EVALUATION OF THE APPLICABILITY OF AQUACROP MODEL TO SIMULATE CROP RESPONSE TO DEFICIT IRRIGATION

BANCHU BEKELE

A THESIS SUBMITTED TO DEPARTMENT OF WATER RESOURCES ENGINEERING,

SCHOOL OF CIVIL ENGINEERING AND ARCHITECTURAL

PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER'S IN WATER RESOURCES ENGINEERING (SPECIALIZATION IN IRRIGATION ENGINEERING)

OFFICE OF GRADUATE STUDIES

ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

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APPROVAL OF BOARD OF EXAMINERS

We, the undersigned, members of the Board of Examiners of the final open defense by Banchu Bekele [ID Nº: PGR/18280/11] have read and evaluated her thesis entitled **"Evaluation of the Applicability of Aquacrop Model to Simulate Crop Response to Deficit Irrigation** and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master's in Water Resources Engineering (specialization in Irrigation Engineering).

__________________	______________________	________________
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DECLARATION

I hereby declare that this MSc Thesis is my original work and has not been presented for a degree in any other university and all sources of material used for this thesis have been duly acknowledged.

Name: Banchu Bekele

Signature: ____________

This MSc Thesis has been submitted for examination with my approval as thesis advisor.

Name: ____

Signature: ____

Date of submission: __________________________________

ADVISOR’S APPROVAL SHEET

To: Water Resources Engineering Department

Subject: Thesis Submission

This is to certify that the thesis entitled **“Evaluation of the Applicability of Aquacrop Model to Simulate Crop Response to Deficit Irrigation”** submitted in partial fulfillment of the requirements for the degree of Master’s in Water Resources Engineering (specialization in Irrigation Engineering), the Graduate program of the department of Water Resources Engineering, and has been carried out by **Banchu Bekele Mesebo [ID №: PGR/18280/11]** under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby she can submit the thesis to the department.

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Name of major Advisor	Signature	Date

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Name of co-Advisor	Signature	Date

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ACRONYMS AND ABBREVIATION

AGB	Above Ground Biomass
CC	Canopy Cover
Cco	Initial Canopy Cover
DAP	Days After Planting
DI	Deficit Irrigation
Dzr	Maximum Effective Root Zone Depth
Etc	Cumulative Evapotranspiration
FC	Field Capacity
HI	Harvesting Index
Kctr	Crop Coefficient
MARC	Melkassa Agricultural Research Center
PWP	Permanent Wilting Point
Peff.	Effective rain fall
RAW	Readily Available Soil Water
SWC	Soil Water Content
TAW	Total Available Water
Tr	Crop Transpiration
WP	Water Productivity
WP*	Normalized Water Productivity
WUE	Water Use Efficiency
Y	Yield

ABSTRACT

Water is a scarce resource and requires the development of new strategies to save water and energy that improving water use efficiency. Simulation models are useful tools for improving farm-level water management and optimizing water use efficiency. The field study was carried out to evaluate the effects of different levels of irrigation water application imposed at different growth stages of haricot bean and validate the AquaCrop model with the outcome of field study under Melkassa climatic condition. The treatments considered in the field experimentation were 100% ETc,75% ETc, 50% ETc, and 25% ETc applications under the four growth (Initial, development, mid-season, and late-season) stages of haricot bean. The treatments were arranged in a randomized complete block design with three replications. The AquaCrop model was calibrated using experimental data collected from 100%ETc application during all growth stage and model performance was evaluated in simulating haricot bean yield, biomass, and water use efficiency. The result from the experiment showed that the highest yield of 2.5603 ton/ha was found from the control treatment where 100% ETc was applied during all growth stages and whereas a minimum yield of 1.123 ton/ha was obtained from 25%ETc application in all growth stages of haricot bean. The highest (1.06 kg/m^3) and lowest (0.65 kg/m^3) water use efficiency was recorded under treatment irrigated with 50% ETc and 100% ETc throughout the growth stage, respectively. Yield predictions over a wide range of values were very good, with RMSE of 0.26 ton/ha, Willmott's index degree of agreement of 0.825,, and the coefficient of determination of 0.951. The field study indicated that the haricot bean was sensitive to moisture stress during development and mid-growth stages. Therefore, applying moisture stress during development and mid-stages had significantly reduced the yield of haricot bean, and also for enhancement of water productivity without a significant yield reduction applying irrigation at the initial and late stages is recommended. The results of this study showed that the aquacrop model is capable of simulating above ground biomass, water use efficiency and grain yield of a haricot bean for treatments with some water deficit; but under sever water deficit condition the model performed less satisfactorily.

***Keywords*:** AquaCrop, deficit irrigation, haricot bean, water productivity.

1 INTRODUCTION

1.1 Background

Fresh water is an indispensable natural resource, which plays a vital role in the development of any country. Presently, many countries and regions of the world are experiencing scarcity of freshwater. Water demand for drinking and hygiene by the ever-growing population, agricultural water demand to feed the population, demand from industry and to sustain ecology, are all competing with one another and aggravating the scarcity situation. Therefore, allocation of water resources is a challenge to policymakers and proper management of the resource are important to increase agricultural productivity. Water scarcity originates not only from the physical constraints of freshwater resources but also due to its inefficient use and poor management (FAO, 2008).

Today's agriculture sector faces a complex series of challenges: to produce more food of better quality while using less water per unit of output, to produce sustainable diets and to reduce malnutrition. Population growth, land-use change, climate change, and increasing demand in non-agricultural sectors profoundly affect the availability and quality of water resources for irrigated agriculture.

Agriculture represents the major water user worldwide, and a general perception that agricultural water use is often wasteful and has less value than other uses in widespread (Jury and Vaux ,2005). Hence, increased in food production will largely have to originate from improved productivity per unit water used (Hofwegen Van and Svendsen, 2000). Good performance of irrigated agriculture system is not only a matter of high output but also of efficient use in available water resource. For example inefficient use of irrigation water in arid areas is not only wasteful but often lead to salinization of soil profile (Sijali, 2001). Therefore, innovations are needed to increase the efficiency of use of water that is available to meet future food demands and growing competition for water.

In Ethiopia, greater than 50% of the area is categorized under a semi-arid climatic zone and less than 10% as arid (NRMRD, 1998).In the semi-arid areas of Ethiopia, water is the most limiting factor for crop production. Ethiopia has vast areas of fertile and irrigable land, a diverse climate and a large labor pool for agricultural development despite this potential, Ethiopian agriculture has remained underdeveloped thus food insecurity has remained the major problem that is a great concern to the country. Therefore, it is imperative to bring large areas of the arid, semi-arid and sub-humid regions with uneven rainfall distribution under irrigation. Options in irrigation water management and developing new irrigation approaches, not necessarily based on full crop water requirement, but designed to ensure the optimal use of water are important in areas where water scarcity is severe. Various studies have shown that one of the promising irrigation strategies might be deficit irrigation wherewith less water than required is applied during the growing period of the crop,(Farre and Faci, 2009).

Deficit irrigation has been suggested as an alternative strategy for making better use of irrigation water. Deficit irrigation provides a means of reducing water consumption while minimizing adverse effects on yield. Although this inevitably results from crop water stress and yield depression, high yield can still be obtained by supplying the required amount of irrigation water during sensitive crop growth stages and by restricting the water stress to tolerant growth stages (Geerts and Raes , 2009). Examining the yield response to different water applications in the field and/or controlled experiments is laborious and expensive. In this context, Accurate crop development models are important tools in evaluating the effects of water deficits on crop yield or productivity and predicting yields to optimize irrigation under limited available water for enhanced sustainability and profitable production. The Food and Agriculture Organization (FAO) newly developed a water-driven model called AquaCrop with the aim to improve crop production for the regions relatively scarce in water resources.

The FAO AquaCrop simulation model provides a sound theoretical framework to investigate crop yield response to environmental stress. This model has successfully simulated crop growth and yield as influenced by varying soil moisture environments for crops like sunflower(Todorovic *et al*., 2009), winter wheat (Rezaverdinejad *et al*.,20014) and bambara groundnut (Karunaratne *et al*.,2011). Geerts *et al.*(2009) suggest that this model maintains a good balance between robustness and accuracy it does not require advanced skill for its calibration or operation and does not require a large number of input parameters. The relatively small number of input data describes the soil–crop–atmosphere environment in which the crop develops, most of which can be derived by simple methods.

The proposed study targeted haricot bean that plays a vital role in human nutrition, especially proteins, and ensures food security in Sub-Saharan Africa, (Namugwanya *et al.*,2014). In Ethiopia, haricot bean is one of the most economically important cash crops grown by small-scale farmers (Shaun and Elly,2008). It is grown during the dry season (February –May) and wet season (June – September) as an irrigated and rain-fed crop, respectively. However; the shortage of water is one of the major challenges of production (Habtu and Zadoks,1996).

This study was initiated with the aim of validating the AquaCrop model and evaluate the performance of the model using the outcome of field study on haricot bean deficit irrigation on crop yield and water productivity to optimize irrigation under limited available water for enhancing sustainability and profitable haricot bean production.

1.2 Statements of the Problem

In arid and semi-arid areas of Ethiopia like the central rift valley (CRV), food insecurity is a major problem due to the erratic and non-uniform distribution of rainfall. In the study area, haricot beans are mostly produced under irrigation rather than rainfed because of unpredictability and low amount of rain fall. With growing irrigation-water demand to produce more food and increasing competition across the water-using sectors, farmer in the stud area faces a challenge to produce sustainable diet with less water. Therefore, innovations that are economically and technologically feasible for more effective and rational use of limited supply of water are crucial.

Deficit irrigation practice is one possible irrigation water management strategy that may help farmers to apply limited amounts of water to their crops in time and amount vital for optimum crop water productivity. In order to allocate the scarce water resources among competing uses and to schedule irrigation water, the level of water deficit which maximizes crop water productivity has to be identified. Although the application of deficit irrigation can be studied by either field experiments or model simulations, examining the yield response to different deficit irrigation levels in field experiments is laborious, time-consuming, and expensive. No field experiments can cover all possible combinations of differential drought stress or all environmental factors that affect the yield (Geerts and Raes,2009). Accurate crop development models are important tools in evaluating the effects of water deficits on crop yield and productivity to optimize irrigation under limited available water for enhanced sustainability and profitable production. Hence, this research aims to evaluate the applicability Of aquacrop model to simulate haricot bean crop response to deficit irrigation

1.3.1 General objective

- To Evaluate the applicability Of aquacrop model to simulate haricot bean crop response to deficit irrigation.

1.3.2 Specific objective

i. To investigate the effects of deficit irrigation at different growth stages on haricot bean.

ii. To simulate the growth and yield of haricot bean under different levels of water deficits using AquaCrop.

iii. To compare the growth and yield of haricot bean simulated by AquaCrop with those attained through field experiments under different irrigation level.

1.4 Research question

a) Which level of irrigation water application has adverse effect on haricot bean growth and yield?

b) Which deficit level will best suit to realize optimum haricot bean production and water use efficiency?

c) Is AquaCrop model capable to predict the observed field performance of haricot bean under deferent levels of irrigation?

1.5 Significance

Considering the importance of haricot beans for the study area, the productivity and production should be enhanced with the available limited water resources. This study is important by showing the way to produce haricot beans in areas where irrigation water limiting. The study is also beneficial for a better understanding of how to examining the yield response to different deficit irrigation practices without field experiment using simulation models and help to identify the deficit irrigation level where water stress does not significantly reduce yield. On the other hand, it is not only helpful in the study area but also helpful in other places with similar agro-climatic and soil conditions.

1.6 Scope

The proposed study was covered performance evaluation of haricot bean under different water application levels through field investigation and simulation by using Aquacrop model. This study is only limited towards investigating the effects of water stress on the yield of haricot beans and proper management practices including weeding, pest control, and adequate fertilization application were carried out during the experiment to ensure that the only limiting factor affecting haricot bean plant growth was water. This study was carried out for only one variety and the experimental were carried out in Melkkassa agricultural research center. Therefore, The AquaCrop was calibrated and validated only for one region.

2. LITERATURE REVIEW

2.1 Water for Irrigated agriculture

Irrigated agriculture produces about 40% of all food and fiber on about 16% of all cropped land. As such, irrigated agriculture is a productive use of resources; both in terms of yield per cropped area and in yield per volume of water consumed. Many irrigation projects, however, use much more water than consumed by the crop. The non-consumed fraction of the water causes a variety of undesirable effects ranging from water-logging and salinity within the irrigated area to downstream water pollution (Bos *et al*., 2008). Water shortages are shaping the future of irrigated agriculture over the entire world (English *et al*., 2014).Agricultural production is the major user of the Earth's water resources and the water demand for this sector is increasing steadily with its root on population growth. These days about 70% of the available water we have on Earthis used for agriculture and by 2020 additional 17% more water is needed than is available now if we are to feed the world (Sleper *et al*., 2007).

2.2 Irrigated agriculture Development in Ethiopia

Traditional irrigation is very old in Ethiopia (Awulachew *et al*., 2007). The traditional small-scale schemes in general are simple river diversion. The diversion structures are rudimentary and subjected to frequent damage by flood. Ethiopian farmers have practiced agriculture since earliest times using the technology sufficient to sustain food supplies of the then low population level. To date agriculture forms the bases of the Ethiopian economy contributing up to 50 per cent of the gross domestic production, 90 per cent of total export earnings and providing a livelihood for 80 per cent of the population (Seid, 2002). Though agriculture is the major economic sector, its production is largely subsistent and predominantly rain-fed and as a result it has suffered from recurrent drought and unreliable rainfall. Irrigation is one of the means by which agricultural production can be increased to meet the growing demands in Ethiopia. A study also indicated that one of the best alternatives to consider for sustainable food security development is expanding irrigation development on various scales, through river diversion, constructing micro dams, water harvesting structures, etc. (Seleshi *et al*. 2005).Currently, the government is giving more emphasis to the sub-sector by way of enhancing the food security situation in the country. Efforts are being made to involve farmers progressively in various aspects of management of small-scale irrigation systems, starting from planning, implementation and management aspects, particularly, in water distribution and operation and maintenance to improve the performance of irrigated agriculture (Seleshi *et al*., 2007). Irrigation development including large and medium-scale irrigation development in the form of public schemes, commercial farming etc. are getting importance since 2004 under the current government. This shows that there are plans of ongoing activities for accelerated and sustained development to end poverty (Seleshi *et al*., 2007).

2.3 Crop Water Requirement and Irrigation Scheduling

2.3.1 Crop water requirement

The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as crop water requirement. Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration. The irrigation water requirement basically represents the difference between the crop water requirement and effective precipitation. The irrigation water requirement also includes additional water for leaching of salts and to compensate for non-uniformity of water application (Allen *et al*., 1998).

The crop evapotranspiration under standard conditions, denoted as ETc, is the evapotranspiration for disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. The crop evapotranspiration under non-standard conditions (ETc adj) is the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions. When cultivating crops in fields, the real crop evapotranspiration may deviate from ETc due to non-optimal conditions such as the presence of pests and diseases, soil salinity, low soil fertility, water shortage or water logging. This may result in scanty plant growth, low plant density and may reduce the evapotranspiration rate below ETc. The crop evapotranspiration under non-standard conditions is calculated by using a water stress coefficient Ks and/or by adjusting Kc for all kinds of other stresses and environmental constraints on crop evapotranspiration (Allen *et al*., 1998).

