal, 1999). Increasing competition among the various sectors (agriculture, domestic uses, industries and the environment), warrants measures to be taken to promote efficient use of the resource to ensure sustainability and universal benefit.

Agriculture constitutes about 70% of global fresh water withdrawals and in most fast-growing economies it is projected to reach 90% (WWAP, 2012). In Kenya, the figure was estimated to be 80% by the year 2003 (FAO, 2013). Agriculture is not only a source of food but is also the primary source of employment and contributor to Kenya’s Gross Domestic Product (GDP) (Poulton & Kanyinga, 2014). The population stood at about 39 million people as per the 2009 national census and is projected to reach approximately 50 million people by the year 2020 (KNBS, 2010). The relentless growth in human population translates to more mouths to feed. Consequently, more water resources will be channeled towards food production. As it stands, Kenya is a water scarce country with a per capita renewable amount of fresh water of less than 647m^3 per year (FAO, 2013). Due to various factors such as climate change and population pressure this figure is projected to fall to 245m^3/capita by the year 2025. Both these figure are well below the UN recommended benchmark of 1000m^3/capita per year (FAO, 2013). This scenario paints a very grim picture of Kenya’s economic future and ability to feed her growing population.

Kenya primarily depends on rain-fed agriculture for its food production; this makes the country susceptible to acute food shortages attributed to the high temporal and spatial variability of rainfall. Irrigation is twice as productive as rain-fed agriculture, but water resources remain limited (Stockle, 2001). Reducing irrigation in order to increase water availability for other uses is unthinkable due to the challenge that lies in growing demand for food. Consequently, the solution lies in identifying ways to improve of agricultural water use through acquisition of relevant knowledge. This will lead to irrigation practices that improve water use efficiency while still achieving enough crop yields to sustain the increasing population the “more crop per drop” paradigm (Giordano et al., 2006).

1.2 Problem Statement

Beans (*Phaseolus Vulgaris L.*) also known as the common bean, dry bean, field or French bean is the most widely cultivated type of bean in Kenya (Doorenbos & Kassam, 1979). It is also the second most important crop after maize. It is the primary source of protein for many households in Kenya and thus an essential component in balancing the diet. Despite this fact, the production of the common bean has fallen short of demand. In 2007, the total yield of common beans was 417,000 ton while the demand was 500,000 ton (Katungi et al., 2011). This disparity is due to complex biological and physical stresses (such as rainfall variability, insect pests and diseases and declined soil fertility) which keep the yield at less than 25% of potential yield (Odendo et al., 2004).

Recently, it has been reported that the yield of beans is estimated to have shrunk by 68% (Michira, 2014). This could be due to decline in long rains and increasing drought spells brought about by climate variability among other factors.

Consequently, there is a need to tackle the problem of the declining bean yields while at the same time ensuring that the available water resources are used sustainably. Hence, this study focused on the effect of water stress on the yield and water productivity of beans in

Uasin-Gishu County, Kenya. The region is located in western Kenya where the rainfall distribution is bimodal with the farmers preferring to grow the beans in the long rainy seasons. Cultivation in the short rainy seasons is avoided due to the risk associated with rains that cannot adequately satisfy the crop water requirements.This leads to low yields and a supply deficit of beans. By using drip irrigation as a means of meeting crop water demands during the dry spell, the effect of water stress on the yield and water productivity of beans was studied. This enabled further understanding into how to optimize yields while ensuring water sustainability.

1.3 Justification of the Study

To alleviate the problem of declining bean yields, irrigation can be practiced during the short rains season to minimize the risk of crop failure and ensure better yields throughout the year. There needs to be a decision-making tool in place which can be used to advise the farmers on the effect of various irrigation strategies on the yield and water productivity of dry beans. This will assist in ensuring proper irrigation scheduling is carried out thus promoting water conservation. Consequently, this study is highly significant for a water-scarce country like Kenya.

AquaCrop has been calibrated for various major crops such as maize, sorghum, and winter wheat (Steduto et al., 2009); however, it is recognized that it is not possible to calibrate the model exhaustively for all the crop species in the near future. For that reason, AquaCrop provides default or sample values for all required parameters as the starting point to use for unexplored crops in the absence of more specific information.

The common bean has not yet been calibrated for AquaCrop and by doing so the study provided water productivity characteristics for beans for the region. When combined with other future calibrated results from other parts of the world, a standardized common bean crop file for AquaCrop can be provided in the future. As a consequence, this study is likely to contribute to the continuous development of AquaCrop for better simulation of beans in the future.

1.4 Main Objective

The purpose of the study was to evaluate the effect of deficit irrigation on the water productivity and yield of beans. This was achieved by calibrating AquaCrop for beans and using it to obtain results on yield output and water productivity under varying irrigation strategies.

1.4.1 Specific Objectives

i. To calibrate AquaCrop for the bean crop using water productivity and yield data from the experimental field.

ii. To evaluate and compare the response of different irrigation treatments on water productivity of beans using the calibrated AquaCrop model.

iii. To develop irrigation schedules guidelines for farmers during the short rains seasons.

1.5 Scope of the Study

This study was carried out for only one variety of beans, and the experimental plots were situated in Moi University as a representation of Uasin-Gishu County. Therefore, AquaCrop was only calibrated and validated for one region and one bean variety. This study is only limited towards investigating the effects of water stress on the yield of beans;

this called for measures to be taken to reduce other factors that affect crop phenology. Consequently, proper management practices including weeding, pest control, and adequate fertilization were carried out on the experimental fields to ensure that the only limiting factor affecting plant growth was water. Salinity stress was not considered because it is not a major problem in the region (Mugai, 2004).

Chapter 2: Literature Review

2.1 Introduction

This Chapter focuses on information on previous studies relevant to this study. First, water productivity and management is discussed. Subsequently, the review on the bean crop variety used in this study, the response of bean yields to water, and deficit irrigation technique was carried out. Finally, the various crop models available were highlighted, and the reason for selecting AquaCrop is discussed.

2.2 Water Productivity and Crop Yield

Water productivity is defined as "the physical mass of production or the economic value of production measured against gross inflows, net inflow, depleted water; process depleted water, or available water" (Molden, 1997). In terms of agriculture, water productivity is defined as the ratio of the mass of marketable yield (Y_a) to the volume of water evapotranspired (consumed) by the crop (ET_a) (Geerts & Raes, 2009).

$$\wp = \frac{Y_a}{ET_a} \left(Eq.2.1 \right)$$

Where:

WP = water productivity (kg/m^3)

Y_a = mass of marketable yield (kg)

ETa = volume of water evapotranspired on the field (m^3)

Improved water productivity means that there would be an increase in crop yields per amount of water used. Consequently, more water is available for expansion of the irrigated area or other uses (Pereira et al., 2002). To achieve this, the crop yield response to water must be known. This enables the farmer to understand the water requirements of the crops and how much water stress the crops can endure and still obtain reasonable yields. This is the basis of deficit irrigation.

2.3 Bean Varieties in Kenya

In Kenya, there are a number of bean varieties grown e.g. Rosecoco, Mwitemania, Canadian Wonder, Mwezi Moja, and many more (NCPB, 2013). These are common names, the seed type (color, size, shape, and surface texture) is the character most commonly used to classify beans (van Schoonhoven, 1991). However, oftentimes the place of origin and the unique qualities of the bean variety are also used. The climatic conditions of a particular region dictate which variety performs well in that region. In this study, the Mwezi Moja (GLP 1127) bean variety was used. This variety is a high yielder and takes a shorter time to mature (80-85 days) as compared to other varieties and thus is ideal for growing during dry spells. Additionally, the Mwezi Moja (GLP 1127) variety is highly tolerant to rust and other diseases (NCPB, 2013).

2.3.1 Yield response to Water

The effect of water stress on final yield is not constant throughout the growing season. Beans, as well as other crops, show a different response to water stress at different growth stages. In order to carry out irrigation management practices, a functional model (Eq.2.2) describing the relation between stress and the corresponding expected yield is very helpful

(Doorenbos & Kassam, 1979). The relationship only considers water stress as the factor affecting crop yield while other factors such as salinity stress, temperature stress, and nutrients remain constant.

$$1-\frac{Y_a}{Y_m}=K_y\left(1-\frac{ET_a}{ET_c}\right)(Eq.2.2)$$

Where:

Y_a = actual yield

Y_m = maximum yield for no water stress conditions

K_y = yield response factor

ETa = actual evapotranspiration

ETc = crop evapotranspiration for no water stress conditions

The yield response factor (K_y) quantifies the response of yield to water stress for a given environment. The actual yield (Y_a) is expressed as a fraction of the maximum yield (Y_m) that can be expected under non-limiting water conditions. In Eq. 2.2, ET_a refers to the actual crop evapotranspiration under the given growing conditions while ET_c refers to crop evapotranspiration under non-limiting water conditions. According Doorenbos & Kassam (1979), the linearity assumed by the relationship holds to about 50% of water stress (

$$1-\frac{ET_a}{ET_c}\leq 0.5$$

).

They further described five growth stages in the growing period in terms of yield response to water. Each stage has a varying number of days, depending on the crop being cultivated as shown in Table 2.1.

Table 2.1: Indicative lengths of growth stages (days) of beans (source: Doorenbos and Kassam, 1979).

Crop	(0)Crop establishment	(1) Vegetative	(2) Flowering	(3) Yield formation	(4) Ripening stage	Total
Bean (Dry)	10-15	20-25	15-25	25-30	20-25	90-120
Bean (Green)	10-15	20-25	15-25	15-20	0-5	60-90

Furthermore, the yield response factor (K_y) also varies in each of the stages (Table 2.2). Crops that are not very sensitive to water stress have low K_y factors of < 1, whereas crops that are very sensitive to water stress have high K_y factors normally > 1.

Table 2.2: Yield response factors (K_y) for beans well adapted to the growing environment (source: Doorenbos and Kassam, 1979).

Crop	(1) Vegetative period	(2) Flowering period	(3)Yield formation period	(4) Ripening	Total growing Period
Bean	0.20	1.10	0.75	0.20	1.15

Generally, beans are sensitive to water stress, during the flowering period and yield formation period being the most sensitive. Frequent irrigation during these sensitive stages results in the highest response to production. However, during periods of limited water supply, water can be saved during the less sensitive periods, that is, the vegetative period and the ripening periods that are quite tolerant to water stress.

2.3.2 Water uptake

Doorenbos and Kassam (1979) gave the following account regarding water uptake of the bean crop. At emergence, the rooting depth of beans is about 7cm, at the flowering stage 30 to 40 cm, and at maturity 1 to 1.5 m. Water uptake occurs mainly in the first 50 to 70 cm depth ($z = 0.5$-0.7 m). Under conditions when the ETc is 5 to 6 mm/day, 40 to 50 percent of the total available water can be depleted before water uptake is affected (p = 0.4-0.5).

2.3.3 Crop water management

Crop water management is essential to ensure adequate amounts of water are applied to crops in order to maximize quality and yield. This requires the determination of the crop water requirement, which is the amount of water a crop evapotranspires throughout the growing season. This can be estimated by using the crop coefficient (Kc). The crop water requirement is not constant throughout the season; rather it varies according to the growth stages of the crop, among other factors.

Different crops have different Kc coefficients and the characteristics of the crop during the growing season also affect the Kc coefficient. For the common bean (dry), the Kc values are approximated as shown by Figure 2.1. During the initial stage, K_c ranges from 0.3-0.4 (15-20 days); the developmental stage Kc ranges from 0.7-0.8 (15-20 days); the mid-season stage Kc ranges from 1.05-1.2 (35 -45 days), late stage Kc ranges from 0.65-0.75 (20-25 days) and at harvest 0.25 -0.3 (Doorenbos & Kassam, 1979).

Object 9

Figure 2.1: Kc values for beans (dry) at the various growth stages during the growing season.

The calculation of the crop water requirement facilitates the determination of irrigation requirement and irrigation scheduling.

2.3.4 Irrigation Water Requirement

The irrigation water requirement is the amount of water to be supplied to the plants to prevent stress and yield reduction. It is essential to apply irrigation water at the right time and in the right quantity. Under or overwatering can lead to reduced yields, lower quality and inefficient use of nutrients. Short term irrigation requirements, when combined with soil water holding characteristics, enables specification of when and how much water to apply (irrigation scheduling).

In irrigation, the practice is normally to express the amount of irrigation water applied in equivalent water depth. This is known as the net water application depth (d_{net}). The application depth is affected by the soil type, crop type, stage, climate and irrigation method.

Soil water holding characteristics determine the potential amount of water that can be applied. Therefore, the textural class of the soil has to be determined in order to establish its hydraulic properties.

The quantity of water that can infiltrate into the soil with the locally used irrigation method has to be verified in the field. For example, when using basin irrigation, more water is infiltrated during one irrigation event than when using furrow irrigation. In particular, with small-scale irrigation (small water flows and small fields) it is often the irrigation method which is the most limiting factor when determining the maximum irrigation application (Allen et al., 1998). Consequently, in this study, drip irrigation method was used; it has a typical application depth of 10-30 mm.

2.4 Deficit Irrigation

Deficit irrigation is an irrigation strategy whereby water is applied only during the drought-sensitive growth stages of a crop (Geerts & Raes, 2009). This technique results in reduction in the crop yield, but as stated by Kipkorir et al. (2001) the amount of water saved can be used to irrigate more land on the same farm or be utilized by other water users. Hence, the high opportunity cost of water compensates for the economic loss due to reduction in yields.

Field experiments can be carried out to determine crop response to water stress under various strategies. However, in order to formulate detailed irrigation schedules for beans in the study area, reliance on field experiments alone would be rather expensive and time-consuming. Thus, the use of crop models which provide an array of treatments and tests to which the user can subject the crop to and obtain the results in a timely manner.

Various studies on the common bean (*Phaseolus Vulgaris*) response to water yield have been carried out. Calvache et al. (1997) studied the effects of deficit irrigation at different growth stages of the common bean. Their findings showed that common beans are most sensitive to water stress at the flowering stage. In addition, this period had the lowest water use efficiency. Consequently, a full supply should be ensured during this period. It was also concluded that deficit irrigation reduces crop yield.

Similar results were obtained by Bourgault et al. (2010) when studying the effectiveness of regulated deficit irrigation as a way of improving water use efficiency of the common bean. Experimental plots were used to carry out the study and data analyzed using statistical tools. The findings revealed that the seed size and biomass were reduced as a result of the increasing water stress.

Water productivity (WP) can also be improved by reducing the evaporation losses in the evapotranspiration component ET_a in Equation 2.1. Mehrpouyan et al. (2011) compared the effect of surface irrigation and localized (drip) irrigation on the seed yield of the common beans cultivated. Field experiments were carried out and results analyzed using statistical tools. The findings showed that the highest water use efficiency of 0.79 Kg dry matter/ m^3 was obtained from common beans subjected to a combination of drip irrigation and furrow/ridge planting method.

Accordingly, it was recommended as the most effective method for reducing soil evaporation and obtaining high yields per amount of water used.

From the discussions above it is seen that deficit irrigation does indeed lead to reduction in yields. Despite this fact, it should be noted that the issue at hand is not that of maximizing yields, rather it is that of striking a balance between improved yields and water productivity in order to simultaneously address issues of water scarcity and food shortages.

2.5 Crop Models

The challenges facing food production coupled with the problems of limited water resources are diverse. Reliance on long-term experiments will not provide quick solutions that are promptly needed. Consequently, crop models are useful to better understand and formulate innovative technologies. Crop models can be described as a quantitative scheme for predicting the growth, development, and yield of a crop, given a set of genetic features and relevant environmental variables (Monteith, 1996). Crop models are predominantly used for interpretation of experimental results. Extensive and costly experiments can be pre-assessed through a well-proven model to refine field tests and reduce their overall costs (Steduto et al., 2009). Additionally, models can be used as decision support tools for optimum management practices, planning and policy making.

From the 1960's various researchers such as Brouwer and de Wit (1969) were already working on crop simulation modelling. Their efforts mainly involved the integration of crop physiological knowledge. Later exertions led to the development of more advanced models, some of them more oriented towards the single-plant scale, such as CERES (Jones and Kiniry, 1986). Others more oriented toward canopy–level scale and utilized as management tools to assist in decision-making such as EPIC (Williams et al., 1986) and its later derivation the DSSAT cropping system model (Jones et al., 2003). The above mentioned models are mostly used by scientists, graduate students and advanced users in highly commercial farming.

Depending on the purpose and objectives of the crop model, two main modelling approaches can be distinguished: scientific and engineering (Steduto et al., 2009). The former mainly aims at improving the users understanding of crop behavior, its physiology and response to environmental changes. While the latter attempts to provide sound management advice to farmers or predictions to policymakers (Passioura, 1996). The scientific models presented considerable complexity for the majority of targeted users, such as extension personnel, water use associations, consulting engineers, irrigation and farm managers and economists. Additionally, these models required extended number of variables and input parameters not easily available for the various range of crops and locations around the world (Steduto et al., 2009). Typically, these variables are much more familiar to scientists than to end users. To tackle all these concerns a new model named AquaCrop (Steduto et al., 2009, Raes et al.,2009, Hsiao et al., 2009), was developed by FAO.

AquaCrop is a canopy-level and engineering type of model, mainly focused on simulating the attainable crop biomass and harvestable yield in response to the water applied (Steduto et al., 2009). The model emphasizes on water because it is a key driver of agricultural production (Steduto et al., 2009). The increase in human population and prosperity has led to an increase in pressure on our finite water resources, making water an increasingly critical factor affecting crop production. Furthermore, the input requirements are commonly available and relatively few numbers of parameters are required. Consequently, it strikes a balance between simplicity, accuracy and robustness (Raes et al., 2009). This being an engineering study involving the investigation into the effects of deficit irrigation on the production of beans, AquaCrop was thus selected as the most appropriate model to undertake this task.

2.6 Summary

The literature review suggests that deficit irrigation reduces yields but, on the other hand, it can improve the crop water productivity of irrigated crops. Therefore, this study was aimed at not only evaluating the effects of deficit irrigation on beans but by using the AquaCrop model; a decision-making tool would be provided to aid in striking a balance between improved yields and water productivity. This would aid in the formulation of guidelines that would be used to advise farmers on proper water resource management.

Chapter 3: Materials and Methods

3.1 Introduction

In this chapter the study area is introduced, the experimental design and the model used in the study was discussed together with the data collection requirements. Finally, the statistical methods used for analysis of model performance are presented.

3.2 Study Area

The study was carried out at Moi University, main campus (0 °17' N, 35°20' E, altitude 2240 m) in Uasin Gishu County about 35 km South East of Eldoret town (Fig. 3.1). Rainfall in this region is characterized by two seasons, long rains from April to September and the short rains season starts from October to December (Fig. 3.2).The field experiments were carried out at the university’s irrigation farm from 18th April 2014 to 20th July 2014.

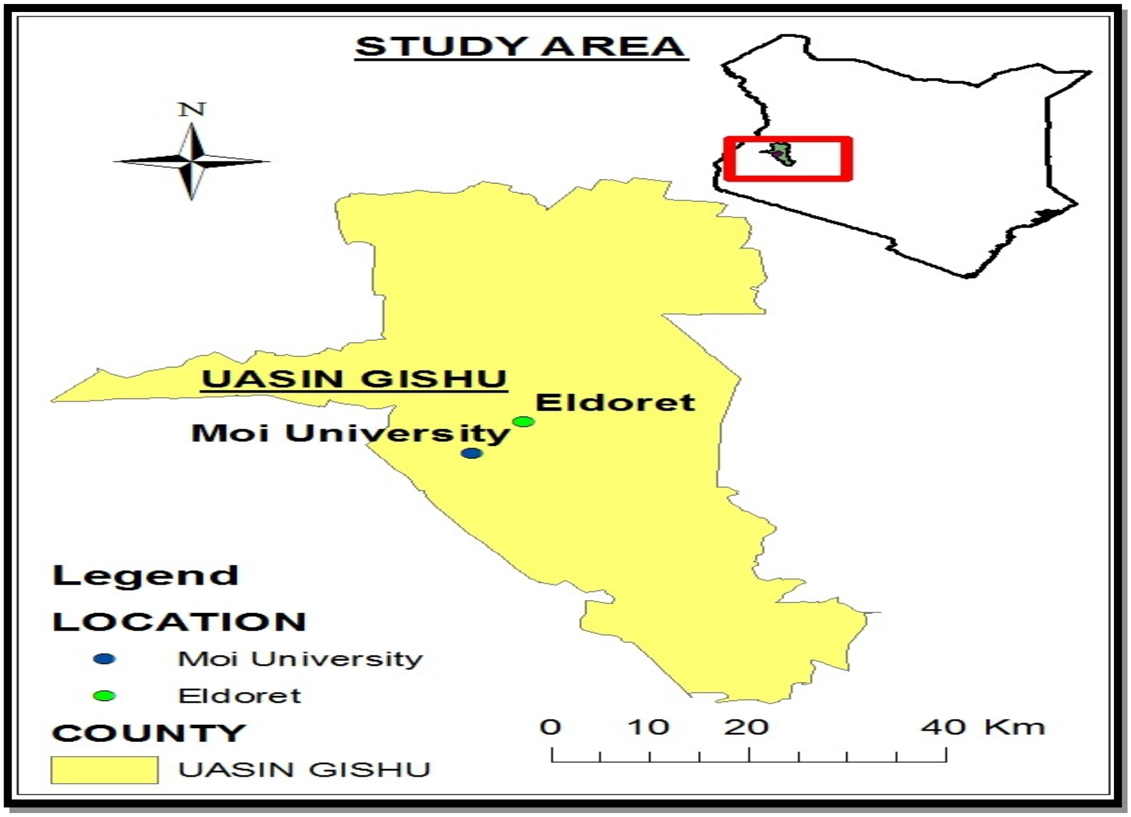
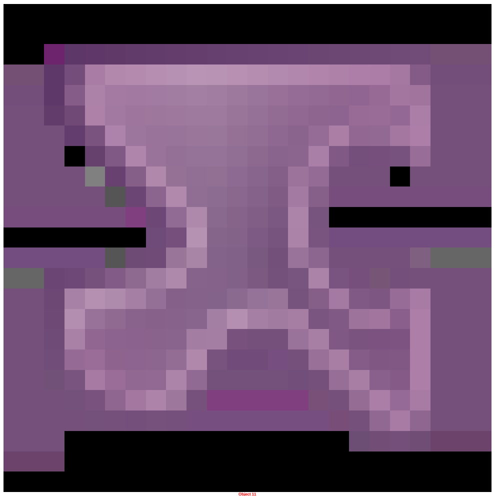


Figure 3.1: Location of the study area and meteorological stations.



Object 11

Figure 3.2: Mean precipitation and the reference evapotranspiration (ET_0) distribution for Eldoret (source: FAO New_LocClim, 2005).

3.3 Experimental Design

The field experiments were in a Randomized Complete Block Design (RCBD) arranged in split plots and replicated three times. As illustrated in Figure 3.3, the size of the experimental plots was 10m^2 (5m x 2m) with a spacing of 0.5m between the plots and a spacing of 1.0 m between the replicates. This was based on a similar research by Tsegay (2012).

Four different water treatments were applied. There was one full irrigation treatment where the crop was kept at 100% of irrigation requirements (T100); soil moisture and crop data was collected from these fields throughout the season and was used for AquaCrop calibration. In the other three treatments, the crops were subjected to deficit irrigation, where the crops were kept at 80%, 60% and 50% of irrigation requirements (T80, T60, and T50). Data collected from these water-stressed fields was used for model validation. The four treatments were replicated thrice resulting in a total of 12 plots (Fig. 3.3). In the T100 treatment, the estimated root zone was refilled to field capacity (FC) when soil water in the root zone approached 45% of total available water (TAW) (Doorenbos & Kassam, 1979). In the deficit irrigated treatments, irrigation occurred on the same day as the fully irrigated plots, but the irrigation depth was reduced to 50%, 60%, and 80% of the T100 treatment.

In order to carry out the deficit irrigation, rainfall was eliminated in the experiment by use of a rain shelter. It was made of a wooden framework and a polyethene cover; it had an area of 260 m^2 and height of 2 m to minimize the greenhouse effect over the experiment as shown in Plate 3.1. Additionally, lateral movement of water was prevented by use of polythene sheet placed up to a depth of 1m around the plots. The shelter was only used during rain events. Consequently, the only water input considered was from the irrigation water applied.

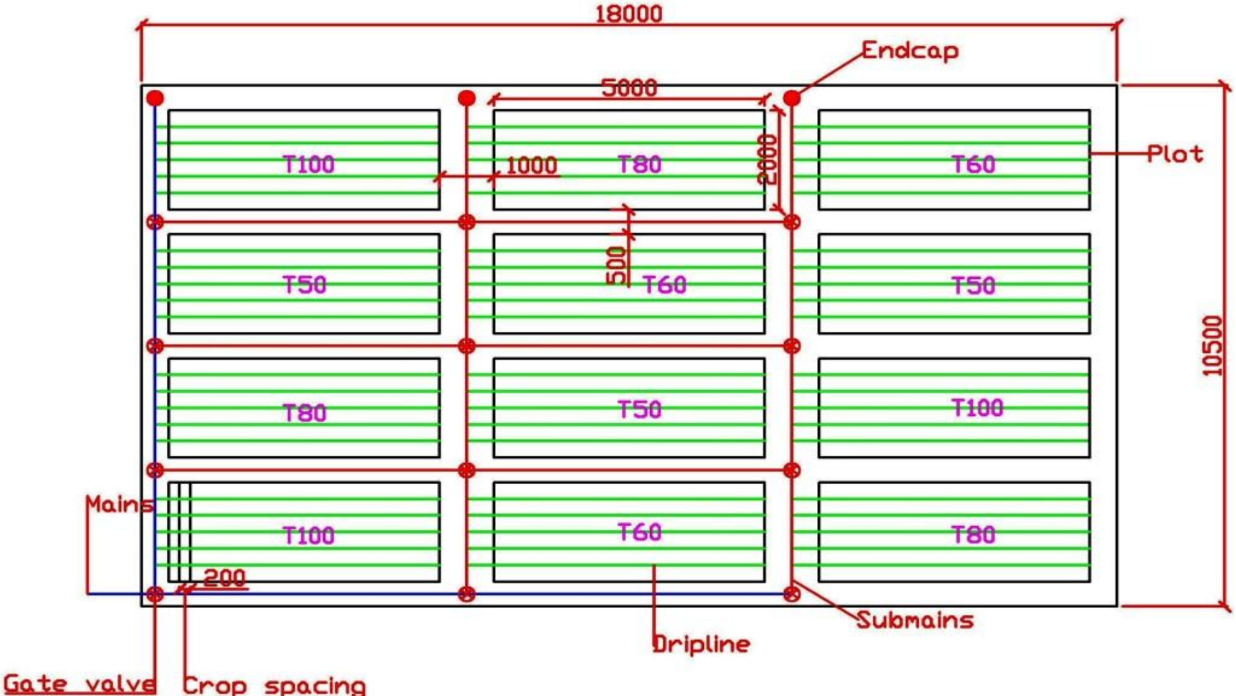


Figure 3.3: Layout of the drip irrigation system under full irrigation (T100) and Deficit irrigation (T80, T60, and T50). Units (mm).