The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ETo. The reference surface is a hypothetical grass reference crop with specific characteristics. The use of other denominations such as potential ET is strongly discouraged due to ambiguities in their definitions. The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices.

Relating ET to a specific surface provides a reference to which ET from other surfaces can be related. It obviates the need to define a separate ET level for each crop and stage of growth. ETo values measured or calculated at different locations or in different seasons are comparable as they refer to the ET from the same reference surface. The only factors affecting ET_o are climatic parameters. Consequently, ET_o is a climatic parameter and can be computed from weather data. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors (Allen *et al.*, 1998).

ET_o is computed using the FAO Penman-Monteith method. This method is recommended as the sole standard method. It is a method with strong likelihood of correctly predicting ET_o in a wide range of locations and climates and has provision for application in data-short situations. The use of older FAO or other reference ET methods is no longer encouraged (Allen *et al.*, 1998).

2.3.2 Irrigation scheduling

Irrigation scheduling refers to when and how much water to apply to satisfy the crop water demand. Irrigation schedule can be established after the three parameters (daily water requirements, available soil moisture and effective root zone depth) are known. While estimated values of ETc, based on climatic data, are sufficient for planning and designing purposes, for more accurate scheduling more accurate field data are necessary. These can be obtained by the use of Class A pans and/or soil moisture monitoring devices like tensiometers. This, however, requires proper recording and some management skills, since timing of the different irrigations will depend on the day to day variability of climatic factors. If no class A pan or tensiometers are available, the crop water and irrigation requirement calculations can be used as a guideline for irrigation scheduling (Savva and Frenken, 2002).

Irrigation scheduling involves preventing the soil water deficit from falling below some threshold level for a particular crop and soil condition. Scheduling water application is very critical to make the most efficient use of irrigation system, as excessive irrigation reduces yield, while inadequate irrigation causes water stress and reduces production. Establishing irrigation scheduling requires knowledge about availability of water supply, crop water use or evapotranspiration (ET), irrigation and effective rainfall, soil water-holding capacity and current available soil moisture

content. This information is the main factor to decide when to apply water and how much water to apply. This often results in lower energy and water use and optimum crop yield, and increases irrigation efficiency. The amount of water applied is determined by using a criterion to determine irrigation need and a strategy to prescribe how much water to apply in any situation. The most common irrigation criteria are soil moisture content and soil moisture tension. The critical soil water content can be found at different level.

2.3.3 Crop growth stages

The ground cover, crop height and leaf area change with the development of the crop. Due to differences in rooting depth and evapotranspiration during the various growth stages, the crop coefficient for a given crop will vary over the growing period. The growing period can be divided into four distinct growth stages that are; initial, crop development, mid – season and late season (Allen et al., 1998).

Initial stage: The initial stage runs from planting date to approximately 10% ground cover. The length of the initial period is highly dependent on the crop, the crop variety, the planting date and climate. During the initial period, leaf area is small, and evapotranspiration is predominantly in the form of soil evaporation. Therefore, the Kc during the initial period is large when the soil is wet from irrigation and rainfall and is low when the soil surface is dry.

Crop development stage: The crop development stage runs from 10% ground cover to effective full cover. Effective full cover for many crops occurs at the initiation of flowering. For row crops where rows commonly inter lock leaves such as beans, sugar beets, potatoes and corn, effective full cover can be defined as the time when some leaves of plants in adjacent rows begin to intermingle so that soil shading becomes nearly complete, or when plants reach nearly full size if no intermingling occurs. For some crops, especially those taller than 0.5m, the average fraction of the ground surface covered by vegetation at the start of effective full cover is about 0.7 – 0.8.

Mid-season stage: The mid–season stage runs from effective full cover to the start of maturity. The start of maturity is often indicated by the beginning of ageing, yellowing or senescence of leaves, leaf drop, or the browning of fruit to the degree that the crop evapotranspiration is reduced relative to the reference ETo. The Mid – season stage is the longest stage for perennials and for many annuals, but it may be relatively short for vegetable crops that are harvested fresh for their green vegetation. At the mid – season stage the Kc reaches its maximum value. The value for Kc at the mid-season stage (Kc mid) is relatively constant for most growing and cultural conditions.

Late season stage: The late season stage runs from the start of maturity to harvest or full senescence. The crop coefficient at the end of the late season stage reflects crop and water management practices (Allen et al., 1998).

2.3.4 Soil water balance

The root zone can be presented by means of a container in which the water content may fluctuate. To express the water content as root zone depletion is useful. It makes the adding and subtracting of losses and gains straightforward as the various parameters of the soil water budget are usually expressed in terms of water depth. Rainfall, irrigation and capillary rise of groundwater towards the root zone add water to the root zone and decrease the root zone depletion. Soil evaporation, crop transpiration and percolation losses remove water from the root zone and increase the depletion (Allen et al., 1998).

$$Wi = (Wi - 1 - (P - RO)i - Ii - CRi + ETc,i + DPi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.1$$

where: W_i root zone depletion at the end of day i [mm],

W_{i-1} water content in the root zone at the end of the previous day, i-1[mm],

P_i precipitation on day i [mm],

RO_i runoff from the soil surface on day i [mm],

I_i net irrigation depth on day i that infiltrates the soil [mm],

CR_i capillary rise from the groundwater table on day i [mm],

$ET_{c,\ i}$ crop evapotranspiration on day i [mm],

DP_i water loss out of the root zone by deep percolation on day i [mm]

2.3.5 Total available water

Soil water availability refers to the capacity of a soil to retain water available to plants. After heavy rainfall or irrigation, the soil will drain until field capacity is reached. Field capacity is the amount of water that a well-drained soil should hold against gravitational forces, or the amount of water remaining when downward drainage has markedly decreased. In the absence of water supply, the water content in the root zone decreases as a result of water uptake by the crop. As water uptake progresses, the remaining water is held to the soil particles with greater force, lowering its potential energy and making it more difficult for the plant to extract it. Eventually, a point is reached where the crop can no longer extract the remaining water. The water uptake becomes zero when wilting point is reached. Wilting point is the water content at which plants will permanently wilt (Allen et al., 1998).As the water content above field capacity cannot be held against the forces of gravity and will drain and as the water content below wilting point cannot be extracted by plant roots, the total available water in the root zone is the difference between the water content at field capacity and wilting point.

2.3.6 Readily available water

Although water is theoretically available until wilting point, crop water uptake is reduced well before wilting point is reached. Where the soil is sufficiently wet, the soil supplies water fast enough to meet the atmospheric demand of the crop, and water uptake equals ETc. As the soil water content decreases, water becomes more strongly bound to the soil matrix and is more difficult to extract. When the soil water content drops below a threshold value, soil water can no longer be transported quickly enough towards the roots to respond to the transpiration demand and the crop begins to experience stress. The fraction of TAW that a crop can extract from the root zone without suffering water stress is the readily available water (RAW) given by (Allen *et al.,* 1998):The factor p differs from one crop to another. It normally varies from 0.30 for shallow rooted plants at high rates of ETc (greater than 8 mm/day) to 0.70 for deep rooted plants at low rates of ETc (less than 3 mm/day) (Savva and Frenken, 2002). Management Allowable Depletion (MAD) is the degree to which volume of water in the soil is allowed to be depleted before the next irrigation is applied. MAD is considered as the ratio of readily available water (RAW) and total available water (TAW). The desired Management Allowable Deficit (MAD) value of Haricot bean is 40 to 50% (Doorenbos and Pruitt, 1983).

2.3.7 Effective root zone depth

In addition to crop water requirements and soil factors, the root zone depth is the third parameter to be considered when preparing irrigation schedules. Like allowable soil moisture depletion, the root zone depth is another area of interesting controversies. Published data on the depth from where the crops extract most of their water differ greatly. As a rule, for most field crops 40% of the water uptake takes place from the first quarter of the total rooting depth, 30% from the second quarter, 20% from the third quarter and 10% from the fourth quarter (Savva and Frenken, 2002). According to FAO (1984), ETc is not affected even when rooting depth is severely restricted, as long as plants are sufficiently anchored and proper growing conditions, including available water, nutrients, soil aeration, soil temperature and soil structure prevails.

2.3.8 Irrigation efficiency

Irrigation efficiency is a basic engineering term used in irrigation science to characterize irrigation performance, evaluate irrigation water use, and to promote better or improved use of water resources, particularly those used in agriculture and landscape management. Irrigation efficiency is defined in terms of the irrigation system performance, the uniformity of the water application, and the response of the crop to irrigation. Each of these irrigation efficiency measures is interrelated and will vary with scale and time (Terry, 2003).Among the factors used to judge the performance of an irrigation system or its management, the most common are efficiency and uniformity. These parameters have been subdivided and defined in a multitude of ways as well as named in various manners. There is not a single parameter which is sufficient for defining irrigation performance. Conceptually, the adequacy of irrigation depends on how much water is stored within the crop root zone, losses percolating below the root zone, losses occurring as surface runoff or tail water, the uniformity of the applied water, and the remaining deficit or under-irrigation within the soil profile following irrigation.

2.3.9 Water productivity

Water productivity is defined as the ratio of the benefits from crop, forestry, fishery, livestock, and mixed agricultural systems to the amount of water required to produce those benefits. In its broader sense, it reflects the objectives of producing more food, income, livelihoods, and ecological benefits at the less social and environmental cost per unit of water used. Increasing water productivity is particularly appropriate where water is scarce compared with other resources involved in crop production. Increasing the productivity of water in agriculture plays a vital role in easing competition for scarce water resources, prevention of environmental degradation, and provision of food security, (Molden *et al*., 2003).

The present general practice in irrigated agriculture is to maximize crop yield per unit land by applying full crop irrigation requirements and often over-irrigating. For some crops, such as cereals, maximizing yield is at the account of water productivity (WP). For many crops, maximum WP drops at high yield levels, i.e. maximizing water production implies lower yields. In areas where water is the most limiting resource for production, maximizing WP may be more profitable to the farmer than maximizing crop yield. This is because the water saved when deficit irrigation is applied becomes available to irrigate more land since the latter is not the limiting factor (Oweis and Zhang, 1998).

Kirda and Kanber (1999) indicated that establishing deficit irrigation to cope with water scarcity not only requires knowledge on crop demand for water and yield response to water but also appropriate economic evaluation of alternative solutions. From an applied water management viewpoint, maximum yield per unit area is attained when irrigation systems are operated to supply sufficient water for plants to meet the day-to-day evaporative demand and with a frequency that maintains the high soil water potential in the upper root zone. Thus deficit irrigation is scheduled either to maximize yield per unit area or per unit water applied.

Improving the WP does not necessarily lead to a water-saving because it is necessary to distinguish between consumptive and non-consumptive water use. However, that distinction is often not made. It is important to consider the economic issues relative to WP since the objective of a farmer is to achieve the best income and profit. Depending on how the terms in the numerator and denominator are expressed, WP can be expressed in general physical or economic terms. The physical water productivity can be defined as the ratio of the kilogram of actual yield to the meter cube of water consumed (Seckler *et al*., 1998).

2.4 Water Use Efficiency and Yield Response

The relationships encountered between crop, climate, soil and water are complex and many biological, physiological, chemical and physical processes are involved. When the full crop water requirements are not met water deficit in the plant can develop to a point where crop growth and yield are affected. The manner in which water deficit affects crop growth and yield varies with the crop species and crop growth period (Doorenbos *et al.*, 1979).

Before implementing a deficit irrigation program, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season (Kirda and Kanber, 1999). High-yielding varieties are more sensitive to water stress than low-yielding varieties; for example, deficit irrigation had a more adverse effect on the yields of new maize varieties than on those of traditional varieties (Doorenbos *et al.*, 1979).

In order to ensure successful deficit irrigation, it is necessary to consider the water retention capacity of the soil and agronomic practices may also require modification that is decrease plant population, apply less fertilizer, adopt flexible planting dates, and select shorter-season varieties. Irrigation water use efficiency (IWUE) refers to the ratio of grain yield to total irrigation water supplied. Water use efficiency (WUE) has been the most widely used parameter to describe irrigation effectiveness in terms of crop yield.

To evaluate the effect of plant water stress on yield decrease through the quantification of relative evapotranspiration (ET_a/ET_m), an analysis of research results shows that it is possible to determine relative yield losses if information is available on actual yield (Y_a) in relation to maximum yield (Y_m) under different water supply regimes. Where economic conditions do not restrict production and in a constraint free environment $Y_a=Y_m$ when full water requirements are met. When full water requirements are not met by available water supply $Y_a<Y_m$ (Doorenbos *et al*., 1979).

$$1-\left(\frac{Ya}{Ym}\right)=ky\left(1-\frac{ETa}{ETm}\right)\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots..2.2$$

where, Y_a is actual yield (kg/ha),

Y_m is maximum yield (kg/ha),

ET_a is actual evapotranspiration (mm),

ET_m is maximum evapotranspiration (mm), and

K_y is yield response factor.

2.5 Deficit Irrigation

Deficit irrigation is an irrigation water management strategy whereby water is applied only during the drought-sensitive growth stages of a crop (Geerts and Raes,2009). Deficit irrigation may result in a 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. This leads to higher yield, reduced production costs and, ultimately, maximum investment returns. Furthermore, the use of efficient water management and application techniques is essential for sustainable agricultural development, based on the best use of the natural resources (Kirda and Kanber, 1999).

Agronomic measures such as varying tillage practices and mulching can reduce the demand for irrigation water. Another option is deficit irrigation, with plants exposed to certain levels of water stress during either a particular growth period or throughout the whole growth season, without significant reduction in yields. Yield reductions from disease and pests, losses during harvest and storage, and arising from insufficient applications of fertilizer are much greater than reductions in yields expected from deficit irrigation. On the other hand, deficit irrigation, where properly practiced, may increase crop quality. For example, the protein content and baking quality of wheat, the length and strength of cotton fibers, and the sucrose concentration of sugar beet and grape all increase under deficit irrigation (Kirda and Kanber, 1999).

In Deficit irrigation, the irrigation water requirement is not completely fulfilled, allowing the soil water to be depleted to a threshold, such that the crop experiences mild water stress. The crop response, which may or may not include a reduction in the rate of water use and/or yield reductions, depends on the degree of soil drying, the crop characteristics and the timing of the water deficit. It is generally thought that withholding water during the vegetative period, as opposed to the flowering or yield forming stages, has less impact on final yields, (Loveys *et al*., 2004).

Oweis and Zhang (1998) stated that when strategies for deficit irrigation are derived from multi-factorial field trials, the optimal irrigation schedules are often based on the concept of water productivity (WP) or, as often named, water use efficiency (WUE). The present general practice in irrigated agriculture is to maximize crop yield per unit land by applying full crop irrigation requirements and often over irrigating. For some crops, such as cereals, maximizing yield is at the account of water productivity (WP). For many crops, maximum WP drops at high yield levels, i.e. maximizing water production implies lower yields. In areas where water is the most limiting resource to production, maximizing WP may be more profitable to the farmer than maximizing crop yield. This is because the water saved when deficit irrigation is applied becomes available to irrigate more land since the latter is not the limiting factor (Oweis and Zhang, 1998).