Plate 3.1: Rain shelter structure: (a) outside, (b) inside.

3.4 Irrigation

Water was supplied to the beans via a drip irrigation system. The system consisted of a PVC main line and sub main lines of diameters 50 mm and 32 mm respectively. Polyethylene drip lines (laterals) of 25 mm in diameter was used to irrigate the beans. The drip lines had built in emitters with a nominal discharge of 1.2 l/hr spaced 20 cm from each other. Additionally, control valves were installed at the entry of each plot to adjust and control the amount of irrigation water delivered to each plot (Fig. 3.3).

In order to apply water in the right quantity and at the right time a soil balance equation described by Allen et al. (1998) and given in equation 3.2 was used. First, historical climatic data of the area was used to estimate daily evapotranspiration (ET_0) by means of the FAO Penman-Monteith equation. After which, the crop evapotranspiration (ETc) was calculated with the crop coefficient (Kc) and reference evapotranspiration (ET_0) using Equation 3.1. The depth of the irrigation application was determined by Equation 3.2.

$$ET_C = K_C ET_0 (Eq.3.1)$$

$$I_{T1} = \left(Wr_{Fc} - Wr_{T0} \right) + \left(\sum_{T0}^{T1} ET_C - \sum_{T0}^{T1} RF - I_{T0} \right) (Eq.3.2)$$

$$Wr_{Fc} - Wr_{T0} = 1000 \left(\theta_{FC} - \theta_{T0} \right) Zr \, (Eq.3.3)$$

where

ETc = crop evapotranspiration under optimal conditions

Kc = crop coefficient

ET_0 = reference evapotranspiration

I_{T1} = irrigation depth required at time T1 (mm),

Wr_{FC} = soil water content in root zone at field capacity (mm),

Wr_{T0} = soil water content in root zone at time T0 (mm),

I_{T0} = irrigation depth at time T0 (mm),

θ_{FC} = moisture content at field capacity (vol%),

θ_{T0} = moisture content at time T0 (vol%),

RF = rainfall (mm),

Zr = rooting depth (m).

To determine the duration of water application, the irrigation depth (mm) was converted to time in seconds (s). First, the area of the soil surface wetted by the drip system was measured using a tape measure and the area calculated. This value combined with the rate of discharge of the emitters enabled conversion of the amount of irrigation water applied (Eq.3.4).

$$T_a = \frac{d * A}{q} * 3600 \left(Eq.3.4 \right)$$

where

Ta = duration of irrigation (s)
A = area of wetted soil surface (m^2)
q = emitter discharge (l/hr)
d = irrigation depth (mm)

3.5 Crop Management

Proper crop management was carried out to ensure optimum crop development. These involved weed control and fertilizer application. The zig-zag path method (Carter, 1993) was used to sample the soil in the experimental field for testing purposes. Consequently, the amount of fertilizer required was determined thus ensuring that the only limiting factor affecting the crops was water.

3.6 AquaCrop

AquaCrop is a crop model developed by FAO. It is used in assessing crop yield response to water and is based on accurate plant physiological and soil water budgeting process. It is a water driven simulation model. Figure 3.4 shows the calculation scheme as it is carried out in the model. It can be observed that AquaCrop calculates yield based on the amount of water transpired. Crop development is characterized by an expanding green canopy cover (CC) which transpires water and an increase in root depth for uptake of water. The water transpired is converted to biomass (B) by means of normalized water productivity (WP^*) parameter (Eq. 3.5). For most crops, only a fraction of the biomass produced is converted to the harvested parts to give yield (Y), and the ratio of yield to biomass is known as harvest index (HI) (Eq. 3.6). It should be considered that other factors affecting crop phenology such as salinity, management practices are factored into the model. However, there are other factors such as weeds, pests, and diseases that are still under research and are being developed for AquaCrop (Raes et al., 2009).

$$B=\wp^{\text{¿}}.\sum_{i=1}^{n}\frac{Tr_i}{ET_{0i}}\left(Eq.3.5\right)$$

$$Y=HI.B\left(Eq.3.6\right)$$

where

WP^* = normalized water productivity in (g/m^2)

B = above ground biomass (g/m^2)

Tr_i = daily crop transpiration (mm/day)

ETo_i = daily reference evapotranspiration (mm/day)

Y = yield production (g/m^2)

HI = harvest index (%)

The WP parameter introduced in AquaCrop is normalized for the local climate, defined by ET_0, and the CO_2 concentration in the atmosphere. Calibration of WP and normalization for evaporative demands is based on the Eq. 3.7 (Steduto et al., 2012).

$$\wp^{\text{¿}} = \left[\frac{B}{\sum \frac{Tr}{ETo}} \right]_{[CO_2]} \quad (Eq.\, 3.7)$$

Where

ET_0 = reference evapotranspiration (mm)

In this study normalized water productivity (WP^*) was estimated inversely by using the simulated transpiration and the observed above ground biomass. This was achieved by deriving the WP^* from the linear regression between the simulated cumulative transpiration (standardized by ET_0) and observed biomass during and at the end of the growing season (Tsegay, 2012).

Crop phenology is highly affected by water stress, but there are other factors which are equally important such as soil salinity, soil fertility, and air temperature all of which are factored into the model. However, this study was focused on only the effects of water stress while the other factors remaining constant.

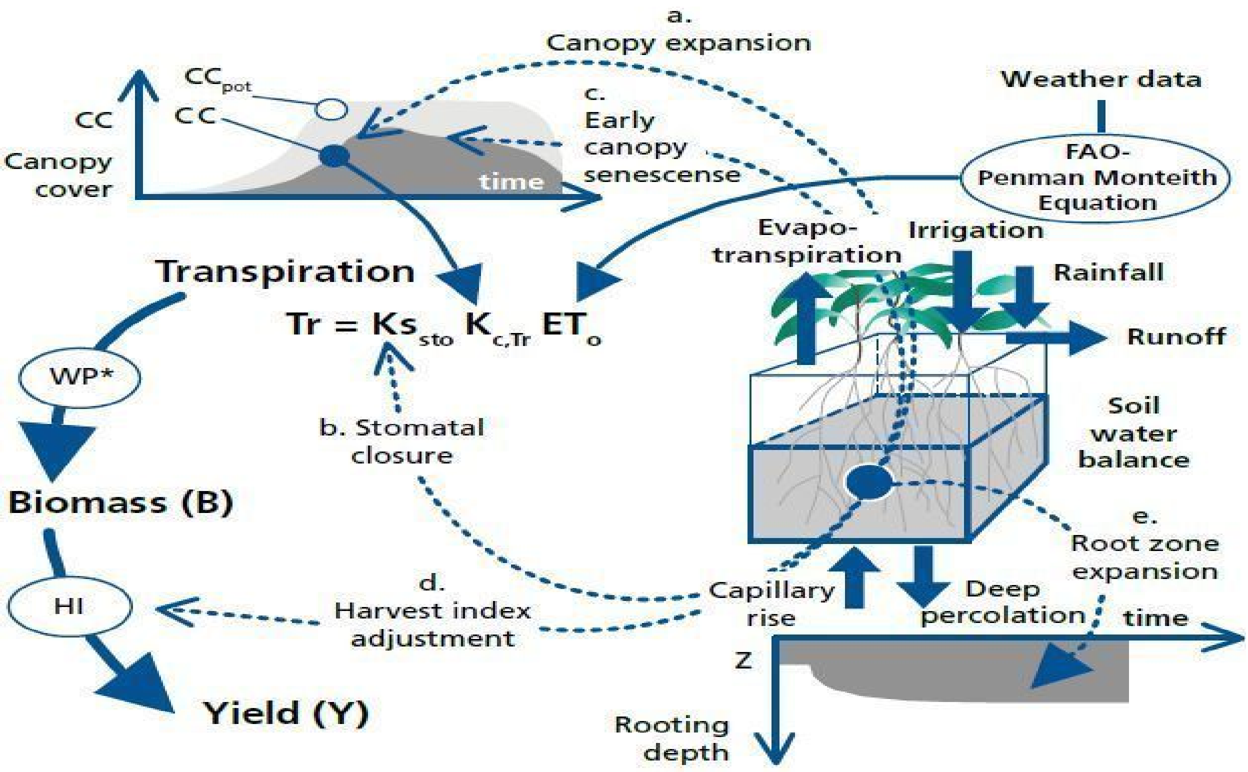


Figure 3.4: Flowchart of the calculation scheme of AquaCrop (bold lines). The dotted lines show the effect of water stress on canopy cover, root zone expansion, crop transpiration and yield (Source: Raes et al., 2009).

3.7 Data Collection

AquaCrop requires certain input data for it to carry out simulations; these are - climatic, crop, soil, irrigation and field management data which can be stored in the files provided. The period of simulation and initial conditions at the start of the simulation also need to be provided.

3.7.1 Climatic data

AquaCrop requires- daily minimum and maximum temperatures, daily reference evapotranspiration (ET_0), daily rainfall data and annual CO_2 concentration as input in its climatic file.

During the experiment period, daily weather data (daily maximum and minimum temperature, average wind speed at 2m height, mean relative humidity) was collected from the Moi University weather station for calculation of the daily ETo. A software, the ETo calculator (FAO, 2009) which uses the FAO Penman-Monteith equation (Allen et al., 1998), aided in the computation.

The annual CO_2 concentration levels are already incorporated into the model by default. The values are obtained from the Mauna Loa Observatory in Hawaii. Mauna Loa is regularly used as an illustration of rising carbon dioxide levels because it is the longest, continuous series of directly measured atmospheric CO_2 (NOAA, 2015). Consequently, CO_2 data from Mauna Loa can be used as a proxy for global CO_2 levels because CO_2 mixes well throughout the atmosphere. Consequently, the trend in Mauna Loa CO_2 (1.64 ppm per year) is statistically indistinguishable from the trend in global CO_2 levels (1.66 ppm per year) (NOAA, 2015).

For purposes of creating irrigation schedules, historical weather data of 22 years (1990-2011) was also collected from the Moi University meteorological department.

3.7.2 Soil data

The derivation of water retention characteristics of soils requires that soil physical characteristics such as textural class and soil moisture holding characteristics be determined. This was achieved by the use of soil samples collected from the field. Three profile pits were excavated at representative locations within the field. Undisturbed soil samples were then collected at two depths of between 0 to 0.5m by use of a Kopecky ring ($100cm^3$).The mass of soil sample was then oven-dried at 107 ℃ for 24 hours and weighed. For purposes of calculating the soil water holding characteristics, the bulk density of the soil was then determined (Eq. 3.8).

$$\rho_b = \frac{m_s}{v_s} \left(Eq.3.8 \right)$$

where:

ρ_b = bulk density (g/cm^3)

m_s= total dry mass of sample (g)

v_s = bulk volume soil (cm^3)

The soil texture was obtained by separating the soil to its relative proportions of sand, silt, and clay. This was carried out by collecting disturbed soil samples from the field after which they were air dried. The particle sizes in the soils were then separated from one another by using the hydrometer method (Bouyoucos, 1962). Afterwards, using the obtained proportions of sand, silt and clay, a pedo-transfer function (Saxton & Rawls, 2006) was employed to extract the soil physical characteristics, i.e.; the textural class, water content at saturation (θ_{SAT}), field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}).

The initial soil water content (SW_0) before sowing and soil water content (SWC) needs to be measured and also monitored during the growing season of the experiment. The SW_0 was determined prior to sowing date using gravimetric methods (Black, 1965). SWC at 50 cm of the root zone (Plate 3.1) was monitored after every two weeks by the gravimetric method (Eq. 3.9). Two samples per plot were collected, and the mean used to represent observed moisture in the root zone per treatment.

Plate 3.2: Soil sample collection for analysis of soil water content taken on 27/05/2014

$$\theta_m = \frac{m_{s+w} - m_s}{m_s} x 100 (Eq. 3.9)$$

where:

θ_m = mass water content (mass %)

m_{s+w} = mass of soil sample (g)

m_s = total dry mass of sample (g)

This can further be expressed in volumetric terms (Eq. 3.10).

$$\theta = \rho_b \theta_m (Eq.3.10)$$

where:

θ = volumetric water content (vol %)

The soil water content in the root zone was eventually obtained by Eq. 3.11.

$$w_r = 10 \theta z (Eq.3.11)$$

where:

w_r = soil water in root zone (mm (water))

z = rooting depth (m)

3.7.3 Crop data

Crop data required included the beans major phenological growth stages (emergence, maximum canopy cover, flowering, senescence (process of deterioration) and physiological maturity) measured in calendar days; these were observed and noted. The plant population density was counted from a 0.40 m by 0.20 m quadrant of the experimental field at the time when about 90% of the crop had emerged.

Maximum effective rooting depth was obtained from the experimental plots by excavating pits during maturity (destructive sampling).

i. Green Canopy Cover

The green canopy cover (CC) is the soil surface covered by the green canopy of the crop per unit surface area. The CC was obtained by use of above ground camera taking digital pictures perpendicular to the experimental plot at a height of about 1.5m (Plate 3.3).This was carried out at an interval of 10 days where four samples per plot were obtained. The pictures were analyzed using SamplePoint (Booth et al., 2006), a manual image classification software which is used to determine the percentage canopy cover of a particular crop per area covered. Thus, enabling the determination of the CC as a percentage (%) of the soil surface covered.

Plate 3.3: Canopy cover for the plot T100 taken on 23/06/2014

ii. Dry above ground biomass

The dry above ground biomass (B) can only be measured by destructive sampling. One sample per plot was taken from a quadrant of 0.40m by 0.20m of the experimental plots at an interval of 14 days during the season and taken to the laboratory. These samples were oven dried at a temperature of 65 ℃ for 48 hours and weighed to determine their mass per area covered (Plate 3.3).

Plate 3.4: Oven drying of biomass samples.

iii. Yield

Final yield (Y) at the end of the season was harvested together with the final biomass from quadrants of 4 m^2 from the plots. The harvest index (HI) was calculated as the ratio of Y to final B.

3.8 Calibration and Validation

Calibration is the adjustment of certain model parameters to make the model match the measured values at the given location. AquaCrop has parameters falling into two groups. One is a set of conservative parameters which are crop-specific and do not change with time, management practices, geographic location, climate or cultivar. The other group is the non-conservative parameters or user- defined parameters. The non-conservative parameters describe predominantly the length of growing stages (time to emergence, time to attain maximum canopy cover, time to flowering, senescence and physiological maturity (in calendar days)) and crop phenology. 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, stomatal closure, and canopy senescence were calibrated in an iterative way by comparing observed CC and SWC with simulated outputs of AquaCrop for the fully irrigated treatment. The observations of CC, SWC, B and Y were used as benchmarks during the calibration process. Calibration was stopped when the simulated output for CC, SWC, B and Y fitted (as 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, and observed data from the deficit irrigated fields (T80, T60, and T50) were used (Fig. 3.5).

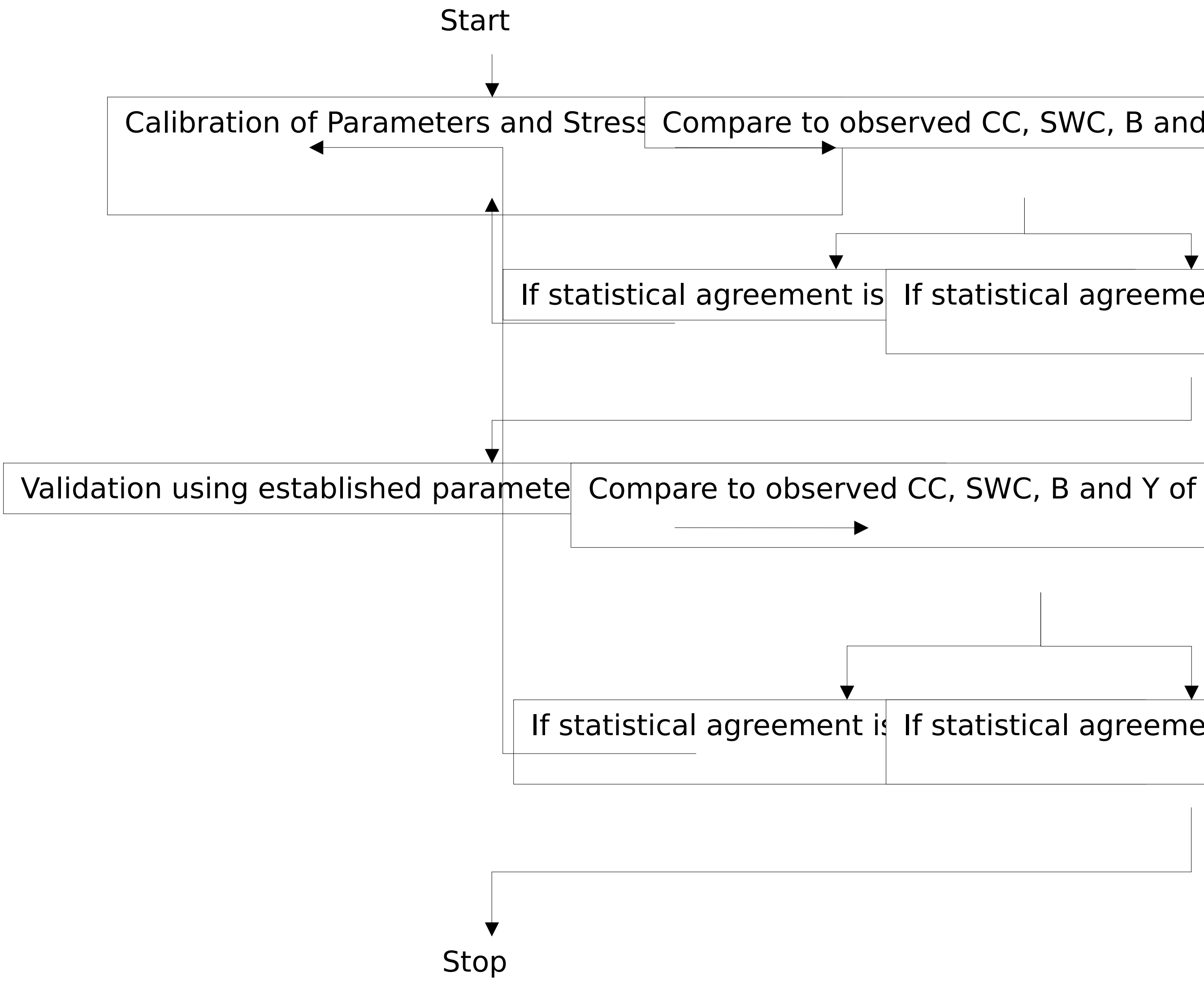


Figure 3.5: Flow chart of the calibration and validation process.

3.9 Simulations

Rainfall is highly variable in time and space. Therefore, in order to design irrigation schedules, particular rainfall depths that can be expected with a specific probability or return period are used. These rainfall depths can only be obtained by frequency analysis of long time series of historic rainfall data. Frequency analysis was carried out on historical rainfall data of 22 years (1990-2011) to determine typical climatic conditions of dry, wet, and average years, Rainbow software (Raes et al., 1996) was employed in carrying out the frequency analysis. Furthermore, the seasonal rainfall for each of the years was obtained by adding up the monthly rainfall for the three months (October, November, and December). After which, a frequency analysis was performed to obtain the dry, wet, and average seasons during the short rains period.

Consequently, the AquaCrop was run for the season (October to December) of typical (dry, wet, and average) season where the timing and depth of irrigation was determined every time the root zone water content was depleted to 45 percent of its total available water. This procedure determined the schedule for the full irrigation.

After that, the process was repeated with deficit irrigation (80%, 60% and 50% of irrigation requirement) using knowledge of the differential sensitivity of common beans to water stress (Table 2.1). The yield and water productivity results obtained from these simulations were then analyzed and discussed, and the irrigation schedules presented.

3.10 Analysis of Model Performance

There are various statistical methods that are used to compare how good the model simulates the beans CC, SWC, B, and Y. By comparing simulated and measured data from the experimental fields the performance of the model can be determined.

3.10.1 Coefficient of determination

The coefficient of determination (R^2) signifies the proportion of the variance in measured data explained by the model. It ranges from 0 to 1, with values close to 1 indicating a good agreement and is computed as shown in Eq. 3.12.

$$R^2=\left[\frac{\sum_{i=1}^{n}\left(M_i-\acute{M}\right)\left(S_i-\acute{S}\right)}{\sqrt{\sum_{i=1}^{n}\left(M_i-\acute{M}\right)^2\sum_{i=1}^{n}\left(S_i-\acute{S}\right)^2}}\right]^2 \quad (Eq.3.12)$$

where:

M_i ¿ measured values

S_i = simulated values

$\acute{M}=$¿ measured mean.

$\acute{S}=$¿ measured simulation.

n = number of observations

3.10.2 Root Mean Square Error

The root mean square error (RMSE) measures the average magnitude of difference between simulations and measured values. It ranges from 0 to positive infinity, with the former indicating good model performance. It is computed as shown in Eq. 3.13.

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(M_i-S_i\right)^2}\,(Eq.3.13)$$

The unit of RMSE is the same as the parameters compared.

3.10.3 Nash-Sutcliffe model efficiency coefficient

The Nash- Sutcliffe model efficiency coefficient (EF) is used to quantify the proportion of variability in the observed values that was accounted for by the model (McCuen et al., 2006). It is computed as shown in Eq.3.14.

$$E=1-\left(\frac{\sum_{i=1}^{n}\left(M_i-S_i\right)^2}{\sum_{i=1}^{n}\left(M_i-\acute{M}\right)^2}\right)(Eq.3.14)$$

An efficiency of 1 (E = 1) corresponds to a perfect match of modeled results to the observed data. An efficiency of 0 (E = 0) indicates 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 mean is a better predictor than the model.

3.10.4 Willmott’s index of agreement

Willmott’s index of agreement (d) is used to measure the degree to which the simulated data approach the measured data. It ranges between 0 and 1, with 0 indicating no agreement, and 1 indicating a perfect agreement between the simulated and observed data. It is computed as shown in Eq.3.15.

$$d=1-\frac{\sum_{i=1}^{n}\left(S_i-M_i\right)^2}{\sum_{i=1}^{n}\left(\left|S_i-\acute{M}\right|+\left|M_i-\acute{M}\right|\right)^2}(Eq.3.15)$$

Chapter 4: Results and Discussion

4.1. Introduction

In this chapter, the results of the soil, irrigation, climatic and crop data collection and analysis are presented and discussed. After that, results of the calibration and validation of AquaCrop are presented. Furthermore, irrigation schedules obtained from model simulation of historical data are presented. Finally, the evaluation of the effect of the various levels of deficit irrigation on the yield (Y) and water productivity (WP) of beans are compared and discussed.

4.2 Soil analysis

The mineral composition of the soil was determined to consist of 64% sand, 25% clay and 11% silt. Based on these textural results, the soil was classified as sandy clay loam according to USDA classification system (Allen et al., 1998). Using a pedo-transfer function (Saxton and Rawls, 2006) the soil texture and other physical characteristics were also obtained (Table 4.1). The soil bulk density was determined to be 1.4 g/cm^3. It was observed that there was no significant difference in soil physical characteristics between the different layers. Therefore, a uniform soil profile was considered in the model simulations.

Table 4.1: Physical characteristics of sandy clay loam from the experimental fields.

Soil Depth (cm)	Soil texture	Permanent wilting point (PWP) (vol %)	Field capacity (FC) (vol %)	Saturation point (SAT) (vol %)	Total Available Water (TAW) (mm/m)	Saturated hydraulic conductivity (Ksat) (mm/day)
0-15	Sandy Clay Loam	16.6	26	42.9	94	276

0-30	Sandy Clay Loam	16.6	26	42.9	94	276

Laboratory: Soil Lab, University of Eldoret and Pedotransfer function.

The basic soil chemical analysis carried out showed that the soil was low in calcium and phosphorous but high in magnesium and potassium (Table 4.2).

Table 4.2: Chemical characteristics of the soil from the experimental fields.

Parameter	Unit	Result	Guide Low	Guide High	Method
pH(H_2O)		5.85	6	7	Potentiometric
Phosphorus	ppm	11.5	20	100	Spectroscopy
Potassium	ppm	742	364	728	Spectroscopy
Calcium	ppm	1790	2240	2800	Spectroscopy
Magnesium	ppm	359	224	358	Spectroscopy
Sodium	ppm	27.3		<214	Spectroscopy
Organic matter	%	4.78	3	7	Colorimetric
Nitrogen	%	0.22	0.2	0.5	Colorimetric

Laboratory: Crop Nutrition Laboratory Services Ltd.

As a result, a soil fertility and correction program was carried out prior to sowing and during the planting season, to boost nutrition and organic matter levels in the soil (Table 4.3).

Table 4.3: Soil fertility and correction program.

Input type	Input	Rate (kg/ha)
Soil correction	Calcite Lime (35 - 40% Ca < 1% Mg)	600
Soil correction	Manure/ Compost	5000
Fertilizers	Di- Ammonium Phosphate (DAP)	70

Laboratory: Crop Nutrition Laboratory Services Ltd.

4.3 Irrigation

Soil water levels in the root zone were used as a measure of when to start and stop irrigation events. Adequate soil water is critical for beans during emergence. The amount of irrigation water was scheduled throughout the growth season by use of the soil-water-atmosphere balance equation (Eq. 3.2). At the beginning of the season, the soil moisture was determined to be close to permanent wilting point (SW_0 = PWP). Therefore, in the first irrigation treatment, the root zone was refilled to field capacity (FC) in all the treatments. There was a total of 22 irrigation events with the total irrigation water being 3970 m^3/ha, 3220 m^3/ha, 246 m^3/ha and 208 m^3/ha for treatments T100, T80, T60, and T50 respectively. A total of 1173 mm of irrigation water used in all the treatments, this is equivalent to 11730 m^3/ha. The amount of irrigation water was added every three days crop water requirement calculations. The water demand was highest at the mid-season growing stage; this is when the crop is at the flowering and yield formation period, and crop water requirements are highest (Table 4.4).

Table 4.4: Amount of irrigation water added throughout the season.