As reported by Kirda (2002)deficit irrigation practices differ from traditional water supplying practices. The manager needs to know the level of transpiration deficiency allowable without a significant reduction in crop yields. The main objective of deficit irrigation is to increase the WUE of a crop by eliminating irrigation that has little impact on yield. The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices. Before implementing a deficit irrigation program, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season (Kirda and Kanber,1999).

2.6 Agronomic Aspects of Haricot Bean

Haricot bean is an annual crop belonging to the family Fabaceae, which is grown predominantly by smallholder producers as a source of food and cash in Ethiopia, (Abebe, 2009). The crop also adapted to most soils and is sensitive to salinity. Adaptability of varieties in different climates varies widely. Successful cultivation markedly depends on the right choice of varieties so that the length of growing period of the crop matches the length of the growing season and the purpose for which the crop is to be grown(Abebe,2009). Maximum effective root depth for haricot bean is 30cm at establishment and 90cm after the mid-season (Samson *et al*., 2006).The lateral root system is extensive and mainly concentrated in the first 0.3m. Under conditions when ETm is 5 to 6 mm/day, 40 to 50% of the total available water can be depleted before the normal water uptake is affected (Doorenbos and Kassam, 1979).

Major constraints in production of Haricot bean are weeds, insect pests and diseases. Proper weed control is crucial to ensure optimum crop performance. Crop loss assessment trials show that uncontrolled weeds growth could result in over 36% yield reduction in haricot bean and more than 50% in soybean **(**Beyenesh, 1988).

2.7 Crop Growth Simulation Model

Crop simulation models can be used to understand crop response to water stress and various management practices, (Farahani and Oweis , 2009). The model usually offers the possibility specifying management options and they can be used to investigate a wide range of management strategies at low cost. Many sophisticated crop-growth models, based on physiological processes, have been developed and applied in water management projects with varying degrees of success. Some widely acceptable cereal models are hybrid models, such as CERES and Decision Support System for Agrotechnology Transfer (DSSAT) that simulate the growth of crops under water-limited conditions. CROPWAT model, as an appropriate tool for irrigation planning, is another example; but due to improper simulations of evapotranspiration, the crop yield reductions estimated by this model should be taken with caution, (Cavero *et al*., 2000).

Nearly, all these models are complicated, demanding advanced skills for their calibration and operation and need a large number of parameters (Heng *et al*., 2009).To address these concerns and in trying to achieve an optimum balance between accuracy, simplicity and robustness, a new crop simulation model named AquaCrop has been developed by FAO, (Steduto *et al*., 2009; Raes *et al*., 2009).

2.8 Aquacrop Model Description

AquaCrop is a crop-water model that is developed by FAO. It aims to predict yield, water requirements and water productivity under different environmental conditions, including water deficits. One target of this model is to strike a balance between simplicity, robustness, and accuracy,(Steduto, *et al*., 2009). comparison to other crop models, AquaCrop is based on a water-driven growth engine that is most effective in areas where water is a limiting factor to plant growth (Voloudakis *et al.*, 2015). Additionally, the model requires a few input parameters that can easily be obtained from field observations (Todovoric *et al*., 2009).

Based on soil, water balance and crop growth processes, AquaCrop simulate crop yields on a daily time step. Figure 2.1. 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 (Raes *et al*.,2009).

The water productivity concept is fundamental and represents the relationship between biomass production and accumulated transpiration, rather than yield determination via crop evapotranspiration (Steduto *et al*.,2009). By separating soil water evaporation and transpiration, the effect of non-productive water losses is avoided (Nyakudya, 2014). The water productivity parameter is a conservative, crop-specific parameter that is normalized using atmospheric evaporative demand and ambient carbon dioxide concentration, which makes the model applicable to a wider range of locations and seasons. Additionally, the model relies on other conservative parameters that are widely applicable and thus, do not require local calibration (Vanuytrecht *et al*., 2014).

In the model first, soil water content is calculated by keeping track of a soil water balance through the input data.

2.8.1 The calculation scheme of AquaCropAquaCrop

according to AquaCrop manual (Raes *et al*.,2009) the aquacrop model simulates final crop yield in four steps that are easy to understand, and which makes the modeling approach transparent. The four steps(which run in series at each daily time step) consist in the simulation of:

- ❖ Development of green canopy cover (CC):In AquaCrop foliage development is expressed through green canopy cover (CC) and not via Leaf Area Index (LAI). The green canopy cover (CC) is the fraction of the soil surface covered by the canopy. It ranges from zero at sowing (0 % of the soil surface covered by the canopy) to a maximum value at mid-season which can be 1 when a full canopy cover is reached (100 % of the soil surface covered by the canopy). By adjusting daily the soil water content in the soil profile, AquaCrop keeps track of the stresses which might develop in the root zone. Soil water stress might affect the leaf and hence canopy expansion and if severe might trigger early canopy senescence;
- ❖ Crop transpiration (Tr):For well watered conditions, Tr is calculated by multiplying the reference evapotranspiration (ETo) with a crop coefficient (KcTr). The crop coefficient is proportional to CC and hence varies throughout the life cycle of the crop in correspondence with the simulated canopy cover. Water stress does not only affect canopy development but might also induce stomata closure and hence affect,also directly, crop transpiration
  - ❖ Above-ground biomass (B):The above ground biomass produced is proportional to the cumulative amount of crop transpiration (ΣTr). The proportional factor is the biomass water productivity (WP) (Eq.2.1). In AquaCrop WP is normalized for the effect of the climatic conditions which makes the normalized biomass water productivity(WP*)valid for diverse locations,seasons,and CO2concentrations.
  - ❖ Crop yield (Y):The simulated above ground biomass (B) integrates all photosynthetic products assimilated by the crop during the season. By using a Harvest Index (HI), which is the fraction of B that is the harvestable product, crop yield (Y) is obtained from B (Eq.2.2). The actual HI is obtained by adjusting, during simulation, the reference Harvest Index (HIo)with an adjustment factor for stress effects

$$B = WP * \sum \frac{Tr}{ET_0} ------------------(2.3)$$

$$Y = B * HI ---------------------(2.4)$$

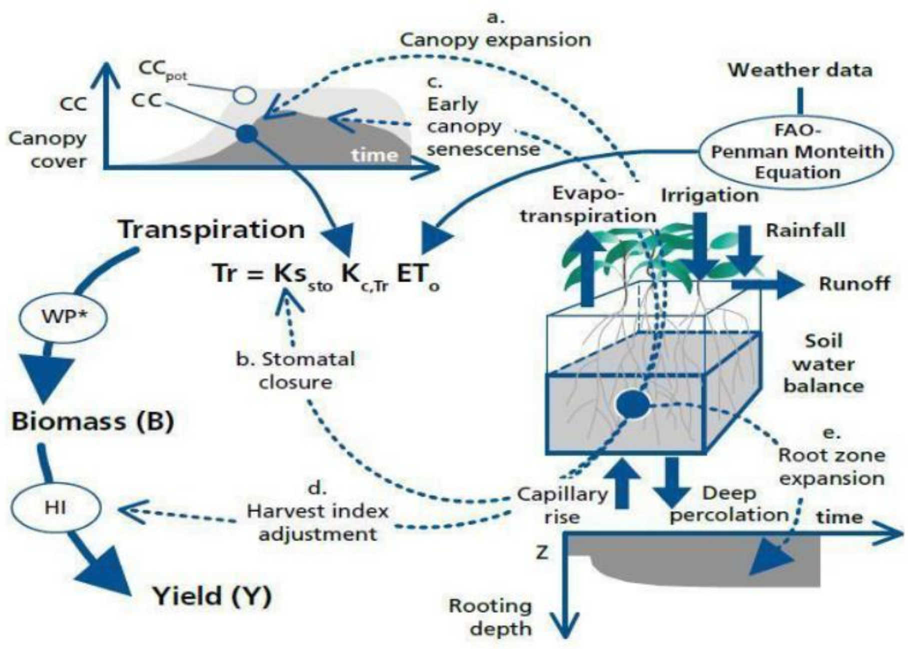


Figure 2. 1. flow chart of the calculation scheme of aquacrop (source : Raes *et al*.,2009)

2.8.2 Studies on AquaCrop Model

The applicability of AquaCrop under water stress conditions has been extensively studied in the world in general and in Ethiopia in particular. Andarzian *et al*. (2011)Validated and tested the AquaCrop model under full and deficit irrigated wheat production in Iran with the objectives of evaluating the AquaCrop model for its ability to simulate wheat (Triticum aestivum L.) performance under full and deficit water conditions in a hot dry environment in south of Iran, to study the effect of different scenarios of irrigation (crop growth stages and depth of water applied) on wheat yield**.** According to the study, the AquaCrop model was able to accurately simulate soil water content of root zone, crop biomass and grain yield, with normalized root mean square error (RMSE) less than 10%.

Yibrha (2015) studded the Performance of AquaCrop model in simulating the tuber yield of potato (Solanum tuberosumL.) under various water availability conditions in Mekelle, Ethiopia. The objective of the study was to validate and apply AquaCrop model for devising better water management strategies for optimal potato production in the region based on experimental data conducted in Mekelle University (MU) and Mekelle Agricultural Research Center (MARC). There were three treatments of water: Full Supplementary (FSI), Deficit Irrigation (DI) and Rainfed (RF). The Results of the study showed that AquaCrop model was able to accurately simulate the final dry tuber yield, water use efficiency, and total biomass at the MU site. Similarly, the model was able to simulate the final tuber yield at MARC. Whereas, biomass yield was not accurately simulated by the model for MARC site.

Gebreselassie *et al*. (2015). Applied Aquacrop model To Field experimentation based simulation of yield response of maize crop to deficit irrigation. The Experiment was conducted from February to June 2012 in the Demonstration farm of Arba Minch University located in the central rift valley of Ethiopia. This study aimed to investigate the effects of different levels of deficit irrigation imposed at different growth stages of maize (BH-140) crop on its development, grain yield and water use efficiency. The water application levels considered were 100% of crop evapotranspiration (ETc), 75%ETc, 50%ETc and 25%ETc. based on these irrigation levels and four growth stages of maize crop, ten treatments were arranged. According to the results of this study the model performed well in stimulating the growth of aboveground biomass, grain yield, and canopy cover (CC) for most of the treatments but it was less satisfactory in simulating the growth performance of treatments under prolonged water-deficit. Considering the overall performance of AquaCopin these above studies, the model is a useful tool to accurately predict yield, soil moisture and hence manage water productivity.

Geneille E and Yu-Min (2016)Taste and validate Aquacrop model for Simulating Maize Growth and Productivity under Deficit Irrigation in a Tropical Environment. field observations from three experiments consisting of four treatments were used to evaluate model performance in simulating canopy cover (CC), biomass (B), yield (Y), crop evapotranspiration (ETc), and water use efficiency (WUE).according to this study Statistics for root mean square error, model efficiency (E), and index of the agreement for B and CC suggest that the model prediction is good under non-stressed and moderate stress environments. Prediction of final B and Y under these conditions was acceptable, as indicated by the high coefficient of determination and deviations <10%. In severely stressed conditions, low E and deviations >11% for Band 9% for Y indicates a reduction in the model reliability. Simulated ETc and WUE deviation from observed values were within the range of 9.5% to 22.2% and 6.0% to 32.2%, respectively, suggesting that AquaCrop prediction of these variables is fair, becoming unsatisfactory as plant water stress intensifies. AquaCrop can be reliably used for evaluating the effectiveness of proposed irrigation management strategies for maize; however, the limitations should be kept in mind when interpreting the results in severely stressed conditions.

Magalhaes *et al*.(2019). Evaluate the Performance of the Aquacrop model for bean (Phaseolus vulgarisL.) under irrigation condition. This work aimed to evaluate the FAO AquaCrop model for bean crops under different levels of irrigation water in the agrometeorological conditions of northeastern Brazil. The experimental design was a randomized block with four replicates. Treatments were composed of six levels of irrigation based on crop evapotranspiration (ETc) fractions (25, 50, 75, 100, 125 and 150% of ETc). The AquaCrop model was calibrated for a common bean during the dry season (October to March) for the region in the 2015/2016 harvest season using experimental data for 100% of ETc. The accuracy of the calibration and validation model was evaluated based on the root mean square error (RMSE), Willmott's index of agreement (d), correlation coefficient (r), and percentage deviation (D). The model showed good performance between observed and simulated values for soil water content; dry biomass accumulation and grain yield in several water conditions and can assist decision making and water management in irrigated crops.

3. MATERIALS AND METHODS

3.1 Description of the Study Area

A field experiment was conducted in the experimental farm of Melkassa Agricultural Research Center (MARC) during the dry period of (February – May) 2020. The center is found near Awash Melkassa town ($8^0$24'N latitude and $39^0$21' E longitude at 1550 m.a.s.l.) 17 km southeast of Adam town and 107 km away from Addis Ababa (Figure 3.1). The climate is characterized as semi-arid with low and erratic rainfall of bimodal pattern of rainfall. Topographically the area is wide flat cultivated land surrounded by scattered trees mainly acacia.

From the long-term (1977–2017) climatic record of the Melkassa agro-meteorological observatory station indicted the average annual rainfall in the area was 824.9 mm and the mean maximum and minimum monthly rainfall were 204.2 mm and 9.6 mm occurs in August and November, respectively. The mean maximum temperature varies from 26.4^{0}C to 30.9^{0}C while the mean minimum temperature varies from 11.1 ^{0}C to 16.5 ^{0}C and the average temperature of the area is 20.12 ^{0}C. The textural classification mainly varies from clay to clay loam. The source of irrigation water in the study area is the Awash River that serves 27% of the total irrigated agriculture of the country (Zemede, 2011). The dominant soil group of the study area is Andosol, which is made up of volcanic rocks.

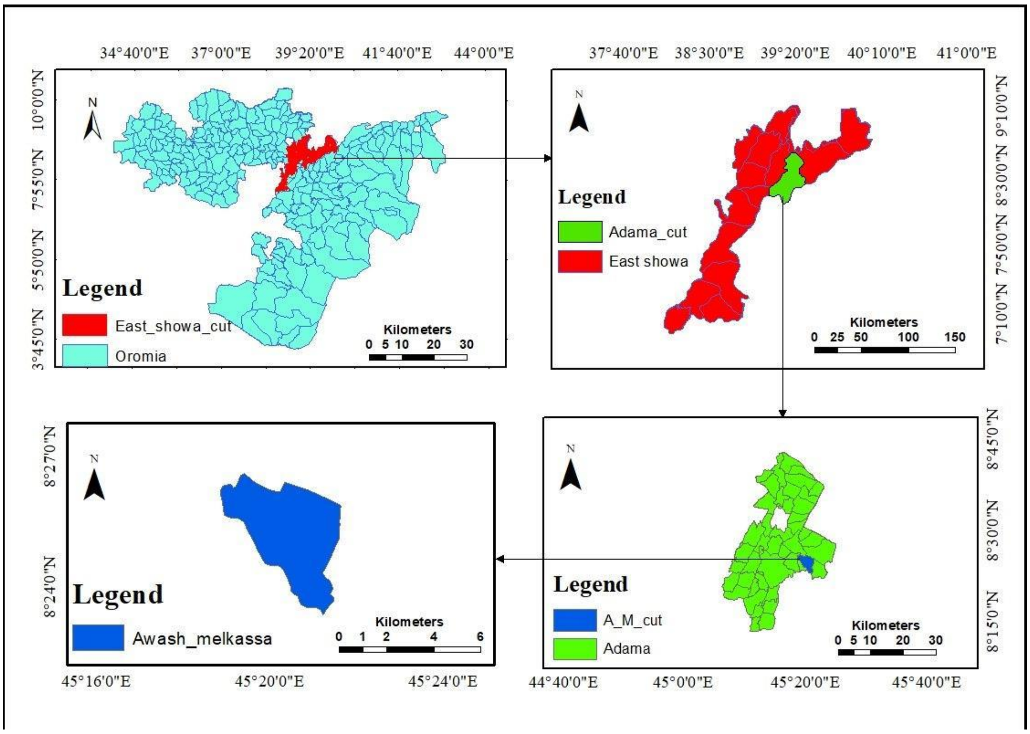


Figure 3.1. Location map of the study area

3.2 Soil Analysis

3.2.1 Soil Physical Characteristics

Representative composite soil samples were collected from the experimental site before the commencement of the study. Soil samples were taken diagonally across the experimental site. Disturbed soil samples were taken from 0- 15, 15-30, and, 30-60 cm soil depth for analysis of soil physics characteristics (textural class, FC, PWP) and chemical characteristics (TN, pH, OM, ECe and K).