				Irrigation treatments			
Dates	Kc	Growth Stage	Interval (days)	T100 (mm)	T80 (mm)	T60 (mm)	T50 (mm)
17/4/2014		Initial	0	19	19	19	19
21/4/2014	0.4		3	8	6	5	4
25/4/2014	0.4		3	8	6	5	4
29/4/2014	0.4		3	8	6	5	4
3/5/2014	0.4		3	8	6	5	4
7/5/2014	0.4		3	8	6	5	4
11/5/2014	0.75	Development	3	14	11	8	7
15/5/2014	0.75		3	14	11	8	7
19/5/2014	0.8		3	15	12	9	8
23/5/2014	0.9		3	16	13	10	8
27/5/2014	0.9		3	17	14	10	8
31/5/2014	1.15	Mid-season	3	22	17	13	11
4/6/2014	1.15		3	22	17	13	11
8/6/2014	1.15		3	22	17	13	11
13/6/2014	1.15		3	22	17	13	11
17/6/2014	1.15		3	22	17	13	11
21/6/2014	1.15		3	22	17	13	11
25/6/2014	1.15		3	22	17	13	11
29/6/2014	1.15		3	22	17	13	11
3/7/2014	1.1	Late season	3	21	17	13	11
7/7/2014	1.1		3	21	17	12	10
11/7/2014	0.95		3	19	15	12	10
15/7/2014	0.88		3	17	14	10	9
19/7/2014	0.3		3	13	10	8	6
Total				397	322	246	208

4.4 Climatic data analysis

The average annual rainfall and reference evapotranspiration (ET_0) collected for 22 consecutive years was 1275.5 mm and 1611.0 mm respectively (Fig. 4.1). The frequency analysis of the rainfall data is presented in Figure 4.2, from which the amount for dry, normal and wet years were extracted as 1105.7 mm, 1275.2 mm and 1445.2 mm respectively.

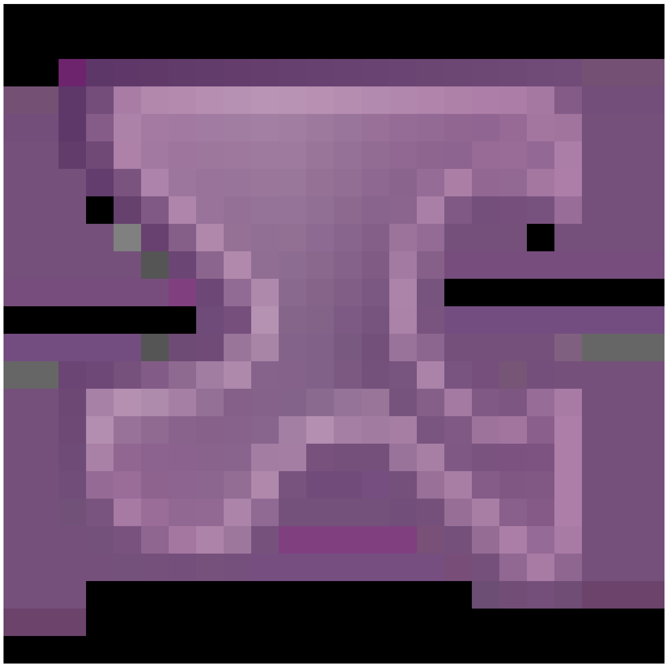


Figure 4.1: Annual rainfall and ET_0 for Moi University (Source: Moi University weather station, data observed from 1990- 2011).

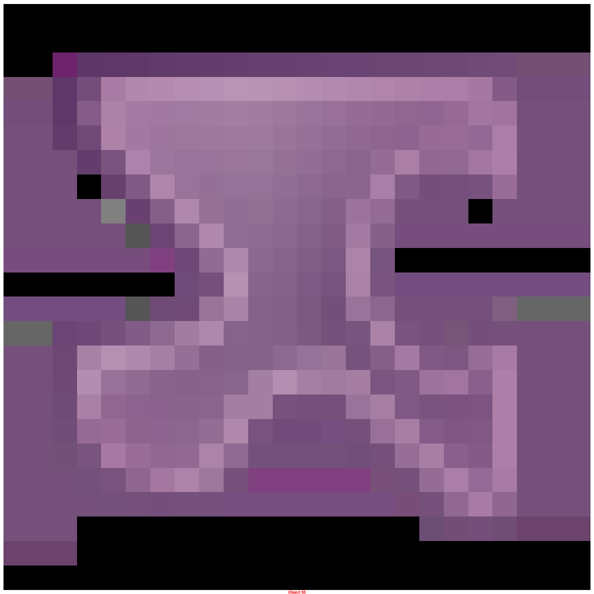


Figure 4.2: Probability plot of the annual rainfall for Moi University (Source: Moi University weather station, data observed from 1990- 2011).

Figure 4.3 shows the monthly rainfall distribution during the year 2005 which is a typical normal year with an annual rainfall of 1235.8mm. It can be observed that the main rainy season runs from April to September, followed by the short rainy season that runs from October to December. ET_0 for the period is also included.

Object 57

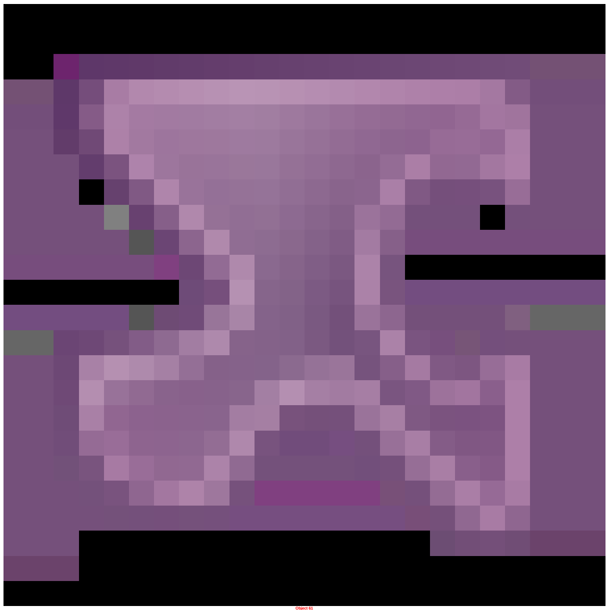
Figure 4.3: Rainfall (bars) and ET_0 (line) distribution in a typical normal year (2005).

In this study, the proposed season for growing the beans is during the short rainy season. The average seasonal rainfall (October-December) and evapotranspiration (ET_0) for the 22 years was 220.06 mm and 415.42 mm respectively (Fig. 4.4).

Object 59

Figure 4.4: Rainfall (bars) and ET$_0$ (full line) during the short rains season (October-December). (Source: Moi University weather station, data observed from 1990- 2011).

During this period, the evaporative demand of the atmosphere, ET$_0$, is much greater than the rainfall. It is important to note that the water requirement for maximum production of the beans is between 300- 500 mm (Doorenbos and Kassam, 1979). Due to this apparent water deficit there is clear need for another source of water to ensure optimum production of beans during this season. Figure 4.5 presents the frequency analysis of the seasonal rainfall data, from which the amount for dry, normal and wet years were extracted as 136.7 mm, 220.1 mm and 303.4 mm respectively. From the frequency distribution, the year 2007, 2002 and 2004 were observed to have typically dry, normal and wet seasons respectively and were subsequently used in model simulation and provision of irrigation schedules.



Object 61

Figure 4.5: Probability plot of the seasonal rainfall for Moi University (Source: Moi University weather station, data observed from 1990- 2011).

The field experiments were carried out from 17th April to 21st July 2014 (Table 4.4). This period was constrained by the availability of financial resources and the time required for completing the study. The advantage of using AquaCrop is that the experiments can be carried out in a particular season for calibration and validation. Subsequently, the model can be utilized for investigating different effects in different seasons. This principle was applied in this study. In this period, the total ET_0 and rainfall was 502.3 mm and 568.6 mm respectively (Fig.4.6).

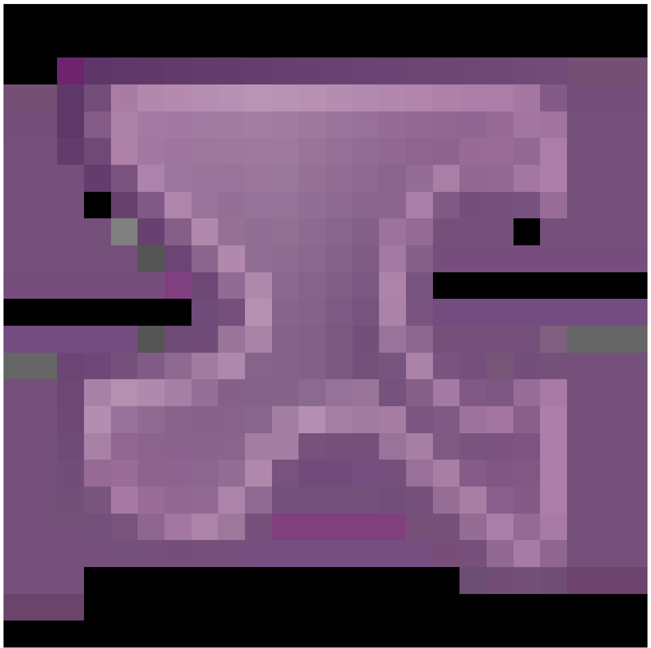


Figure 4.6: Rainfall (bars) and ET_0 (full line) during the growing period (April- July 2014). (Source: Moi University weather station).

It should be noted that a rain shelter was utilized to cover the experimental field during rainfall events. This ensured that the irrigation scheduling designed for this study was adhered to. Therefore, the conditions were kept suitable for practicing deficit irrigation.

4.5 Calibration of AquaCrop

4.5.1 Canopy cover

The correct simulation of canopy cover (CC) is essential to AquaCrop performance, for it affects the rate of transpiration and consequently biomass accumulation. Calibration first involved adjusting the crop's key variables to reproduce field observed CC. The values of crop parameters obtained after calibration are presented in Table 4.5.

Table 4.5: The crop parameters for beans obtained after calibration.

Description	**Value**	**Unit**
Initial canopy cover (CCo)	0.63	%
Canopy growth coefficient (CGC)	19.8	%/day
Canopy decline coefficient (CDC)	11.8	%/day
Initial plant density	12.5	(no. of plants per m^2)
Canopy development		
Emergence	12	DAS
Max. canopy	49	DAS
Senescence	78	DAS
Maturity	95	DAS
Maximum canopy cover (CCx)	80	%
Flowering	44	DAS
Root deepening		
Time to reach maximum rooting depth	44	DAS
Maximum rooting depth	0.7	m
Water stress response factors		
Water productivity normalized for ET_0 and CO2	14.5	(g/m^2)
Soil water depletion threshold for canopy expansion- Upper threshold	0.27	fraction TAW
Soil water depletion threshold for canopy expansion- Lower threshold	0.62	fraction TAW

Soil water depletion threshold for stomatal control- Upper threshold	0.50	fraction TAW
Soil water depletion threshold for canopy senescence- Upper threshold	0.85	fraction TAW
Reference Harvest index	48	%

Figure 4.7 below presents the simulation of CC for non-water stressed conditions (T100) with AquaCrop after calibration. The observed and simulated CC development fitted well with adequate statistical values (Table 4.6) and followed standard logistic growth curve used for AquaCrop for non-stressed conditions (Raes et al., 2010).

In this study, the maximum CC of about 80% was reached 49 days after sowing. The observed canopy cover and simulated canopy cover values did not differ significantly (RMSE = 8.50 %, R^2 = 0.94).

Object 65

Object 67

Figure 4.7: (a) Observed (symbols) and simulated (line) canopy cover for beans in T100 plot (b) Observed and simulated canopy cover

4.5.2 Soil water content (SWC)

Accurate simulation of soil water balance is very important, as all stress thresholds in AquaCrop are a direct function of soil water. The soil water content in the root zone was expressed as an equivalent depth (mm) throughout the growing season (Fig. 4.8). The trend of soil wetting and drying cycles due to irrigation events was predicted satisfactorily by AquaCrop. The model simulated no deep percolation in any of the irrigation treatments, indicating that the irrigation was properly managed. Displayed values for SAT, PWP, and FC were obtained from textural analysis of the soil (Table. 4.1).

Figure 4.8: (a) Observed (symbols) and simulated (line) soil water content for beans T100. (b) Observed and simulated soil water content for beans T100

As shown in Table 4.6 the observed and simulated values fitted well with adequate statistical parameters, with R^2, EF, and d values (close to unity) as well as a low RMSE to confirm a good agreement between simulations and observations.

Table 4.6: Goodness-of-fit analysis for the simulated soil water content (SWC), canopy cover (CC), biomass (B, both final and intermediate biomass)

Parameter	R^2	EF	d	RMSE
Optimal value	1.0	1.0	1.0	0.0
CC	0.94	0.89	0.95	8.50 (%)
SWC	0.88	0.75	0.94	3.90 (mm)

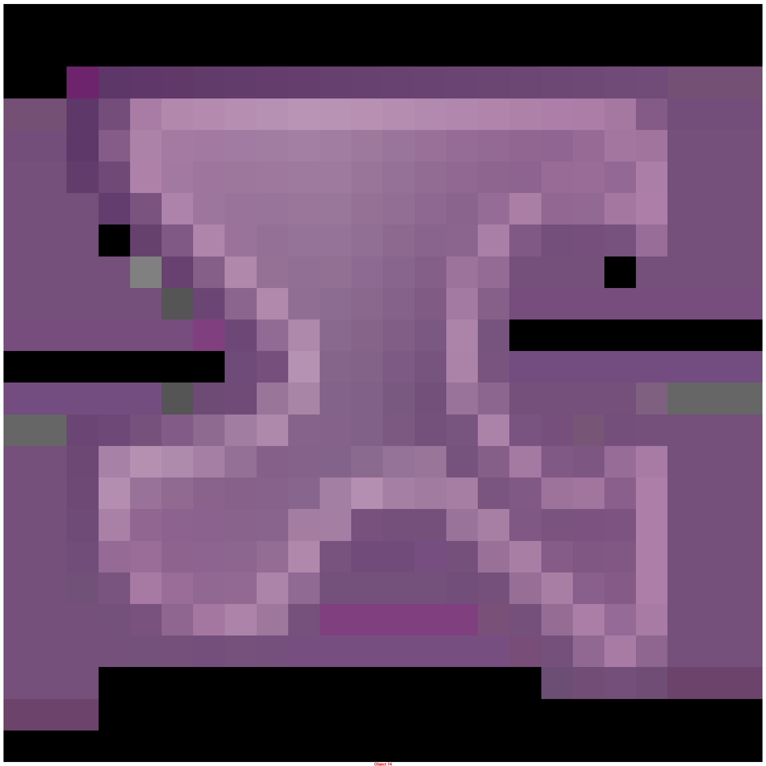
B	0.94	0.94	0.97	0.436 (t/ha)

R^2: coefficient of determination; EF: Nash-Sutcliffe efficiency; d: index of agreement; RMSE: root mean square error.