Soil texture

The hydrometric method was used to identify the particle size distribution of sand, silt and clay content from the collected disturbed soil sample. The textural class of the soil was determined using the USDA textural triangle (USDA, 1975).

Bulk density

The soil bulk density which represents the mass of dry soil (mass of solids) per unit volume of soil (White, 2003) was obtained from undisturbed soil samples using a core sampler at 15 cm intervals up to 60cm, assuming no change in BD below 60 cm. The samples were then dried in an oven at 105^{0}C for 24 hours and the bulk density was then calculated using the following equation.

$$\rho b = \frac{Wd}{Vs} ----------------(3.1)$$

where ρb is soil bulk-density (gm/cm^3), Ws is a mass of dry soil (g) and Vs is the volume of core sampler (cm^3).

Field capacity and permanent wilting point

Field capacity, FC and permanent wilting point, PWP were determined using pressure plate and pressure membrane apparatus, respectively. Soil samples were saturated for one day and a pressure of 1/3 bar and 15 bar was exerted, respectively for FC and PWP, until no water droplets detected out of the apparatus.

Soil infiltration rate

The infiltration rate of the soil was determined from the experimental field using double ring infiltrometer. The field test was set up at three locations in equidistance from each other; forming an isoscales triangle. The level of water in the inner and outer ring was maintained at a similar height. The drop-in water level in the inner ring was recorded with the help of measuring the ruler attached to the inner ring.

whenever the level of water drops to a level that may not guaranty for the next reading, water was refilled immediately after the last reading and the new water level height was recorded. Readings were taken frequently at the beginning of the test, but with an extended interval between readings as the time goes on until the drop in water level over equal time interval remains the same.

3.2.2 Soil chemical characteristics

Soil chemical characteristics of the experimental site such as soil pH, OM, EC and total nitrogen were subjected to laboratory analysis and determined following the standard procedures for determination of each chemical characteristic of the soil to know it is suitability for haricot beans growth.

3.3 Treatments and Experimental Design

Four irrigation levels, viz., 100%, 75%, 50%, and 25% of the crop water requirement was imposed on four growth stages, viz., initial, development, mid-season and late-season stages. A treatment received deficit irrigation only during in one of the crop growth stages except for the control treatment. The remaining treatment received irrigation to satisfy the crop water requirement that brings the soil moisture deficit back to FC. Including the control treatment, there were 16 treatments arranged in RCBD with three replications. The treatment combination is given in Tables 3.1.

Table 3. 1 Experimental treatment

Treatment	Growth stages			
	Initial stage	Development stage	Mid- stage	Late-stage
	Water application (%)			
T1	100	100	100	100
T2	75	75	75	75
T3	50	50	50	50
T4	25	25	25	25
T5	75	100	100	100
T6	100	75	100	100
T7	100	100	75	100
T8	100	100	100	75
T9	50	100	100	100
T10	100	50	100	100
T11	100	100	50	100
T12	100	100	100	50
T13	25	100	100	100
T14	100	25	100	100
T15	100	100	25	100
T16	100	100	100	25

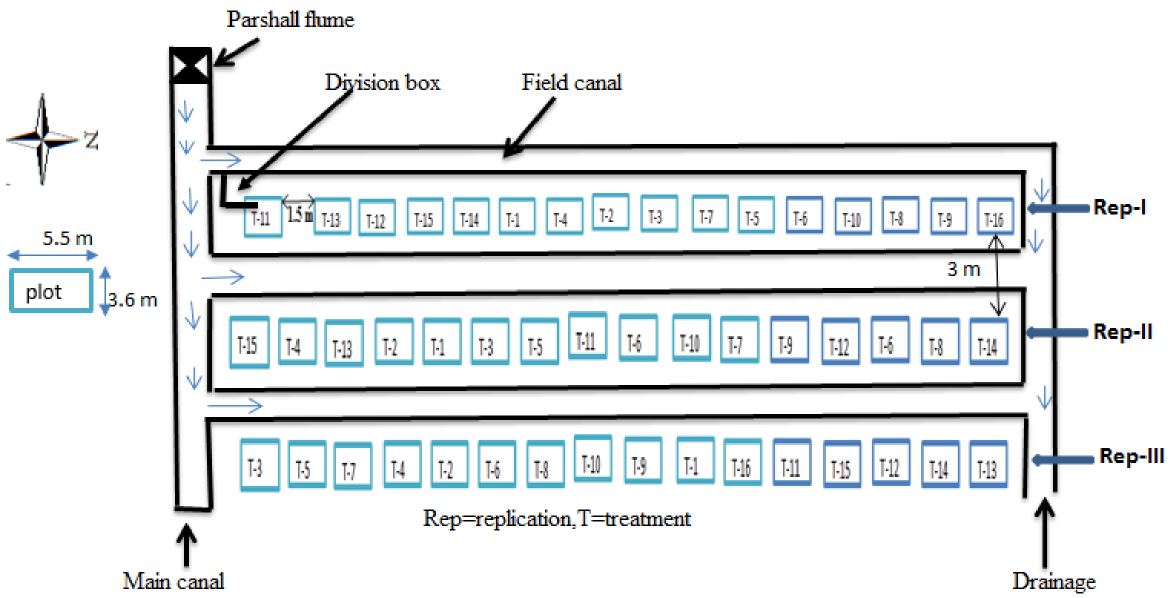


Figure 3.2. Experimental setup

3.4 Agronomy of Haricot Bean

Land preparation was made with the tractor for plowing and harrowing using dick plough and disc harrow, respectively. After land was leveled to improve minor gradient irregularities, the experimental field was divided into 48 plots with plot size of 3.6 m by 5.5 m to accommodate five ridges of 5 m length representing a single treatment. The plots and replications had a buffer zone of 1.5 m and 3 m length respectively (Fig. 3.2).

The plots were leveled manually and a gentle furrow gradient was maintained to all plots to create uniform water distribution within the given treatment. All experimental plots were provided with pre-irrigation two days before planting. Haricot bean variety Awash II was selected for the study and seeded on top of the ridges to a depth of 5 cm with a plant and row spacing of 10 cm and 60 cm, respectively. This crop variety was selected for its early maturing and had been widely cultivated in various parts of the country. Recommended fertilizers for haricot bean under Melkass condition (100 Kg/ha di-amonium phosphate and 100 Kg/ha Urea). di-amonium phosphate was applied during planting time only and Urea was applied in split application, half at sowing and the other half twenty days after sowing.

Irrigation water was applied to each experimental plot through the furrow irrigation method. Light irrigation was given right after sowing. The rooting depth of the haricot bean was considered as 30 cm during the establishment stage (Doorenbos and Kassam, 1979). Thus, the plots were initially provided common irrigation from 30cm soil depth at germination to attain uniform establishment. Differential irrigation commenced when the soil moisture after establishment irrigation reached threshold level for the control plot that irrigated with 100%ETc (T1). Each stage of bean has a varying number of days, depending on the crop being cultivated (Table 3.2). All cultural practices other than treatment variables were standard practices recommended for the area

Table 3. 2 Date of growth stages of haricot bean

growth stage	Days
Initial	15
Development	25
Mid	35
Late	15
Total	90

Source: Allen *et al*., 1998

3.5 Irrigation Water Management

Deficit irrigation was applied throughout the growth stages for treatments T2 to T4. Treatments T5 to T16 received deficit irrigation during only one growth stage of the crop and the remaining crop growth stages received irrigation water to satisfy the crop water requirement that brings the soil moisture deficit back to field capacity.

The depth of water to be applied was based on allowable soil moisture depletion fraction (p) and irrigation water was applied at regular soil moisture observation when 40% of the total available water (TAW) depleted within the root depth during the growing season. Allen *et al*. (1998) indicated the p-value for dry bean to be 0.45 and pointed out that for hot dry weather conditions, where ETc is high, the depletion fraction is 10-25% less than the value indicated.

The irrigation schedule was fixed based on readily available soil water (RAW), the fraction of TAW that a crop can extract from the root zone without suffering water stress and ultimately provide maximum crop production. The RAW was obtained from the following expression.

$$\mathrm{RAW} = \mathrm{p} * \mathrm{TAW} \quad ------------- (3.2)$$

where RAW is the readily available water (mm), p is depletion fraction (fraction) and TAW is the total available water in the root depth (mm/ depth of soil).

The total available water (TAW), stored in a unit volume of soil, was computed from the moisture content of field capacity and permanent wilting point and expressed as:

$$\mathrm{TAW} = (\mathrm{FC} - \mathrm{PWP}) * \mathrm{Dzr} \quad --------- (3.3)$$

where, FC and PWP (% weight basis), Dzr is the maximum effective root zone depth (mm)

The soil moisture depleted between irrigation at any time was computed using the equation:

$$SMD = (\theta_{FC} - \theta_{SMC}) * Sg * D_{rz} \quad ------(3.4)$$

where, SMD is the depth of soil moisture depleted after last irrigation at the time of moisture testing in mm; θ_{FC} is soil moisture contents at FC (g/g); θ_{SMC} is soil moisture content at the time of moisture testing (g/g), Sg is soil specific gravity, and D_{rz} is the maximum effective root zone depth at times of sampling (mm).

The net depth of irrigation supplied at any time was obtained from a simplified water balance equation and is expressed as:

$$\mathrm{IRn} = \mathrm{ETc} - \mathrm{peff} ------------(3.5)$$

where, IRn is the net irrigation depth (mm), ETc is the crop water requirement (mm) and P_{ef} is the effective rainfall (mm).

The daily P_{eff} was estimated using the method given by (Allen *et al.*, 1998) as:

$$\mathrm{P_{eff}} = 0.6 \times \mathrm{P} - \frac{10}{\frac{30}{31}} \text{ for month} \leq \frac{70}{\frac{30}{31}} \text{ mm} ------- (3.6)$$

$$\mathrm{P_{eff}} = 0.8 \times P - \frac{24}{\frac{30}{31}}\ for\ month > \frac{70}{\frac{30}{31}}\ mm ------(3.7)$$

where, P is daily rainfall (mm)

The gross irrigation requirement, IRg was computed by adopting field application efficiency, Ea of 60% for surface irrigation and computed from the following expression as:

$$\mathrm{IRg} = \frac{\mathrm{IRn}}{\mathrm{Ea}} -----------------(3.8)$$

where IRg is the gross depth of irrigation (mm), IRn is net irrigation requirement (mm) and Ea is the field application efficiency (%).

The depth of irrigation water to be applied in each plot was measured using a 3 inch Parshall flume installed in the upper stream near the experimental field. Accordingly, the time required to deliver the desired depth of water into each plot was calculated using the following equation.

$$\mathrm{T} = \frac{\mathrm{IRg} * \mathrm{A}}{60 * \mathrm{q}} ------------------ (3.9)$$

where IRg is the gross depth of water applied (mm), A is the area of the experimental plot (m^2), T is application time (min) and q is the flow rate (l/s.).

The irrigation interval was computed using the following equation:

$$\mathrm{I} = \frac{\mathrm{RAW}}{\mathrm{ETc}} ---------------- (3.10)$$

where RAW is readily available water (mm), I is irrigation interval (days) and ETc is crop water requirement (mm/day).

3.6 Data Collection

Some of the data collected from field experiment and awash Melkass Research Center were used in the calibration and validation of AquaCrop model. The model requires climatic, crop, soil, irrigation and field management data which can be stored in the files provided.

3.6.1 Weather data

Data on daily rainfall, temperature, humidity, sunshine hours, wind speed and others were collected from the Melkasa Meteorological Station for the period of the experiment. AquaCrop requires daily minimum and maximum temperatures, daily reference evapotranspiration (ETo), daily rainfall data and annual CO_2 concentration as input. 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.

3.6.2 Soil Data

Soil moisture

The quantity of water contained in soil was measured gravimetrically for experimental field. The gravimetric method is a simple approach to determine the mass of water present in the soil sample. Gravimetric water content was measured directly by finding the mass of water lost when a soil was dried in an oven at 105°Cfor24 hours. The soil samples were collected at 15 cm interval for the first two soil depth and at 30 cm interval for the remaining effective root depth of 90 cm of the crop for gravimetric soil moisture analysis (Allen *et al.*, 1998). the gravimetric water content (θw),is expressed as the difference between wet and dry mass divided by dry mass.: (Cuenca, 1989).

$$\theta w = \frac{Ww - Wd}{Wd} \text{ -------------- } (3.11)$$

where, θw is the soil water content (g/g), w_w is the weight of wet soil sample (g) and w_d is the dry weight of the soil sample (g).

Volumetric water content (θv) is usually preferred over gravimetric water content as it expresses the volume of water per volume of soil (White, 2003)

The gravimetric soil water content expressed in volume bases (θv) and expressed as:

$$\theta v = \theta w * \frac{\rho b}{\rho w} \text{ ---------------- } (3.12)$$

where, θv is volumetric moisture content in (cm^3/cm^3); ρb is soil bulk density (g/cm^3), and ρw is water density (g/cm^3).

The volumetric moisture content was also converted to an equivalent depth by multiplying with the root depth considered as indicated in Eq. (3.13).

$$d = \theta v * drt \text{ -------------- } (3.13)$$

where, d is the depth of water (mm) and drt is the root depth of the crop (mm)

3.6.3 Crop data

Crop data required included the haricot beans major phonological growth parameters including emergence, maximum canopy cover, flowering, senescence, and physiological maturity measured in calendar days and these were recorded in the field during the experimental period.

Green canopy cover

To calculate the canopy cover value the field images were measured at a perpendicular height 1 meter above the crop using Canopeo software installed on a mobile phone. The software automatically calculates the average Percent canopy cover. The output values were entered into the Aquacrop model. The time and maximum Canopy cover was determined when no increment was noted in the percent canopy cover.

Aboveground biomass

An area of 0.5 m x 0.5m was selected to harvest the plants from the ground level. The plants were oven-dried for 24 hours at around 60^0C until a constant weight before measuring their weight Then the aboveground biomass per hectare was estimated.

Crop yield

The data on final yield at the end of the season was harvested together with the final biomass from the net area of 4 m by 1.8 m of haricot bean. Grain yield obtained from each plot was adjusted to standard moisture content (12%) and converted to kilogram per hectare for each treatment.