4.5.3 Biomass and Yield

The goodness of fit between observed and simulated CC and SWC indicated that crop transpiration was well simulated. Consequently, the WP^* was determined inversely by using the simulated transpiration and the observed above ground biomass (Fig. 4.9). The WP^* was derived from the linear regression between the simulated cumulative transpiration (standardized by ET_0) and observed biomass during and at the end of the growing season.

A WP^* of 0.145 t/ha (14.5 g m^{-2}) was selected and used in the model. The coefficient of determination (R^2) for the determined WP^* was 0.95, indicating that there is an excellent correlation between the cumulative normalized transpiration and biomass.



Object 74

Figure 4.9: Regression between the observed Dry aboveground biomass and simulated cumulative transpiration (standardized by ET_0)

From the fully irrigated field, the average reference harvest index (HIo) of 48% was obtained as the percentage ratio of beans seeds yield to total biomass (E.q 3.6). As a result, simulation for biomass (B) and yield (Y) was obtained. Figure 4.10 shows the simulated and observed B for the full irrigation treatment. It can be observed that the simulations fitted the observed data well and with adequate statistical values (Table 4.6).

Object 77

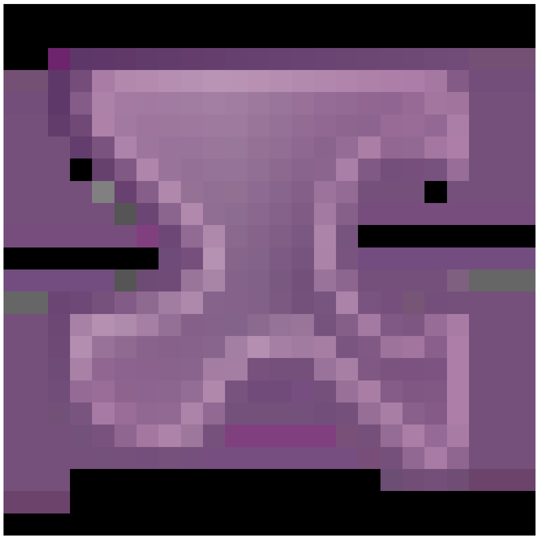


Figure 4.10: Observed (symbols) and simulated (line) dry above ground biomass for beans under full irrigation after calibration. (b) Observed and simulated above-ground biomass.

From the statistical analysis of the simulation results (Table 4.5), it can be concluded that the main features of beans, as affected by water stress, were well modeled by AquaCrop. R^2 for all variables was ≥ 0.88, and d approached unity. The relatively small RMSE confirmed the goodness of fit between the observed and simulated results. The EF had a reasonable range ≥ 0.75. Subsequently, the calibration process was satisfactory, and the resulting crop model parameters were adapted.

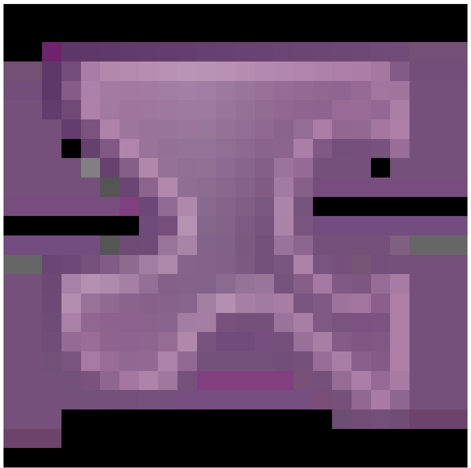
4.6 Validation of AquaCrop

A calibrated model for an existing climate, soil and crop condition needs to be validated to assess its practical application and the precision of its predicted results. Consequently, AquaCrop model was validated using the calibrated crop parameters (Table 4.6) and data sets from the field observations of the T80, T60, and T50 treatments. Validation results suggested that the model simulated parameters such as canopy cover, biomass, soil water content, and yield reasonably well.

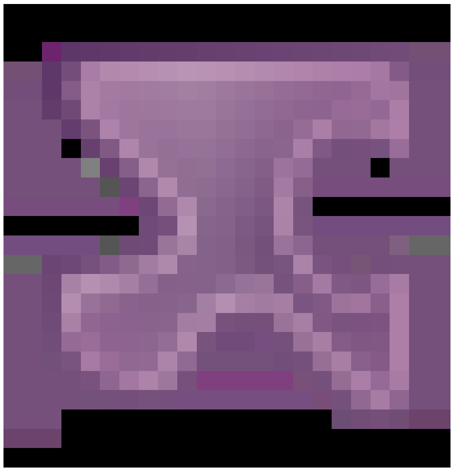
4.6.1 Evaluation of the canopy cover

The model was able to simulate CC adequately in the water-stressed fields (T80, T60, and T50). Figure 4.11 presents the validation results for CC. It was observed that with an increase in water stress there was a decline in the maximum CC achieved (CCx), with the lowest CC% at 46% in the T50 water treatment. This represented a decline of 35% compared to that of the T100 field which had an 80% maximum CC. However, there was only a slight effect in the T80 water stressed field where the maximum CC achieved was 78.7% (Fig. 4.11 (a)). Additionally, the model over-predicted the CC by 20% and 15% respectively in the T60 and T50 treatment. This results are similar to those obtained by Salemi et al. (2011) in a similar study on Winter Wheat.This is attributed to the fact that the model outputs are highly sensitive to the depth of irrigation water applied (Salemi et al., 2011)

It was also evident that the increase in water stress led to delayed development. These results are in accordance with Farahani et al. (2009) who found that severe water stress lead lesser biomass and the crop took a longer period to develop. The model was less satisfactory in simulating severe water-stress treatments this was evident in the manner in which the model over-predicted the maximum CC in the T60, and T50 treatments; this is also consistent with results obtained by Farahani et al. (2009).



Object 82



Object 84

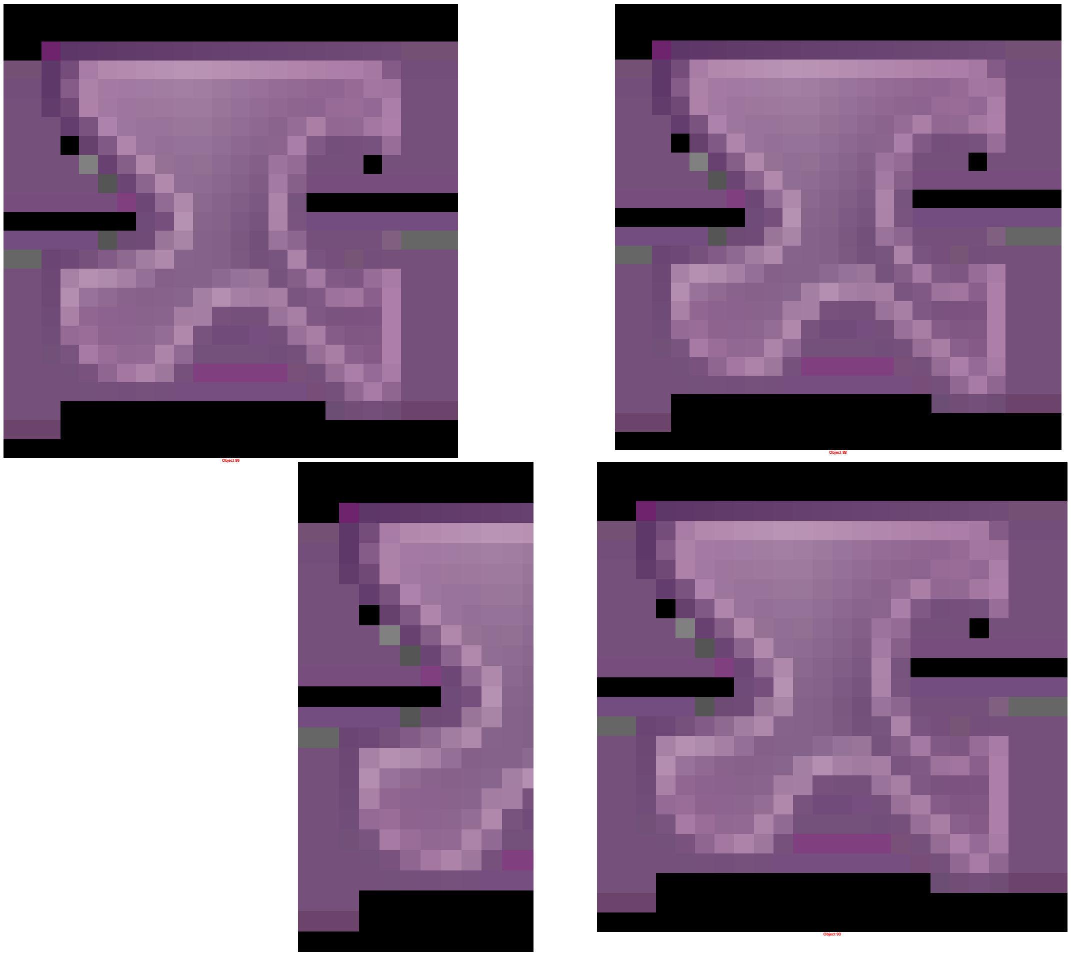


Figure 4.11: Observed (symbols) and simulated (line) canopy cover for beans under different levels of irrigation treatment (b) Observed and simulated canopy cover for beans under different levels of irrigation treatment

4.6.2 Evaluation of the soil water content

Data sets of SWC collected from the fields under T80, T60 and T50 irrigation treatments were used in the validation process. The comparison between observed soil water contents in the root zone matched the simulated values reasonably well during validation (Fig. 4.12). This suggested that the calibration of AquaCrop for beans was satisfactory, and crop water requirement (ETc) was well predicted. An overview of the statistical parameters in

Table 4.7 confirms the ability of the model to simulate the calibrated crop parameters for different data observations used for the validation.

Table 4.7: Goodness-of-fit analysis for the simulated soil water content (SWC), canopy cover (CC), biomass (B, both final and intermediate biomass)

Irrigation treatment	Parameter	R^2	EF	d	RMSE
	Optimum value	1.0	1.0	1.0	0
80%	CC	0.94	0.90	0.97	4.3 (%)
	SWC	0.94	0.73	0.82	4.5 (mm)
	B	0.94	0.90	0.97	0.779 (t/ha)
60%	CC	0.94	0.68	0.94	12.2 (%)
	SWC	0.86	0.79	0.78	4.9 (mm)
	B	0.96	0.87	0.95	0.652 (t/ha)
50%	CC	0.94	0.69	0.92	11.9 (%)
	SWC	0.88	0.64	0.82	6.8 (mm)
	B	0.95	0.88	0.97	0.625 (t/ha)

R^2: coefficient of determination; EF: Nash-Sutcliffe efficiency; d: index of agreement; RMSE: root mean square error.

Figure 4.12: Observed (symbols) and simulated (line) soil water content for beans under different levels of irrigation treatment. (b) Observed and simulated soil water content for beans under different levels of irrigation treatment

4.6.3 Evaluation of Biomass

An overview of the validation results of the biomass for the T80, T60 and T50 irrigation treatments is given in figure 4.13. As anticipated the time taken to build biomass was longer with an increase in water stress. This was coupled with a decline in biomass as well. However, the goodness-of-fit values in Table 4.7 present a fair to excellent simulation results.

Object 110

Object 112

Object 114

Object 117

Object 120

Object 122

Figure 4.13: Observed (symbols) and simulated (line) dry above ground biomass for beans under different levels of irrigation treatment. (b) Observed and simulated biomass for beans under different levels of irrigation treatment

4.6.4 Evaluation of yield and water productivity

The observed and simulated yield and water productivity for all the irrigation treatments are presented in Table 4.8.

Table 4.8: Observed and simulated yield and water productivity under different irrigation treatments.

Irrigation treatments	Yield (t/ha)		PD (%)	WP (kg/m^3)	
	Observed	Simulated		Observed	Simulated
T100	4.238	4.387	-3.516	1.01	1.12
T80	4.138	3.952	4.495	1.29	1.23
T60	2.254	2.848	-11.691	0.92	1.01
T50	1.702	2.179	-28.026	0.77	0.981

PD% = percentage difference between observed and measured yield.

The model prediction of bean yield showed a good agreement with observed values with an R^2 of 0.83 (Fig. 4.14). The Willmott's index of agreement was 0.97 and root mean square error was 0.4 t/ha.

Object 124

Figure 4.14: Observed and simulated yield of beans under the different levels of irrigation treatment.

The T100 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 T80, T60 and T50 irrigation treatments had lower yields because of the reduced evaporation rate due to the closure of stomata which retarded growth.