Harvest index

was calculated by dividing the seed yield by the total biomass

$$\mathrm{HI} = \frac{\mathrm{Y}}{\mathrm{B}} - - - - - - - - - - - - - - - - - 3.14$$

Where HI is harvest index, Y is the yield per unit area in kg/ha and B is biomass in kg/ha

3.7 Crop Water Use Efficiency (CWE)

Araya *et al*. (2011), the crop water use efficiency (kg m-3) was calculated by dividing harvested total yield in kilogram to unit volume of water in cubic-meter or hectare-meter.

$$CWE = \frac{Y}{ETc} -------------- 3.15$$

Where CWE is crop water use efficiency in Kg/m^3, Y is the yield per unit area in Kg/ha and ETc is net water used to produce the grain yield of haricot bean in m^2/ha.

3.8 Statistical Analysis

Statistical data analysis was done after all relevant data associated with the study were organized. All measured variables were subject to statistical analysis of variance following the standard procedures applicable to RCBD using statistix-8 software. Whenever treatment effects were found significant, treatment means were compared using the least significant difference, LSD.

3.9 Calibration and Validation of the Aquacrop Model

Calibration is the adjustment of certain model parameters to make the model match the measured values at the given location. Observations of phonological parameters of the crop (Time to emergence, time to attain maximum canopy cover, time to flowering, time to senescence and physiological maturity) in calendar days was used in the calibration.

The canopy cover (CC) was calibrated first, followed by aboveground dry matter. Similarly, fine-tunings and adjustments of other parameters were done until good matches between simulated and measured values of the respective variables were attained. In the calibration process, non-conservative crop parameters were directly obtained from field observations and were used to describe the crop development under full irrigation requirement. During validation, the model is run without any modification of the model's parameters or code, which is compared to independent experimental data.

Validation of the model was performed using the calibrated model and data from the other treatments not used for calibration. In particular, the following crop growth parameters were analyzed: final biomass, harvestable yield and water use efficiency. Validation of Aquacrop model for biomass (B), yield (Y) and WUE) were done by comparing simulated outputs against the observed data collected from the field using the following statistical techniques.

3.9.1 Statistical analysis of model performance

To evaluate the goodness of fit between AquaCrop simulation results and observed biomass, yield, and WUE, statistical variables were used, viz., coefficient of determination, NRMSE (normalized root mean square error), root mean squared error (RMSE) and Willmott’s index of agreement (d). The coefficient of determination (r^2) where 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. The r^2 was computed using Eq. (3.16):

$$\boldsymbol{r^2} = \left[\frac{(\boldsymbol{Oi}-\boldsymbol{O})(\boldsymbol{Si}-\boldsymbol{S})}{\sum_{i=1}^{N}(\boldsymbol{Si}-\boldsymbol{S})\sum_{i=1}^{n}(\boldsymbol{Oi}-\boldsymbol{O})}\right]^{\boldsymbol{2}} -------- 3.16$$

The RMSE also represents a measure of the overall, or mean, a deviation between observed and simulated values, that is, a synthetic indicator of the absolute model uncertainty. In fact, it takes the same units of the variable being simulated, and therefore the closer the value is to zero, the better the model simulation performance. The RMSE is computed following Eq. (3.17):

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{n}^{1}(O-S)^2} -----------(3.17)$$

The NRMSE expresses how much the overall deviation between observed and simulated values departs from the overall deviation between observed values (Oi) and their mean value (O). The NRMSE is computed following Eq. (3.18):

$$\text{NRMSE} = \sqrt{\frac{1}{n}\sum_{n}^{1}(O-S)^2} * \frac{100}{Oi} -------- 3.18$$

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. The d is computed following Eq. (3.19):

$$\boldsymbol{d} = \boldsymbol{1} - \frac{\sum_{i=1}^{n}(\boldsymbol{si}-\boldsymbol{oi})^{\boldsymbol{2}}}{\sum_{i=1}^{n}(|S-O| + |\boldsymbol{Oi}-\boldsymbol{O}|)^2} ------- (3.19)$$

where Oi is measured values, Si is simulated values, O is measured mean ,S is the simulation mean and n is the number of observations.

4 RESULT AND DISCUSSION

4.1 Soil Physical and Chemical Properties

4.1.1 Soil physical properties

The result of laboratory soil analyses on physical and chemical characteristics, like soil infiltration, soil texture, ρb , FC, PWP, TAW, soil pH, electrical conductivity (EC), organic carbon (OC) content and organic matter (OM) content,. Are given in Table 4.1. and 4.2, and Fig. 4.1.

Soil texture

Table 4.1 indicates the textural class of the experimental field at different depths of the soil. The sand, silt and clay content of the experimental field was varied in a narrow range with an average value of 34, 43 and 23 %, respectively. Based on the USDA soil textural classification the dominant textural class of the experimental site was classified as a loam soil.

Table 4. 1 Soil particle size distribution

Depth (cm)	Particle size distribution (%)			Textural class
	%Sand (wt/wt)	%Silt (Wt/wt)	%Clay(wt/wt)	
0 – 15	32	49	19	Loam
15 – 30	36	41	23	Loam
30 – 60	33	40	27	Loam
Average	34	43	23	Loam

Bulk density, field capacity, permanent wilting point and water holding

Table 4.2 indicate bulk density and water holding characteristics of the experimental field at different depth of the soil. The soil bulk density shows a slight variation with depth this could be because of a slight decrease of organic matter with depth and compaction due to the weight of the overlying soil layer (Brady and Weil, 2002). It varied from 1.05 g/cm^{3}at the upper root zone (0-15 cm) to 1.19 g/cm^{3}at the lower root zone layer (30-60 cm).Generally, the top surface soil had slightly lower bulk density than the subsurface. This could be because of the slight decrease of organic matter with depth and compaction due to the weight of the overlying soil layer. The average bulk density of the soil was evaluated to be 1.13 g/cm^3.

The moisture content at field capacity for the experimental site soil varies between 29.6 and 37.25 on weight base for the soil depths considered. The moisture content at the permanent wilting point also showed variation with depth and ranged between 18.4 and 21.25on weight base for the soil depths considered. The representative value of TAW was 167 mm/m.

Table 4. 2.Soil physical properties of the experimental area

Soil depth (cm)	BD (g/cm^3)	FC (%)	PWP (%)	TAW (mm/m)
0-15	1.05	29.61	18.4	117.71
15-30	1.16	35.28	18.53	194.3
30-60	1.19	37.25	21.25	190.4
Mean	1.13	34.05	21.9	167.47

Infiltration rate

The field-level soil infiltration test indicates that the basic infiltration rate in the experimental area is 18 mm/hr and the result obtained was presented in Figure 4.1. This rate of infiltration is in a range with a basic infiltration rate of 10 to 20 mm/hr for loam soils indicated by (Brouwer *et al.*,1998). In the beginning, water infiltrates rapidly as more water replaces the air in the pores, the water infiltrates more slowly and eventually reaches a steady rate which is called the basic infiltration rate.

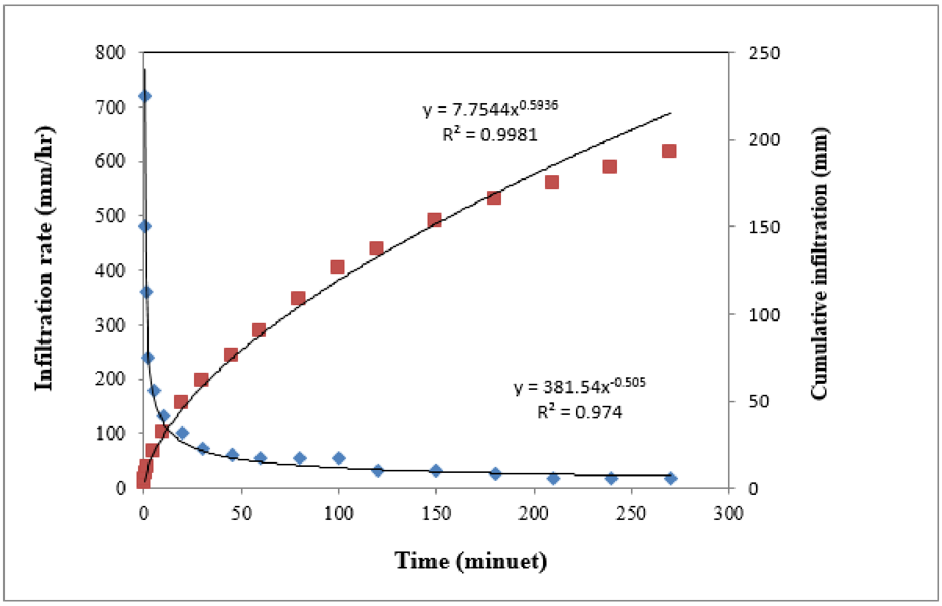


Figure 4.1. Soil infiltration characteristic of the experimental area

4.1.2 Chemical characteristics of the soil

The laboratory results of the average soil chemical properties of the experimental site are presented in Table 4. 3 below. The organic matter (OM) content of the surface soil (0-15 cm) was 4.2 %, but this declined with depth to 3.2% at (30-60 cm). The average organic matter content of the soil to 60 cm depth was about 3.73 %. As shown in Table 4.3, the pH of the soil profile was varied from 7.12 to 7.79. The average value of soil pH is 7.25 and according to Brady and Weil (2002), it is slightly alkaline and is within an acceptable range (6.00-7.50) for most crops. Soil EC decreased with depth while pH increased this might be related to the OM decrease with depth. The soil had an average electrical conductivity of soil 0.28 dS/m through a 60 cm profile which is classified as salt free and had negligible effect on most crop growth and yield (Hazelton and Murphy, 2007) **.**

Table 4. 3.Chemical properties of experimental soil

Depth (cm)	pH	EC_s (dS/m)	%OC	%OM	%TN
0-15	7.12	0.33	2.3	4.2	0.21
15-30	7.25	0.26	2.1	3.8	0.19
30-60	7.79	0.25	1.36	3.2	0.13
Average	7.25	0.28	1.92	3.73	0.18

4.2 Crop Water Requirement

The total amount of water required during the growing season of haricot bean and irrigation water applied in each treatment plot is presented in Tables 4.4 and 4.5, respectively. Water requirement at the initial stage was low and reached a peak at the mid-season growing stage (Table 4.4). The crop water requirements are highest during the mid-crop growth stage (flowering and yield formation period) compared to any crop growth stages. According to Doorenbos and Kassam (1979) the water requirement of dry bean was between 300 and 500 mm depending on the climate. The net depth and gross irrigation required for each treatment are shown in Table 4.5. The gross irrigation requirement was varied from the highest 552.13 mm which is irrigated with 100%ETc application throughout the growth stage to the lowest 166.03 mm which is irrigated with 25%ETc throughout the growth stage including common irrigation.

Table 4. 4 .Crop water requirement and net irrigation requirement of haricot bean

Crop growth stage	Kc	ETc(mm)	P_{eff} (mm)	IRn(ETc-P_{eff}) (mm)
Initial	0.37	11.06	0	11.06
Initial	0.37	11.29	0	11.29
Initial	0.37	10.75	0	10.75
Development	0.48	11.45	5.7	5.75
Development	0.59	13.28	16.6	0
Development	0.7	18.24	0.7	17.54
Development	0.81	23.46	0	23.46
Development	0.92	30.37	0	30.37
Mid	1.15	37.00	1.5	35.50
Mid	1.15	27.17	6.4	20.77
Mid	1.15	27.11	0	27.11
Mid	1.15	26.00	5.4	20.60
Mid	1.15	26.65	18.0	8.65
Mid	1.15	27.08	10.8	16.28
Mid	1.15	29.51	0	29.51
Late	0.89	29.84	0	29.84
Late	0.62	19.35	0	19.35
Late	0.35	13.45	0	13.45
Total (mm)		393.06	65.1	331.28

Table 4. 5.Net and gross irrigation requirement applied for all treatment

Treatment	Irrigation level (%)	Stages of Application	IRn (mm)	IRg (mm)
T-1	100	At all stages	331.28	552.1
T-2	75	At all stages	258.06	430.1
T-3	50	At all stages	178.84	298.1
T-4	25	At all stages	99.62	166.0
T-5	75	At initial stage	330.65	551.1
T-6	75	At development stage	317.39	529.0
T-7	75	At mid-stage	298.18	497.0
T-8	75	At late stage	323.68	539.5
T-9	50	At initial stage	324.02	540.0
T-10	50	At development stage	297.5	495.8
T-11	50	At mid-stage	259.08	431.8
T-12	50	At late stage	310.08	516.8
T-13	25	At initial stage	317.39	529.0
T-14	25	At development stage	277.61	462.7
T-15	25	At mid-stage	219.98	366.6
T-16	25	At late stage	296.48	494.1

4.3 Effect of Irrigation Level on Haricot Bean Physiology

Plant response to deficit irrigation in each treatment is depicted in Table 4.6. Deficit irrigation significantly ($P<0.05$) affected days to 50%flowering and days to maturity. Early flowering and maturity was observed in 25% ETc and 50% ETc application throughout the growth period. This might be due to accelerated maturity and senescence (Sionit and Kramer, 1972).The control treatment took longer days to 50% flowering and had shown no significant difference with all treatments except with 25% and 50% ETc application throughout the growth period and with single stage deficit irrigation of 25% ETc and 50% ETc during the development stages of the crop. The control treatment also took longer days to maturity and had no significant difference with all treatments except with 50% ETc and 25% ETc application throughout the crop growth stages and with 50% ETc and 25% ETc application in single-stage deficit irrigation during late-stage and 25% ETc application in mid-stage

Table 4. 6. Day to 50 % flowering and maturity of the crop

Treatment	Days to maturity	Days to 50% flowering
T-1	90^{a}	50^{a}
T-2	87^{ab}	49^{a}
T-3	85^{bc}	46^{bc}
T-4	83^{c}	45^{c}
T-5	90^{a}	49^{a}
T-6	90^{a}	49^{a}
T-7	89^{ab}	49^{a}
T-8	89^{ab}	49^{a}
T-9	90^{a}	49^{a}
T-10	89^{ab}	46^{bc}
T-11	90^{a}	48^{ab}
T-12	85^{bc}	48^{ab}
T-13	90^{a}	48^{ab}
T-14	89^{ab}	46^{bc}
T-15	85^{bc}	49^{a}
T-16	85^{bc}	49a
Grand mean	87.85	48.06
CV	3.09	2.52
LSD(0.05)	1.92	2.16

4.4 Effect of Deficit Irrigation on Yield Components of Haricot Bean

Deficit irrigation application produced a highly significant effect on yield components of haricot bean (Table 4.7). The control treatment gave the highest plant height, seeds per pod and thousand seed weight. Significant ($P<0.05$) plant height difference was observed in treatment which was subjected to 25% and 50% of ETc throughout the growth period of the crop. As observed from the result deficit irrigation level of 25%ETc during the total growth period and during mid-stage highly reduced number of seeds per pod and 100 seed weight. This is due to the fact that water applied during this stage mainly is used for grain filling process. These are in agreement with White *et al.*(1994) who found out that the deficit irrigation during flowering stage increased flower failure , reduced number of pods per plant and number of seed per pod .

Table 4. 7. Yield components of haricot bean

Treatment	Plant Height (cm)	No. Seed Per Pod	100 Seed Weight (gm)
T-1	60.0[a]	7.0[a]	24[a]
T-2	56.5[a]	6.7[ab]	22[bcd]
T-3	46.9[b]	5.3[cde]	19[ef]
T-4	34.6[c]	3.7[f]	17[g]
T-5	59.7[a]	6.8[ab]	23[ab]
T-6	59.1[a]	6.7[ab]	22[abc]
T-7	58.2[a]	6.1[abcd]	21[bcd]
T-8	58.7[a]	5.7[bcd]	21[cdef]
T-9	57.7[a]	6.76[ab]	22[abc]
T-10	56.9[a]	5.4[cde]	21[bcde]
T-11	59.3[a]	5.9[abcd]	20[def]
T-12	58.4a	6.1[abcd]	20[def]
T-13	55.3[a]	6.2[abc]	23[ab]
T-14	55.6[ab]	5.1[de]	21[bcde]
T-15	58.1[ab]	4.5[ef]	19[fg]
T-16	59.2[a]	5.9[abcd]	22[bcd]
Grand Mean	55.906	5.8723	21.077
CV	7.08	8.72	4.32
LSD(0.05)	8.8937	1.1498	2.0466

4.4 Effect of Irrigation Level on Yield And Biomass Production of Haricot Bean.

The grain yield and aboveground dry-biomass of the haricot bean plant are presented in Table 4.8. The highest biomass production was obtained from the control treatment (6.95 ton /ha) and had no significant difference with all treatment except with 50% ETc and 25% ETc at all stages, and 25% ETc in single-stage deficit irrigation during development and mid-season stages. As shown in Table 4.8, the highest grain yield was obtained from the control treatment (2.56 ton /ha) which was subjected to 100% ETc application throughout the growing season and had no significant difference with all treatments except with 75% ETc, 50% ETc and 25% ETc application throughout the crop growth stage and with 25% ETc and 50% ETc application in single-stage deficit irrigation during the mid-season. The minimum yield of haricot bean was obtained under treatment which was subjected to 25%ETc throughout the crop growth stage (1.12 ton /ha). The result indicated that the water deficit at the initial stage and late-season stage for all level deficits (25% ETc,50% ETc, and 75% ETc) gave non-significantly different yields from the optimum application of treatment T-1 (100% ETc throughout the growth stage). However applying 25% ETc and 50% ETc application in single-stage deficit during mid-season and 75%ETc, 50% ETc, and 25% ETc throughout the growth stages of the crop the yields were significantly ($p < 0.05$) different with control treatment.

Table 4. 8 Grain yield and biomass of haricot bean for different irrigation application levels under different growth stage.

Treatment	Grain yield (ton/ha)	Biomass (ton/ha)
T-1	2.56[a]	6.95[a]
T-2	2.32[bcd]	6.48[abc]
T-3	2.11[d]	5.77[d]
T-4	1.12[e]	4.56[e]
T-5	2.51[ab]	6.94[a]
T-6	2.48[ab]	6.82[a]
T-7	2.45[ab]	6.92[a]
T-8	2.50[ab]	6.93[a]
T-9	2.49[ab]	6.94[a]
T-10	2.47[ab]	6.65[a]
T-11	2.31[bcd]	6.51[ab]
T-12	2.47 [ab]	6.94[a]
T-13	2.49[ab]	6.94[a]
T-14	2.37[abc]	5.96[cd]
T-15	2.20[cd]	5.99[bcd]
T-16	2.49[ab]	6.67[a]
Grand mean	2.34	5.30
CV	5.8	4.89
LSD (0.05)	1.1	5.30

4.5 Crop water use efficiency(CWUE), Yield Reduction and Harvesting Index

The analysis of variance showed that irrigation levels had a significant ($p<0.05$) effect on CWUE. As shown in Table 4.9, treatments with lower yield (50%ETc throughout the growth stage) due to less water application had higher water use efficiency (1.06kg/m3) and treatments with high yield due to high water application had less water use efficiency. The result indicated that the lower depth of water received with the higher the water use efficiency. The seam result was reported by Sezen *et al*. (2005) who reported that higher water use efficiency was obtained with the lowest irrigation level in field-grown beans.

According to this result applying 50%ETc of crop water requirement during the crop growing season has better water use efficiency than applying optimal irrigation with 100%ETc crop water requirement. The highest yield reduction depended on the amount of water applied, as indicated by Kirda and Kanber (1999) and Doorenbos and Kassam(1979). The 25%ETc levels of water application throughout the growth period of the crop gave a highly reduced the grain yield with a yield reduction of 56.1%, followed by 50%ETc water application throughout the growth period gave 17.5% yield reduction (Table 4.9).

The harvest index, HI which refers to grain yield to dry matter as the percentage varied from 41.9% to 24.6%. The highest harvest index was obtained when a single-stage deficit with 25%ETc 50%ETc and 75%, was applied during the development stage. The result showed that deficit irrigation application during the development stage resulted in a higher harvest index than deficit irrigation application during the other stages of development. A study by Aspinal and Paleg, (1981) indicated similar results that water stress during the development stage results in a high harvest index.

Table 4. 9. Crop water use efficiency

Treatment	Grain yield (ton/ha)	HI (%)	Yield Reduction (%)	CWUE (kg/m^3)
T-1	2.56	36.8	0	0.65
T-2	2.32	36.6	9.2	0.78
T-3	2.11	36	17.5	1.06
T-4	1.12	24.6	56.1	1.05
T-5	2.51	36.1	1.7	0.65
T-6	2.48	36.4	2.9	0.67
T-7	2.45	35.5	4.1	0.72
T-8	2.50	35.8	2.1	0.66
T-9	2.49	36	3.1	0.66
T-10	2.47	37.5	3.4	0.72
T-11	2.31	35.5	9.8	0.79
T-12	2.47	35.6	2.5	0.68
T-13	2.49	35.9	2.4	0.66
T-14	2.37	41.9	7.1	0.74
T-15	2.20	36.8	13.9	0.91
T-16	2.49	35.6	2.5	0.72

4.6 Calibration and Validation of AquaCrop model

4.6.1 Calibration of aquacrop model

The final crop parameters after model calibration were presented in Table 4.10. Soil and crop data collected were used to estimate the crop parameters for model calibration. The key conservative and non-conservative input parameters were used to calibrate the AquaCrop model. The non-conservative input soil water stress coefficients for canopy expansion, stomata closure and curve shapes were iterated to calibrate the model well. The model has been calibrated based on the measured crop data from a non-soil-water limiting regime (100% Etc). Since for this amount of irrigation, the amount of water required by the crop was adequately supplied, with no water stress due to water deficit or excess water. Crop parameters were iteratively adjusted until the close agreement was achieved between the measured and simulated CC, above-ground biomass and grain yield. The process of calibration was compiled when the lowest root mean squared error between simulated and measured CC, aboveground biomass, and grain yield was obtained.

Table 4. 10. The crop parameters for haricot beans obtained after calibration.

Description	Value	Unit
Initial canopy cover (Co)	0.83	%
canopy growth coefficient (CGC)	17.4	% day
Canopy declined coefficient (CDC)	14.3	% day
Plant density	16.7	plant/m^2
DAP to emergency	9	Day
Maximum canopy cover	90	%
Maximum effective root depth	0.9	M
DAP to senescence	70	Day
DAP to maximum canopy cover	50	Day
DAP to maturity	90	Day
DAP to flowering	50	Day
DAP to maximum root depth	70	Day
normalized Water productivity	16	g/cm^2
Soil water depletion threshold for canopy expansion- Upper	0.16	% TAW
Soil water depletion threshold for canopy expansion- Lower	0.55	% TAW
Soil water depletion threshold for stomatal closure- Upper	0.5	% TAW
Soil water depletion threshold for canopy senescence-Upper	0.64	% TAW
Reference Harvest index	36	%

4.6.1.1 Canopy cover

Figure 4 .2 shows the simulation of CC for non-water stressed conditions (100%Etc) with AquaCrop.Accurate calibration for CC is important as it determines the transpiration rate, biomass production, and grain yield**.** After calibration, the observed and simulated CC development fitted well with adequate statistical values (Table 4.12). The fitting of the calibration data and model simulation for canopy cover was very good with statistical parameters as indicated in Table 4.12.(R^2=0.98 and RMSE=7.2%.)

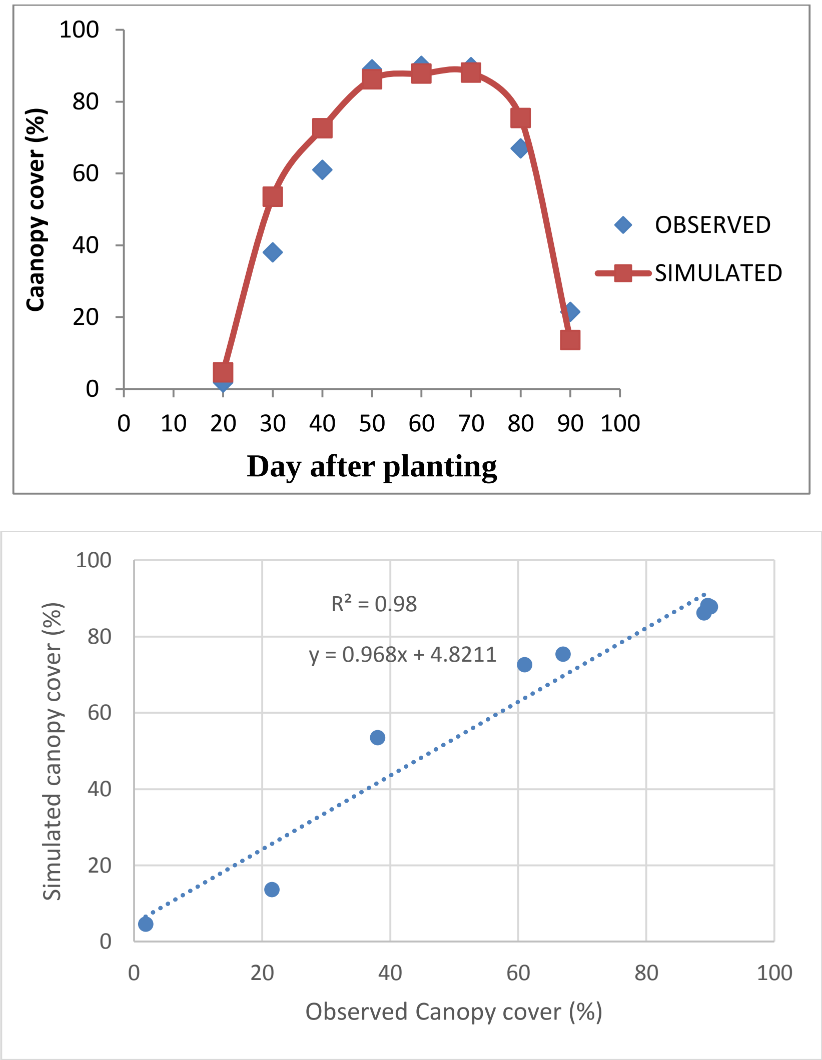


Figure 4. 2. Measured and simulated values of crop canopy cover for the Calibration treatment.

4.6.1.2 Soil water content (SWC)

The total amount of soil water depletion from the profile was well simulated by AquaCrop as shown (Fig. 4.3). Accurate simulation of soil water balance is very important, as all stress thresholds in AquaCrop is a direct function of soil water. It is expressed as an equivalent depth (mm). The fitting of the calibration data and model simulation was very good with statistical parameters as indicated in Table 4.12.R^2=0.93 and RMSE=11.6 mm.

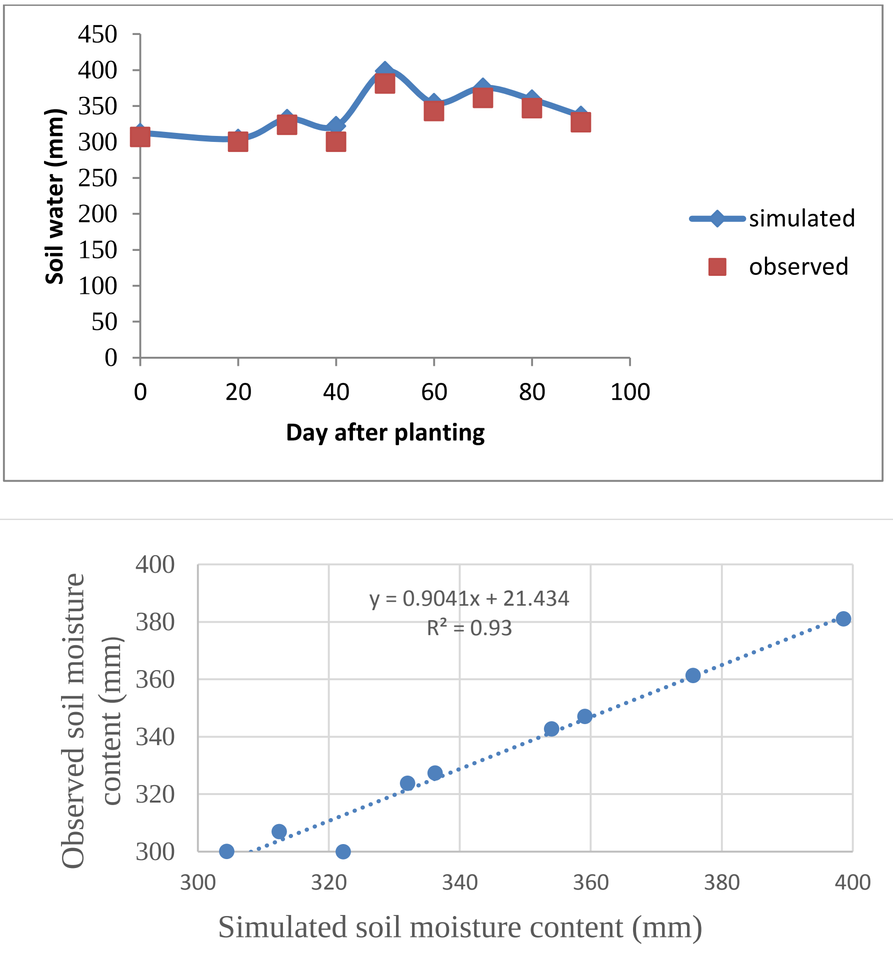
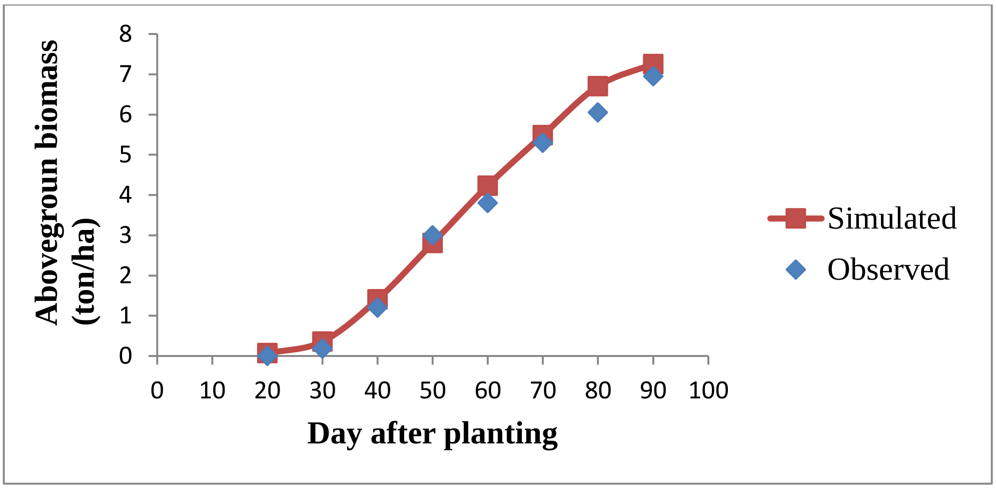


Figure 4.3. Observed and simulated soil water content for 100%ETc application throughout the growth stage.