Water productivity was, however, highest in the T80 treatment in both the observed and simulated values (Fig. 4.15). This was an indication that the yield output per amount of water applied was highest in this treatment. The lowest yield reduction was also obtained in the T80 treatment, where saving 20% of full irrigation which translates to 750 m^3/ha reduced bean yield by 2.36% and 9.32% in the observed and simulated results respectively (Table 4.9). Whereas, the highest yield reduction was obtained in T50 irrigation treatment i.e. 59.84% and 50.31% in the observed and simulated results respectively. This is consistent with the fact that common beans with a $K_{y\,>}$ 1 are sensitive to severe water stress. Therefore, the lower drop in yield in the T80 treatment is attributed to the fact that the crop experiences significantly less stress during the drought sensitive stages as compared to the T60 and T50 treatments (Eq.2.2).

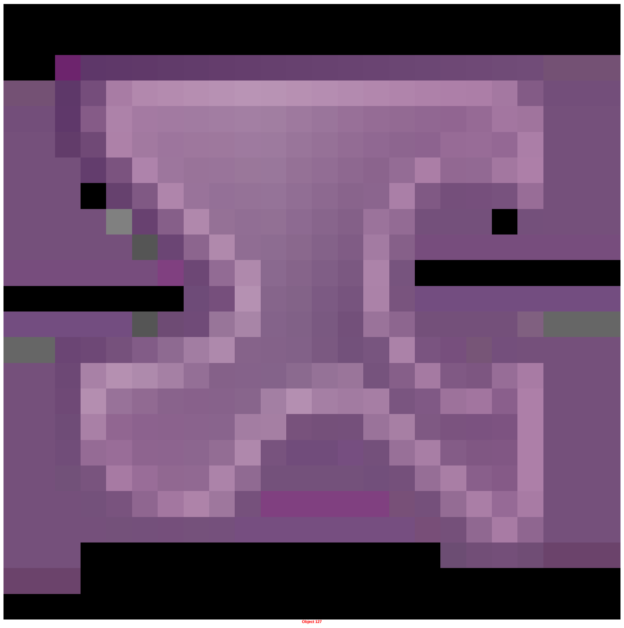


Figure 4.15: Observed (blue bars) and simulated (red bars) water productivity for beans under the different levels of irrigation treatment.

Table 4.9: Observed and simulated yield under different irrigation treatments.

Irrigation treatments	Yield (t/ha)	PR (%)	Yield (t/ha)	PR (%)
	Observed		Simulated	
T100	4.238	0	4.387	0
T80	4.138	2.360	3.952	9.323
T60	2.254	46.815	2.848	35.081
T50	1.702	59.840	2.179	50.331

PR% = percentage reduction between observed and simulated yield.

4.6.5 Summary

Satisfactory results were obtained from the calibration and validation process with adequate statistical parameters. The T80 treatment had the highest water productivity with least yield penalty. Therefore, 20% of water savings can be made with a well-designed irrigation schedule and still attain reasonable yield. To illustrate this, the calibrated model with a combination of historical weather data was used hereafter to develop irrigation schedules to be used by farmers in the field.

4.7 Simulation of irrigation requirement and generation of irrigation schedules

From the statistical analysis carried out on the historical data, representative dry, normal and wet years for the selected season (October to December) were obtained as 2007, 2002 and 2004 respectively. First, AquaCrop was run for each of these typical years to determine the irrigation requirement and schedule at each of the growing stages (Table 4.10). After which, the deficit irrigation was designed according to the water stress sensitivity of the growing stages. This was carried out in a trial and error manner while optimizing the yield obtained and the schedule with the highest yield was thus selected.

Table 4.10: Irrigation water requirement at each growth stage for the typical dry, normal and wet years.

Year	2007 (Dry)					Total
Stage	Establishment	Vegetative	Flowering	Yield formation	Ripening	
K_y		0.2	1.1	0.75	0.2	-
Inet (mm)	39.3	65.1	146	105.2	63.8	419.4
80% (mm)	39.3	32.55	146	77.3	40	335.1
60% (mm)	39.3	32.55	99.5	52	28	251.3
50% (mm)	39.3	32.55	71.06	47	20	209.9
Year	2002 (normal)					
Inet (mm)	40.6	76.5	94	82.8	35	328.9
80% (mm)	40.6	38.3	94	72.4	18	263.3
60% (mm)	40.6	38.3	58	50	10	196.9
50% (mm)	40.6	30.5	47	41.4	5	164.5
Year	2004 (wet)					
Inet (mm)	41.3	31.3	50.1	67.5	34.7	224.9
80% (mm)	41.3	15.65	50.1	55	16	178.0
60% (mm)	41.3	15.65	29.58	32.4	16	134.9
50% (mm)	41.3	13	26	24	8	112.3

K_y – crop growth stage yield response factor to water stress, Inet- net irrigation requirement.

In all the irrigation treatments, the crop was not stressed at the establishment stage because crops require a sufficient supply of water for establishment. In the 80% irrigation water (IW) treatment, the crop was stressed in three stages vegetative, yield formation, and ripening. While in the 60% IW and 50% IW the crop was stressed in all the four stages, that is including the flowering stage.

The irrigation schedules obtained are presented in Table 4.11, 4.12 and 4.13. There were 29, 23 and 15 irrigation events for the dry, normal and wet season respectively. The high evaporative demand in the dry season warrants nearly double the irrigation requirement of the wet season.

Table 4.11: Irrigation schedule for a typical dry year.

Events	**Date**	**100% (mm)**	**80% (mm)**	**60% (mm)**	**50% (mm)**
	Establishment				
1	1/10/2007	15	15	15	15
2	6/10/2007	15	15	15	15
3	10/10/2007	15			
4	13/10/2007	15	15	15	15
	Vegetative period				
5	15/10/2007	15	15	15	15
6	21/10/2007	15			
7	24/10/2007	15			
8	27/10/2007	15			
9	30/10/2007	15	15	15	15
	Flowering stage				
10	1/11/2007	15	15	15	15
11	3/11/2007	15	15		
12	7/11/2007	15	15	15	
13	10/11/2007	15	15	15	15
14	13/11/2007	15	15	15	
15	16/11/2007	15	15		
16	19/11/2007	15	15	15	15
17	23/11/2007	15	15		
18	26/11/2007	15	15	15	15
	Pod filling				
19	29/11/2007	15	15	15	15
20	3/12/2007	15	15	15	
21	6/12/2007	15	15	15	15
22	10/12/2007	15	15		
23	14/12/2007	15	15	15	15
24	17/12/2007	15			
	Ripening				
25	20/12/2007	15	15	15	15
26	23/12/2007	15	15		
27	27/12/2007	15	15	15	15
28	1/1/2008	15			
Total		420	330	255	210

Table 4.12: Irrigation schedule for a typical normal year.

Events	Date	100% (mm)	80% (mm)	60% (mm)	50% (mm)
	Establishment				
1	1/10/2002	15	15	15	15
2	6/10/2002	15	15	15	15
3	10/10/2002	15			
4	12/10/2002	15	15	15	15
	Vegetative period				
5	16/10/2002	15	15	15	15
6	18/10/2002	15			
7	21/10/2002	15	15	15	
8	23/10/2002	15			
9	26/10/2002	15	15	15	
10	29/10/2002				15
	Flowering stage				
11	1/11/2002	15	15	15	15
12	3/11/2002	15	15		
13	6/11/2002	15	15	15	15
14	11/11/2002	15	15		
15	20/11/2002	15	15	15	15
16	24/11/2002	15	15		
	Pod filling				
17	27/11/2002	15	15	15	15
18	30/11/2002	15	15		
19	3/12/2002	15	15	15	
20	7/12/2002	15	15		
21	10/12/2002	15		15	15
	Ripening				
22	14/12/2002	15	15	15	15
23	18/12/2002	15			
Total (mm)		**330**	**255**	**195**	**165**

Table 4.13: Irrigation schedule for a typical wet year.

Event	**Date**	**100% (mm)**	**80% (mm)**	**60% (mm)**	**50% (mm)**
	Establishment				
1	1/10/2004	15	15	15	15
2	6/10/2004	15	15	15	15
3	11/10/2004	15	15	15	10
	Vegetative period				
4	16/10/2004	15			
5	19/10/2004		15	15	15
6	22/10/2004	15			
	Flowering stage				
7	9/11/2004	30	30	15	15
8	12/11/2004	15	15		
9	16/11/2004	15	15	15	15
	Pod filling				
10	1/12/2004	15	15	15	15
11	4/12/2004	15	15		
12	7/12/2004	15	15		
13	11/12/2004	15		15	
	Ripening				
14	15/12/2004	15	15	15	15
15	1/1/2004	15			
Total		225	180	135	115

AquaCrop was further used to simulate the yield output under the various irrigation treatments for the representative years. The results are presented in Table 4.14 and further illustrated in Figures 4.16 and 4.17.

Table 4.14: Simulated yield and water productivity (WP) for the different irrigation treatments in the typical dry, normal and wet year.

Irrigation treatments	IW (mm)	Rainfall (mm)	Yield (t/ha)	PR%	Wp (kg/m3)	PR%
2007 (dry year)						
100%	420	88.7	4.274	0.00	0.84	0.00
80%	330	88.7	4.068	-4.82	0.97	15.64
60%	255	88.7	3.163	-25.99	0.92	9.53
50%	210	88.7	2.595	-39.28	0.87	3.40
2002 (normal year)						
100%	330	193.5	4.181	0.00	0.80	0.00
80%	255	193.5	3.87	-7.44	0.86	8.04
60%	195	193.5	3.282	-21.50	0.84	5.78
50%	165	193.5	2.651	-36.59	0.74	-7.41
2004 (wet year)						
100%	225	275.9	4.22	0.00	0.84	0.00
80%	180	275.9	4.219	-0.02	0.93	9.84
60%	135	275.9	4.17	-1.18	1.01	20.46
50%	115	275.9	4.03	-4.50	1.03	22.37

PR% = percentage reduction.

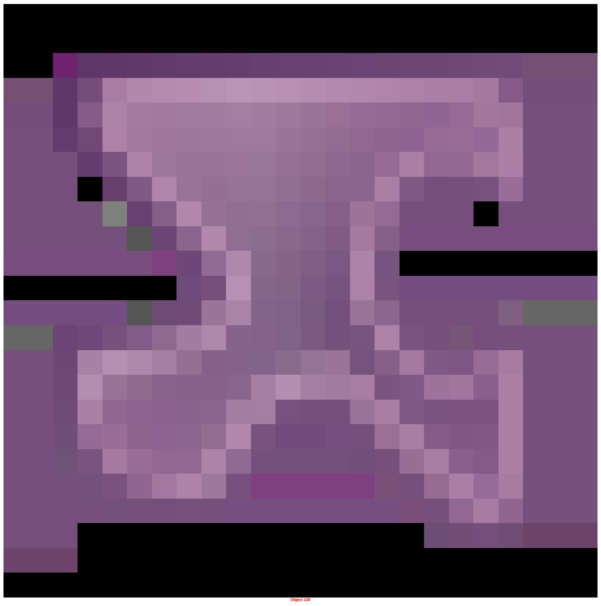


Figure 4.16: Yield in response to irrigation water treatments in the typical dry, normal and wet year.

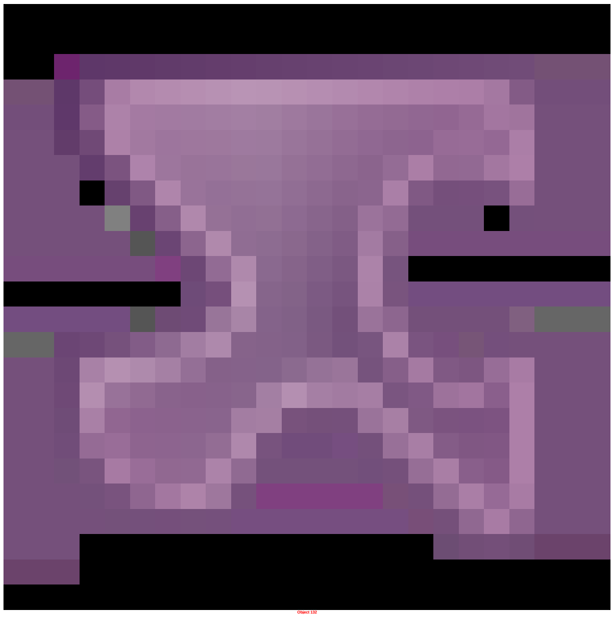


Figure 4.17: Water productivity in response to irrigation water treatments in the typical dry, normal and wet year.

Typically, the yield is expected to be higher when more water is applied. This was the case in the simulations with the 100% treatments having higher yields than the other irrigation treatments in all the years. The 80% treatments exhibited the least reduction in yield while at the same time having the highest increase in water productivity as compared to other irrigation treatments. In 2007 (dry year), the yield reduced by 4.8% while the water productivity is increased by 15.64%. A similar trend was observed in 2002 (normal year) with a yield reduction of 7.4% with an increase in water productivity of 8.04%.

The 50% treatments exhibited the highest yield penalty, with a reduction of 39% in 2007 (dry year) and 37% in 2002 (normal year). The water productivity was also lowest in 2007 (dry year) with a slight increase of 3.4% whereas in 2002 (wet year) a reduction of 7.4% was exhibited. As a result, it can be deduced that for the dry and normal years the most efficient irrigation treatment was the 80% IW because it had the least yield penalty while at the same time having the highest water productivity hence conserving water.

Conversely, a different scenario was observed in the 2004 (wet year). The yield reduction was significantly minimal throughout the different irrigation treatments as compared to the other years, with the highest reduction being 4.5% in the 50% irrigation treatment. The water productivity also increased throughout with a high of 22.3% obtained in the 50% irrigation treatment. These results can be attributed to the increased rainfall events during the wet season. These suggested that in a wet year, irrigation water requirement can be reduced by up to 50% even in the most sensitive stage (flowering stage) and still obtain yields close to the full irrigation requirement. Consequently, significant amount of water savings can be made in the wet season in anticipation of the high water demands in the dry seasons.

However, it should be noted that when the model was tested for the wet season while excluding irrigation, there was total crop failure with a yield of 0.00 t/ha simulated. Therefore, even in a wet season, irrigation is still necessary.

4.7.1 Summary

The calibration of AquaCrop for beans facilitated the simulations which were used to provide the irrigation schedules. After which, the model was used to simulate yield sensitivity to water stress at various growth stages of the beans. Therefore, a powerful tool was provided which can be used for decision-making on the allocation of water resources depending on the prevailing climatic conditions. It should be noted that this irrigation scenarios are designed for only drip irrigation system which is the predominant mode of irrigation for small-scale farmers in this particular region.

Chapter 5: Conclusions and Recommendations

5.1 Introduction

The main conclusions and recommendations of the study are presented below.

5.2 Conclusions

The primary objective of this study was to evaluate the effect of deficit irrigation on the yield and water productivity of beans using AquaCrop. Field experiments were set up in a complete randomized system from April to July 2014 at Moi University, Kenya. The beans were subjected to four water treatments of the irrigation water requirement (100%, 80%, 60% and 50%). The data collected from the experiment included weather data, soil moisture content (SWC), canopy cover (CC) and dry-above ground biomass (B). The 100% irrigation treatment was used for model calibration, and water stressed treatments (80%, 60%, 50% of 100%) were used for model validation. The following conclusions were drawn from the study.

1. By comparing observed and simulated results during calibration and validation, it was concluded that the AquaCrop model was able to satisfactorily simulate the crop development of beans under varying irrigation treatments.

2. The successfully calibrated model was used to simulate water productivity and yield response of the four water treatments (100%, 80%, 60% and 50%) for historical weather data in a typical dry, normal and wet season. From the results

obtained it was deduced that in a dry and normal season, the 80% IW deficit irrigation treatment had the highest water productivity with the least decline in yield in comparison with the 100% IW treatment. However, the 60% IW and 50% IW deficit irrigation treatments had a considerable drop in yield while at the same time having a decline in water productivity. This was attributed to the fact that in these treatments there was considerable water stress during the flowering stage especially in the 50% IW treatment. The simulation in the wet season exhibited a different scenario with the 50% IW treatment showing the highest water productivity with only a 5% drop in yield. Therefore, in a wet season 50% of water savings can be made as compared to 20% during the dry and normal season.

3. The irrigation schedules were presented which can be used to determine the most favorable irrigation strategy with the prevailing water availability. Therefore, a powerful decision-making tool was produced to advise farmers on attaining reasonable yield while at the same time ensuring conservation of water resources. Increasing water productivity is a primary goal and should be accomplished to maintain food security and water sustainability.
4. The study confirmed AquaCrop is robust, simple and applicable, as it tries to keep the balance between accuracy and input requirements. It requires only limited input parameters that can easily be determined in the field.

5.3 Recommendations

From the results obtained, and general observations made, the following recommendations were made:

1. Relying on the short rains (October-December) season for growing beans poses a substantial risk of crop failure due to the high temporal and spatial variability of rainfall. Therefore, farmers should embrace the deficit irrigation strategy to ensure reasonable yields while at the same time ensure water conservation.
2. The calibrated model can be used by farmers as a decision-making tool for information on irrigation scheduling to achieve the desired yields. Demonstrations can be held by the Uasin Gishu County government to create more awareness for the farmers.
3. The calibrated model can be used in other areas of the country, but first the model performance should be validated with data from that particular region before carrying on further simulations.
4. The effects of climate change are with us, leading to the unpredictability of climatic conditions. AquaCrop can be used to carry out further simulations on various scenarios of climate change and effect they will have on the crop yield and irrigation water demand now and in the future.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome, 300(9), D05109.

Black C.A. 1965. “Methods of Soil Analysis: Part I Physical and mineralogical properties”. American Society of Agronomy, Madison, Wisconsin, USA.

Booth, D., Cox, S., & Allen, R. . (2006). Point Sampling Digital Imagery with “Sample Point.” *Environ. Monit. Assess*, *123*, 97–108.

Bourgault, M., Madramooto, C. A., Webber, H. A., Stulina, G., Horst, M. G., & Smith, D. L. (2010). Effects of Deficit Irrigation and Salinity Stress on Common Bean (Phaseolus Vulgaris L.) and Mungbean (Vigna Radiata (L.) Wilczek) Grown in a Controlled Environment. *J. Agronomy & Crop Science*, *196*, 262–272.

Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal*, *54*, 464–465.

Brouwer, R., and C.T. de Wit. (1969). A simulation model of plant growth with special attention to root growth and its consequences. *In* W.J. Whittington (ed.) Root growth. Proc. 15th Easter School in Agric. Sci. Butterworths, London.

Calvache, M., Reichardt, K., Baacchi, O., & Dourado-Neto, D. (1997). Deficit Irrigation at Different Growth Stages of the Common Bean. *Sci. Agric., Piracicaba*, *54*, 1–16.

Carter, M. R. (Ed.). (1993). Soil sampling and methods of analysis. CRC Press.

Doorenbos, J., & Kassam, A. . (1979). Yield Response to water. In *FAO Irrigation and Drainage paper No. 33*. Rome,Italy.

Farahani, H. J., Izzi, G., & Oweis, T. Y. (2009). Parameterization and Evaluation of the AquaCrop Model for Full and Defi cit Irrigated Cotton. *Agronomy Journal*, *101*(3), 469–476.

Food and Agriculture Organization of the United Nations (FAO). (2005). *Local Climate Estimator. The New_LocClim software*. Rome, Italy.

Food and Agriculture Organization of the United Nations (FAO). (2009). *ETo Calculator*. Rome, Italy.

Food and Agriculture Organization of the United Nations (FAO). (2013). AQUASTAT database. Retrieved June 5, 2013, from http://www.fao.org/nr/aquastat

Geerts, S., & Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agriculture Water Management*, *96*, 1275–1284.

Giordano, M., Rijsberman, F., & Saleth, R. M. (2006). More crop per drop:'Revisiting a research paradigm: Results and synthesis of IWMI's research, 1996-2005.

Hsiao, T. ., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., & Fereres, E. (2009). AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize. Agron.J, *101*, 448–459.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. (2003). The DSSAT cropping system model. Eur. J. Agron. 18:235–265.

Jones, J.W., and J.R. Kiniry (ed.) (1986). CERES-Maize: A simulation model of maize growth and development. Texas A&M Univ. Press, College Station.

Katungi, E., Sperling, L., Karanja, D., Farrow, A., & Beebe, S. (2011). Relative importance of common bean attributes and variety demand in the drought areas of Kenya. *Journal of Development and Agricultural Economics*, *3*(8), 411–422.

Kenya National Bureau of Statistics (KNBS). (2010). Kenya Facts and Figures. Retrieved May 6, 2013, from http://www.knbs.or.ke/index.php?

Kipkorir, E. ., Raes, D., & Labadie, J. (2001). Optimal allocation of short-term irrigation supply. *Irrig. Drain Syst*, *15*, 247–267.

McCuen, R. ., Knight, Z., & Cutter, A. . (2006). Evaluation of the Nash--Sutcliffe Efficiency Index. *J. Hydrol. Eng*, *11*, 597–602.

Mehrpouyan, M., Davoodi, F., Farboodi, M., & Ajali, J. (2011). Effect of surface and local irrigation on seed yield of three pinto common bean cultivars (Phaseolus vulgaris L.) (Vol. 24). Paper Presented at the International Conference on Biology, Environment and Chemistry, Singapore: IACSIT Press.

Michira, M. (2014). UN scientists predict global warming to deal Kenya severe blow by 2030. *Standard Digital News*. Retrieved April 1, 2014, from http://www.standardmedia.co.ke/?articleID=2000108349&story_title=un-scientists-chilling-prediction-on-kenya-over-climate

Molden, D. (1997). Accounting for water use and productivity. In *International Irrigation Management Institute-SWIM Paper 1*. Colombo, Sri Lanka.

Monteith, J. L. (1996). The quest for balance in crop modelling. *Agron. J.*, *88*, 695–697.

Mugai, E. N. (2004). Salinity characterization of the Kenyan saline soils. Soil Science and Plant Nutrition, 50(2), 181-188.

National Cereals and Produce Board (NCPB). (2013). Beans. Retrieved June 1, 2013, from http://www.ncpb.co.ke/index.php?option=com_content&task=view&id=32&Itemid=48

National Oceanic & Atmospheric Administration (NOAA). (2015). Welcome to Mauna Loa Observatory! *Welcome to Mauna Loa Observatory!* Retrieved January 21, 2015, from http://www.esrl.noaa.gov/gmd/obop/mlo/

Odendo, M., David, S., & Kalyebara, R. (2004). The Key role of beans in poverty alleviation: Lessons from the Impact of Improved bean varieties in Western Kenya. In *Occasional publications Series, No.43*. Nairobi,Kenya.

Passioura, J.B. 1996. Simulation models: Science, snake oil, or engineering? *Agron. J.* 88:690–694.

Pereira, L. ., Oweis, T., & Zairi, A. (2002). Irrigation management under water scarcity. *Agriculture Water Management*, *57*, 175–2006.

Poulton, C., & Kanyinga, K. (2014). The politics of revitalising agriculture in Kenya. *Development Policy Review*, 32(s2), s151-s172.

Raes, D., Mallants, D., & Song, Z. (1996). RAINBOW - a software package for analysing hydrological data. (pp. 525–534). Presented at the Blain W.R. (Ed.) Hydraulic Engineering Software VI., Southmpton, Boston: Comptational mechanics Publications.

Raes, D., Steduto, P., Hsiao, T. ., & Fereres, E. (2010). *Aqua-crop Reference Manual:Chapter ;Users Guide*. Rome, Italy: Food and Agricultural Organisation of the United nations (FAO).

Raes, D., Theodore, C., & Fereres, E. (2009). AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description. *Agronomy Journal*, *101*, 438–447.

Salemi, H., Soom, M. A. M., Lee, T. S., Mousavi, S. F., Ganji, A., & Yusoff, M. K. (2011). Application of AquaCrop model in deficit irrigation management of winter wheat in arid region. *African Journal of Agricultural Research, 6(10),* 2204-2215.

Saxton, K. E., & Rawls, W. J. (2006). Soil water characteristics estimates by texture amd organic matter for hydrological solutions. *Soil Science Society of America Journal*, *70*, 1569–1578.

Solanes, M., & Gonzalez-Villarreal, F. (1999). The Dublin principles for water as reflected in a comparative assessment of institutional and legal arrangements for integrated water resources management (p. 17). Global Water Partnership Technical Advisory Committee.

Steduto, P., Hsiao, T. ., Raes, D., & Fereres, E. (2009). AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agron.J, 101*, 426–437.

Stockle, C. O. (2001). Environmental impact of irrigation: A review. Retrieved August 5, 2013, from http://www.swwrc.wsu.edu/newsletter/fall2001/IrrImpact2.pdf

Tsegay, A. (2012). *Improving crop production by field management strategies using crop water productivity modelling: case study of tef (Eragrostis tef (Zucc.) Trotter) production in Tigray, Ethiopia.* (Doctoral Thesis). KU Leuven, Leuven, Belgium.

under Uncertainty, W. M. W. Risk. The United Nations World Water Development Report Volume 1. Paris, France: World Water Assessment Program, United Nations Educational, Scientific and Cultural Organization (2012).

van Schoonhoven, A. (1991). Common beans: research for crop improvement. CIAT.

Williams, J.R., C.A. Jones, and P.T. Dyke. (1989). EPIC—Erosion/productivity impact calculator. 1. The EPIC model. USDA-ARS, Temple, TX.

APPENDICES

Appendix A: Annual rainfall and ETo for Moi university from (1990-2011)

Year	Annual ETo (mm)	Annual Rainfall (mm)
1990	1559	1237.1
1991	1660	1339.5
1992	1647	1275.6
1993	1588	1118.7
1994	1560.8	1450.6
1995	1649.6	1114.6
1996	1586.6	1280.2
1997	1657.1	1110.3
1998	1652.4	1647.7
1999	1571.9	1434.3
2000	1577	880.1
2001	1571.9	1503.2
2002	1652.4	1124.4
2003	1657.1	1021.2
2004	1586.5	1178.2
2005	1649.6	1235.8
2006	1560.8	1413.4
2007	1588.5	1363.9
2008	1647.1	1314.3
2009	1660.5	921.1
2010	1559	1483.5
2011	1598.3	1612.56
Mean	1610.96	1275.47

Appendix B: Seasonal (October- December) rainfall and ETo for Moi University from (1990-2011)

Year	Seasonal ETo (mm)	Seasonal rainfall (mm)
1990	414.75	186
1991	414.75	237.6
1992	414.75	225.1
1993	414.75	94.7
1994	414.75	202
1995	414.75	183.3
1996	414.75	102.8
1997	414.75	346.1
1998	414.75	235
1999	414.75	295.8
2000	414.75	175.3
2001	420.5	273.8
2002	429.2	193.5
2003	424.5	89.6
2004	401.1	275.9
2005	459	82.9
2006	374	417.5
2007	456.7	82.5
2008	410.4	247.8
2009	406.7	260.5
2010	399.2	179.7
2011	395.6	454
Average	415.42	220.06