4.6.1.3 Above ground biomass

Calibration for measured and simulated aboveground biomass for crop growing season is presented in Fig. 4.4. Generally; there is a good fit between measured and simulated values, as indicated by the statically indicator presented in Table 4.12. After calibration, the simulated final biomass and grain yield was deviated from observed values by 4.37% and 2.85% respectively (Table 4.10). the results also conform to those of Araya *et al*. (2010)

evaluated the performance of the AquaCrop model and simulated the highest deviation for biomass and yield with 8.5% and 2.9%, respectively.



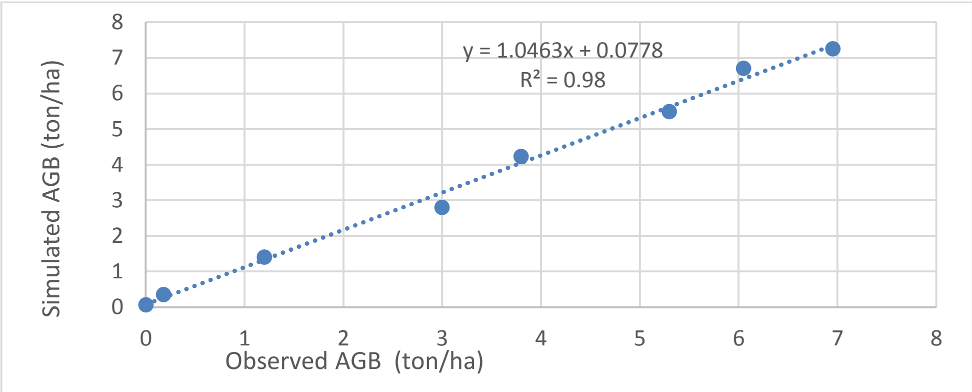


Figure 4. 4. Measured and simulated values of above-ground biomass for the calibration

Table 4. 11. Simulated and measured grain yield and final biomass results for calibration under full irrigation of haricot bean

Treatment	Grain yield (ton/ha)			Above-ground biomass (ton/ha)		
	Observed	Simulated	Dev.%	Observed	Simulated	Dev.%
T1	2.56	2.64	2.85	6.95	7.26	4.37

Table 4. 12. Statistical indices of simulated and observed results for the calibration data.

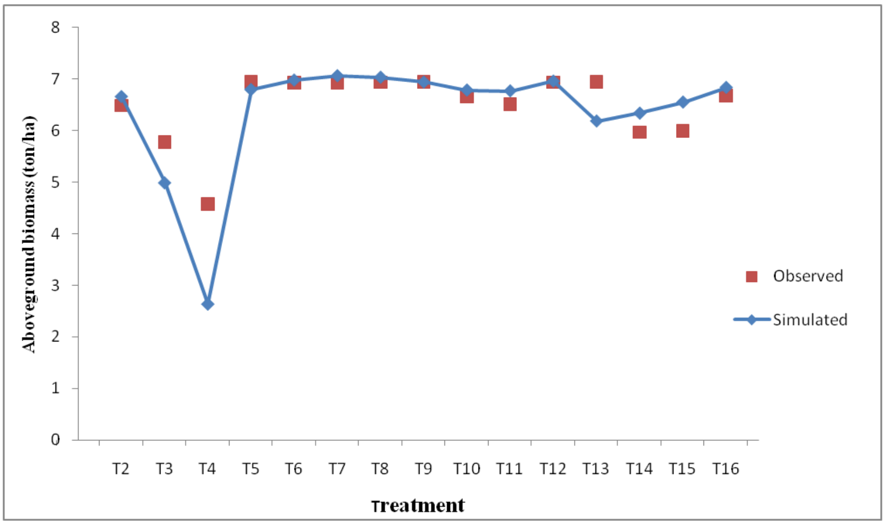
Statistics	Biomass	SWC	Canopy cover
RMSE	0.4 ton/ha	11.6 mm	7.20%
R^2	0.98	0.93	0.98
NRMSE	11.2	3.4	14.3
EF	0.97	0.84	0.94
d	0.97	0.95	0.98

4.6.2 Validation of Aquacrop Model

The Aquacrop model was validation using the data from the experimental field observations from the other treatments not used for calibration. During validation, the observed grain yield, biomass and water use efficiency for all 15 treatments were compared with the result simulated by the model. The model was validated using the calibrated crop parameters shown in Table 4.10. Validation results from this study show that the model performed well in simulating biomass, water productivity and yield for treatment under mild water stress.

4.6.2.1 Evaluation for final above ground biomass

As shown in Figure 4.4 and Table 4.13, except for slight underestimation of the simulated values, the final above ground biomass was adequately simulated. Analysis of above ground biomass showed maximum variation of -42.194% in treatment irrigated with 25%ETc application throughout the growing season as indicated in Table 4.13. This result indicated that the model is not good to simulate biomass in treatment which was consecutively subjected to water deficit throughout the growing season. These are in agreement with Heng *et al*.(2009) who reported that AquaCrop model overestimate maize biomass under water deficit conditions .In the model the above ground biomass is derived from the crop transpiration using the crop water productivity which is normalized for ETo and CO2 (Stedu *et al*., 2009).



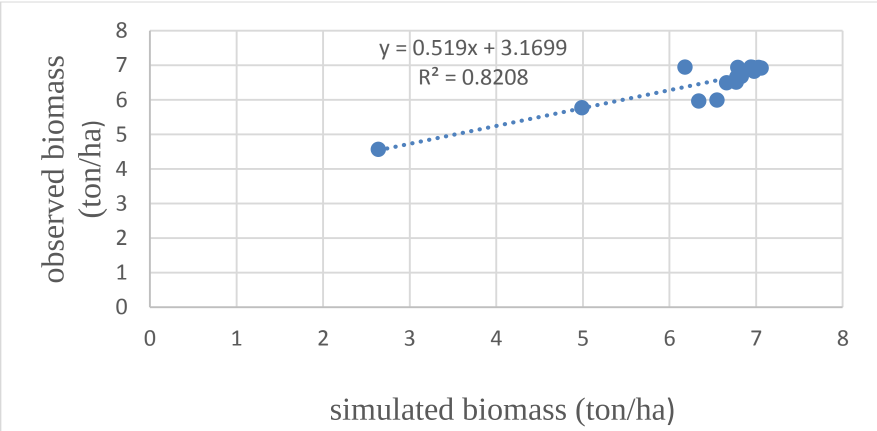
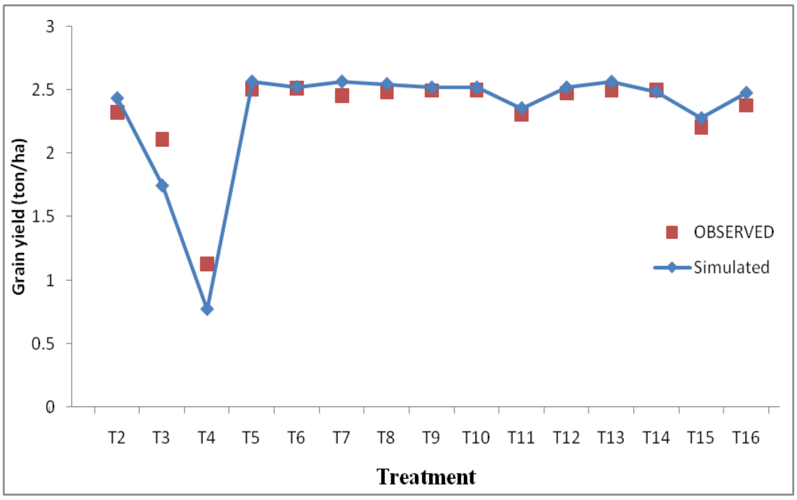


Figure 4.5. Measured and simulated aboveground biomass for all treatments not used in the calibration.

4.6.2.2 Evaluation for grain yield

As shown in Figure 4.6 and Table 4.13, except for slight underestimation of higher values, the grain yield was adequately simulated by the model.



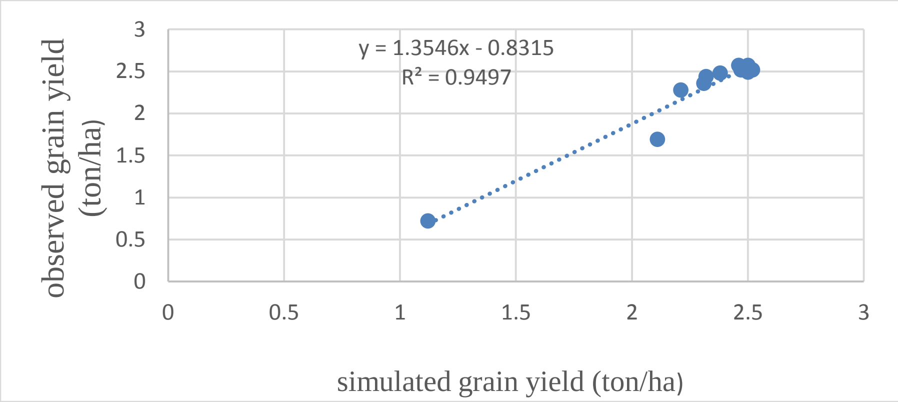


Figure 4. 6. Measured and simulated grain yield for all the treatments not used in the calibration.

The simulated grain yield ranges from 2.636 to 0.721tha^{-1} while the experimental value ranges from 2.56 to 1.1236t ha^{-1}.The highest deviation between observed and simulated results was observed in treatment irrigated with 25% and 50%ETc throughout the growing season and due to the presence of extreme water deficits, the model underestimates the simulated value by 35.8% and 19.75% respectively Table 4.13. This is in agreement with work done by Karunaratine *et al.* (2011) who reported that as the moisture stress level increased to the maximum the aquacrop model fails its efficiency to simulate the yield and biomass.

Table 4. 13.Comparison of observed and simulated values of dry biomass and grain yield.

Treatment	Grain yield(ton/ha)			Biomass (ton/ha)		
	Simulated	Observed	Dev.%	Simulated	Observed	Dev.%
T-2	2.44	2.32	4.71	6.66	6.49	2.59
T-3	1.69	2.11	-19.75	4.99	5.77	-13.63
T-4	0.72	1.12	-35.83	2.64	4.57	-42.19
T-5	2.57	2.50	2.42	6.79	6.94	-2.15
T-6	2.52	2.52	0.27	6.98	6.83	-0.15
T-7	2.57	2.46	4.50	7.06	6.92	1.98
T-8	2.55	2.49	2.49	7.03	6.94	1.36
T-9	2.52	2.50	0.87	6.94	6.95	-0.11
T-10	2.52	2.50	0.77	6.78	6.66	1.85
T-11	2.36	2.31	1.97	6.77	6.51	3.94
T-12	2.52	2.47	1.84	6.96	6.94	0.22
T-13	2.56	2.50	2.71	6.18	6.95	-11.02
T-14	2.49	2.50	-0.45	6.34	5.97	6.17
T15	2.28	2.21	3.26	6.55	5.99	9.31
T-16	2.48	2.38	4.15	6.83	6.68	2.33

The model prediction of haricot bean yield showed a good agreement with observed values with an R^2 of 0.951, The Willmott's index of agreement was 0.825 and root mean square error of 0.26 t/ha.The r^2, d, RMSE and NRMSE were used to evaluate the model performance. These parameters showed well to moderate performance for above-ground biomass and grain yield (Table 4.14).

Table 4. 14. Statistical evaluation parameters for simulated and observed grain yield and aboveground biomass

Parameter	Above-ground biomass	Grain yield
r2	0.826	0.95
D	0.99	0.825
NRMSE	9.38	9.1
RMSE	0.6 ton/ha	0.26 ton/ha

4.6.2.3 Evaluation for water use efficiency

The observed and simulated water use efficiency for all the irrigation treatments are depicted in Table 4.15. The observed water use efficiency was varied from 0.65 to 1.06 while the model simulated water use efficiency was varied from 0.61 to 0.87. The deviation of Simulated WUE from observed values varied from -1 .0 % to -42.1% (Table 4.15). according to the results of this finding, it can be suggesting that AquaCrop model simulation of water use efficiency was fair for mild water stress conditions, becoming unsatisfactory as the level of water stress increased.

The trend of aquacrop model evaluation for water use efficiency in this study is in agreement with the findings of (Todorovic *et al* .,2009, Evett and Tolk 2009) and the authors stated that the AquaCrop model was only reliably to simulates WUE under well-watered conditions but tended to misestimate WUE under conditions of water stress. According to the result from this study high underestimation by model in both harvesting index and water use efficiency was observed in T-4 (25%ETcduring the hole growth stage) which was subjected to severe water stress during the whole growth stages of the crop.

Table 4. 15.Simulated and observed water productivity and harvest index

Treatment	Observed HI	Simulated HI	Dev.%	Observed WP	Simulated WP	Dev.%
T1	36.8	36.3	-1.4	0.65	0.68	4.4
T2	35.8	35.1	-2.1	0.78	0.84	7.5
T3	36.6	35	-4.3	1.06	0.87	-17.6
T4	24.6	34.9	41.8	1.05	0.61	-42.1
T5	36.1	35.3	-2.2	0.65	0.71	9.4
T6	36.3	36.2	-0.3	0.67	0.74	9.8
T7	35.5	36.3	2.3	0.72	0.75	4.7
T8	35.8	36.2	1	0.66	0.74	11.5
T9	36	36.3	1	0.66	0.73	10.7
T10	37.5	35.7	-4.9	0.72	0.77	7.3
T11	35.5	36.3	2.3	0.79	0.73	-7.5
T12	35.6	36.2	1.6	0.68	0.74	9.6
T13	35.9	35	-2.6	0.66	0.68	2.5
T14	41.9	36.7	-12.3	0.74	0.72	-3.0
T15	36.8	36.3	-1.4	0.91	0.9	-1.0
T16	35.6	36.2	1.7	0.72	0.73	1.2

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Irrigation water management strategies that focus on increasing agricultural water productivity, such as deficit irrigation with crop growth simulation modeling to investigate multiple alternatives strategy, have a pivotal role to play in sustainable water development.

In this study, an attempt was made to calibrate and validate the aquacrop model and to evaluate the effects of deficit irrigation at different growth stages of haricot bean. Four irrigation levels, viz., 100%, 75%, 50%, and 25% of the crop water requirement was imposed on four growth stages, viz., initial, development, mid-season and late-season stages. The experimental soil had a loam texture with a bulk density of 1.13g/cm^3 and a basic infiltration rate of 18 mm/hr. The characteristic TAW of the soil was 167.47 mm/m. The aquacrop model has been calibrated based on the measured crop data from a non-soil-water limiting regime (100% Etc) .During validation, the observed grain yield, biomass and water use efficiency for all 15 treatments were compared with the result simulated by the model.

The study shows that deficit irrigation imposed at different growth stages of haricot bean has a significant effect on yield, water productivity and biomass of haricot bean. The maximum yield of 2.56 ton/ha was obtained from 100% ETc throughout the growing season and a minimum yield of 1.1236ton/ha from 25%ETc throughout the growing season. Deficit irrigation shows early flowering and maturity compared to control irrigation treatment (100%ETc). Deficit irrigation application up to 25%ETc during the initial stage and late-stage can lead to considerable water saving without significant yield loss but deficit level during the mid-stage lead to high yield reduction since flower failure results in yield reduction.

The deviation of Simulated water use efficiency from observed values was within the range of -1.0 % to -42.1 %, this can be suggested that the AquaCrop prediction of WUE was fair, but model performance becomes unsatisfactory in severely moisture stressed condition.

Generally, the AquaCrop model can be a useful tool to simulate or predict the yield, biomass and water use efficiency of crops for treatment which were subjected to mild water stress.

5.2 Recommendation

Based on the scope of the study and findings, the following recommendations have been made.

- For the area that has sufficient water resources, it is recommended to use control treatment (100% ETc) and treatments with 75%ETc during the initial and late-stage.
- In water-scarce areas, treatments irrigated with 50%ETc and 25%ETc during the initial and late-stage could be suggested since the deficit level during this stage does not significantly affect the yield of haricot bean.
- According to the results of this study, there was underestimation and overestimation of haricot bean yield, water use efficiency and aboveground dry biomass by the aquacrop model for treatment consequently subjected to water deficit (50%ETc and 25%ETc under all growth stage). From this, it can be recommended that the AquaCrop model is less satisfactorily in simulating sever or prolonged water deficit treatment.
- Based on the findings of this study, it is recommended to use the validated and calibrated aquacrop model as a decision-making tool in the study area for information on irrigation scheduling to achieve the desired yields.
- The experiment is carried out for one crop variety and in one place, Hence, further investigation is recommended using different varieties of crop and in different agro-ecological zones.

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APPENDIX

Appendix A. Table

Table 1: Average monthly climatic data during the study period.

Month	RF mm	T_{max} ^0C	T_{min} ^0C	RH %	WS m/s	SSH hr	E_{pan} mm/day	ET_o mm/day
February	0	30.8	15	56	2.49	8.8	8.84	5.37
March	2.7	32.2	16.1	50	1.91	8.7	8.73	5.4
April	2.81	23.7	16.3	55	2.07	8.1	8.65	5.48
May	1.48	29.8	16.4	57	1.91	9.1	8.8	5.35
Mean	1.7475	29.125	15.95	54.5	2.095	8.675	8.755	5.4

Table 2: Soil infiltration data of experimental area

Elapsed Time (minuet)	Cumulative Time (minuet)	Reading (cm)	Difference (mm)	Cumulative Intake (mm)	Infiltration Rate (mm/hr)
0	0	12.5	0	0	0
0.25	0.25	12.2	3	3	720
0.25	0.5	12	2	5	480
0.5	1	11.7	3	8	360
1	2	11.3	4	12	240
3	5	10.4	9	21	180
5	10	9.3	11	32	132
10	20	7.6	17	49	102
10	30	6.4	12	61	72
15	45	4.8/12.7*	15	76	60
15	60	11.3	14	90	56
20	80	9.3	18	108	54
20	100	7.5	18	126	54
20	120	6.4/13.2*	11	137	33
30	150	11.6	16	153	32
30	180	10.3	13	166	26
30	210	9.4	9	175	18
30	240	8.5	9	184	18
30	270	7.6	9	193	18

"*" indicate reading before and after water addition.

Table 3: Bulk density of the experimental soil

depth (cm)	Volume of core sampler (cm3)	weight of sampler (gm)	weight of dry sample +core (gm)	weight of dry soil sample (gm)	bulk density (gm/cm3)
0-15	98	33	135.5	102.5	1.046
15-30	98	33.1	143.2	110.1	1.123
30-60	98	33.4	147.1	113.7	1.16
Average					1.11
0-15	98	33	137.3	104.3	1.064
15-30	98	33.4	142.5	109.1	1.113
30-60	98	33	147.8	114.8	1.171
Average					1.116
0-15	98	33	136.6	103.6	1.057
15-30	98	33.1	142.8	109.7	1.119
30-60	98	33.4	147.5	114.1	1.164
Average					1.114
Grand mean					1.113

Table 4:Discharge (l/s) for flumes of 3 inch throat width parshall flume

Head(cm)	Discharge (l/sec)
3	0.772
4	1.206
5	1.705
6	2.261
7	2.872
8	3.532
9	4.239
10	4.991
11	5.786
12	6.621
13	7.496
14	8.408
15	9.358
16	10.342

Table 5:Daily climate and ETo during the experiment for month of February

Day	Temp. (°C) Min.	Temp . (°C) Max.	Humidity. (%)	Wind. (km/day)	Sun. (hours)	Rad. (MJ/m2/day)	Eto (mm/day)
1	16.5	28.5	57	95	6.7	18.2	3.95
2	17	29.5	56	199	8.3	20.6	5.03
3	16	29	62	225	8.1	20.4	4.89
4	15	30	62	181	8.8	21.4	4.89
5	13	30.5	56	199	7.2	19.1	4.92
6	13	30.5	56	216	9.6	22.7	5.45
7	14	30	56	225	8.7	21.4	5.31
8	15	30.5	57	268	10.6	24.3	5.93
9	13	31	52	216	10.6	24.3	5.82
10	9.5	30	53	181	10.7	24.5	5.43
11	12.5	31	59	156	10.2	23.8	5.21
12	16	19.5	92	225	0	8.7	1.74
13	14.5	21.5	86	277	1.3	10.7	2.31
14	14.5	24.5	73	259	6.4	18.3	3.92
15	12	29.5	56	251	9.9	23.6	5.65
16	16.5	31.5	46	173	10.5	24.5	5.82
17	14.5	33.5	46	164	10.4	24.4	5.91
18	16.5	33.5	49	233	9.5	23.1	6.31
19	15.5	32.5	50	199	9.5	23.2	5.88
20	14.5	32.5	47	242	9.7	23.5	6.33
21	16	32	54	259	10	24	6.24
22	17	31.5	50	285	9.8	23.7	6.48
23	16.5	31.5	52	277	10.1	24.2	6.4
24	17	32.5	47	216	9.6	23.5	6.19
25	12	33.5	46	138	10.4	24.8	5.71
26	18	31	49	294	9.6	23.6	6.54
27	17.5	30.5	53	302	9.9	24.1	6.4
28	16.5	31.5	51	190	9.8	24	5.84

Table 6:Daily climate and ETo during the experiment for month of march .

Day	Min Temp (°C)	Max Temp (°C)	Humidity (%)	Wind (km/day)	Sun (hours)	Rad (MJ/m2/day)	Eto (mm/day)
1	15	33.5	42	199	9.6	23.7	6.3
2	12.5	32.5	42	190	9.8	24.1	6.11
3	14	33.8	40	121	9.2	23.2	5.48
4	16.5	34	42	130	8.8	22.6	5.55
5	16	34	43	138	8.9	22.8	5.65
6	14.5	33.5	41	164	8.2	21.8	5.75
7	17	34	38	216	10.1	24.7	6.81
8	16	33.5	37	216	10	24.6	6.74
9	18.5	33	44	173	9.2	23.4	6.02
10	17.5	32.5	50	233	8.7	22.7	6.19
11	18.6	30.5	52	233	3.4	14.5	4.9
12	17.5	33	47	164	10	24.7	6.04
13	14	34.5	44	121	9	23.2	5.54
14	17.5	33	47	216	9.1	23.4	6.31
15	17.5	33.5	48	199	6.8	19.8	5.74
16	19.5	32.5	57	156	5.6	18	4.84
17	16.5	32	60	61	5.5	17.9	3.97
18	16	32	57	207	8.4	22.4	5.69
19	16	32.5	55	302	9.4	24	6.61
20	18.5	32.6	55	173	7.6	21.2	5.46
21	16	24.1	55	121	6.3	19.2	4.11
22	17	24	54	173	5.6	18.1	4.32
23	15.6	20.8	72	86	2.8	13.7	2.82
24	15.5	23	64	86	10.8	26.2	4.65
25	16	23	68	121	10	25	4.56
26	16.5	22.5	62	207	10.8	26.3	5.05
27	13.5	22	48	181	11	26.6	5.16
28	12.5	22.3	51	121	11.3	27.1	4.85
29	14.5	23.8	49	121	11.4	27.2	5.09
30	13.5	23	49	156	11.6	27.5	5.21
31	19	26	48	164	11.5	27.4	5.78

Source: MARC

Table 7:Daily climate and ETo during the experiment for month of April .

Day	Min Temp (°C)	Max Temp (°C)	Humidity (%)	Wind (km/day)	Sun (hours)	Rad (MJ/m2/day)	Eto (mm/day)
1	17.6	32.5	46	233	9.9	24.9	6.64
2	16.5	33	48	294	10.7	26.1	7.22
3	19	32.5	46	337	10.8	26.3	7.61
4	16.5	33	48	251	10.8	26.3	6.93
5	18.5	33	43	242	10.9	26.4	7.09
6	14	32.5	41	216	10.7	26.1	6.72
7	17	33	37	216	10.9	26.4	6.99
8	13.5	34	39	181	10.9	26.4	6.64
9	13.5	34.2	41	121	11.1	26.7	6.04
10	14.5	34	43	138	10.6	25.9	6.1
11	15.5	34	43	181	10.9	26.4	6.6
12	18.6	31	47	268	8.1	22	6.37
13	16.5	28	70	216	4.5	16.4	4.13
14	15.5	33	55	181	10.1	25.1	6.06
15	16.6	27	69	138	6.6	19.7	4.23
16	16.5	28.5	65	138	5.4	17.8	4.17
17	18.5	30.6	55	199	5.5	18	5.03
18	16	31	60	147	7.8	21.5	5.04
19	16.5	29.5	63	138	7.7	21.3	4.78
20	17.6	31.5	59	138	6.8	19.9	4.85
21	15.5	26	71	181	3.2	14.4	3.53
22	15	30.5	57	190	8.3	22.2	5.4
23	18.5	29	59	207	3.2	14.4	4.33
24	17	23.5	78	104	0.1	9.6	2.35
25	13	31	56	138	11.4	26.9	5.71
26	16	32	54	112	9	23.2	5.21
27	16	32.2	55	147	7	20.1	5.05
28	16.6	28	66	104	3.8	15.2	3.58
29	17.2	33	56	156	9.9	24.5	5.8
30	16.5	29	67	130	6.4	19.2	4.31

Source: MARC

Table 8 :Daily climate and ETo during the experiment for month of May .

Day	Min Temp (°C)	Max Temp (°C)	Humidity (%)	Wind (km/day)	Sun (hours)	Rad (MJ/m2/day)	Eto (mm/day)
1	17.5	31	62	190	8.3	22	5.32
2	16.5	28	69	181	5.6	17.9	4.22
3	17.5	29.5	66	95	8.4	22.2	4.65
4	18	29.2	64	86	5.3	17.4	3.92
5	15.5	30	62	104	10.9	25.9	5.25
6	14.5	30.5	60	138	10.6	25.4	5.42
7	16.2	28.4	69	112	7.3	20.4	4.31
8	15.5	28.5	66	156	8.4	22	4.76
9	15	20	62	156	9.9	24.3	4.39
10	14.5	20.5	61	156	11	25.9	4.61
11	15.5	32.6	52	156	11.2	26.2	6
12	12.5	32.2	47	156	10.8	25.6	5.9
13	11.5	33	48	156	10.8	25.5	5.95
14	13	34	43	173	10.6	25.2	6.29
15	15.5	34	52	199	10.7	25.3	6.37
16	17	34	50	190	10.9	25.6	6.41
17	17.5	31	55	147	7.5	20.5	5
18	14.5	32	54	190	8.8	22.4	5.63
19	19	32.5	54	138	7.7	20.7	5.14
20	17.5	32.4	56	199	7	19.7	5.35
21	16	31.5	57	216	10.3	24.6	5.95
22	17	31	65	138	6.4	18.7	4.48
23	17.5	31.5	60	173	9.4	23.2	5.46
24	19	32.5	54	190	10.1	24.2	5.99
25	18	33.5	53	147	10.9	25.4	5.93
26	16	32.5	54	164	10.5	24.7	5.81
27	17.8	33.5	51	181	10.7	25	6.19
28	18	30	58	190	7.4	20.1	5.06
29	17.5	31	59	181	5.5	17.3	4.68
30	18.5	33	54	225	8.5	21.7	5.94
31	18	33	53	251	8.8	24.1	54.8

Source: MARC

Table 9 water application time for 80 cm root depth

		Water application level (%)			
		100%	75%	50%	25%
Head (cm)	Q (l/s)	Time in minuet			
3	0.772	33.69	25.27	16.84	8.42
4	1.206	21.57	16.17	10.78	5.39
5	1.705	15.25	11.44	7.63	3.81
6	2.261	11.5	8.63	5.75	2.88
7	2.872	9.06	6.79	4.53	2.26
8	3.532	7.36	5.52	3.68	1.84
9	4.239	6.14	4.6	3.07	1.53
10	4.991	5.21	3.91	2.61	1.3
11	5.786	4.49	3.37	2.25	1.12
12	6.621	3.93	2.95	1.96	0.98
13	7.496	3.47	2.6	1.73	0.87
14	8.408	3.09	2.32	1.55	0.77
15	9.358	2.78	2.08	1.39	0.69
16	10.342	2.51	1.89	1.26	0.63

Table 10:Analysis of variance for day to 50% flowering

Source	DF	SS	MS	F	P
Block	2	1.50	0.750		
Treatment	15	98.81	6.588	2.73	0.0094
Error	30	72.50	2.417		`
Total	47	172.81			
Grand Mean	48.063				
CV	2.52				

$p<0.05$"indicates Significant difference at probability level of 5% ($p<0.05$)

Table 11:Analysis of variance for final biomass (ton/ha)

Source	DF	SS	MS	F	P
Block	2	0.29	0.143		
Treatment	15	21.70	1.447	13.49	0.0000
Error	30	3.22	0.107		`
Total	47	25.21			
Grand Mean	6.415				
CV	5.1				

“P<0.05”indicates Significant difference at probability level of 5% (0.05).

Table 12:Analysis of variance for grain yield (ton/ha)

Source	DF	SS	MS	F	P
Block	2	0.1379	0.0689		
Treatment	15	1.84802	0.1232	7.61	0.0003
Error	30	0.4858	0.001619		`
Total	47	2.4717			
CV	5.25				

“P<0.05”indicates Significant difference at probability level of 5% (0.05)

Table 13:Analysis of variance for WUE (kg/m^3)

Source	DF	SS	MS	F	P
Block	2	0.00434	0.00217		
Treatments	15	0.76154	0.05077	23.5	0.0001
Error	30	0.06481	0.00216		
Total	47	0.83069			
CV	5.35				
Grand mean	0.8689				

Appendix B .Figure

Figure 1 Experimental field

Figure 2:Experimental field during plant establishment stage

Figure 3 Installation of double infiltrometer for infiltration measurement

Figure 4 Parshall flume installation

Figure 5: Soil sampling

Figure 6 :Crop data collection

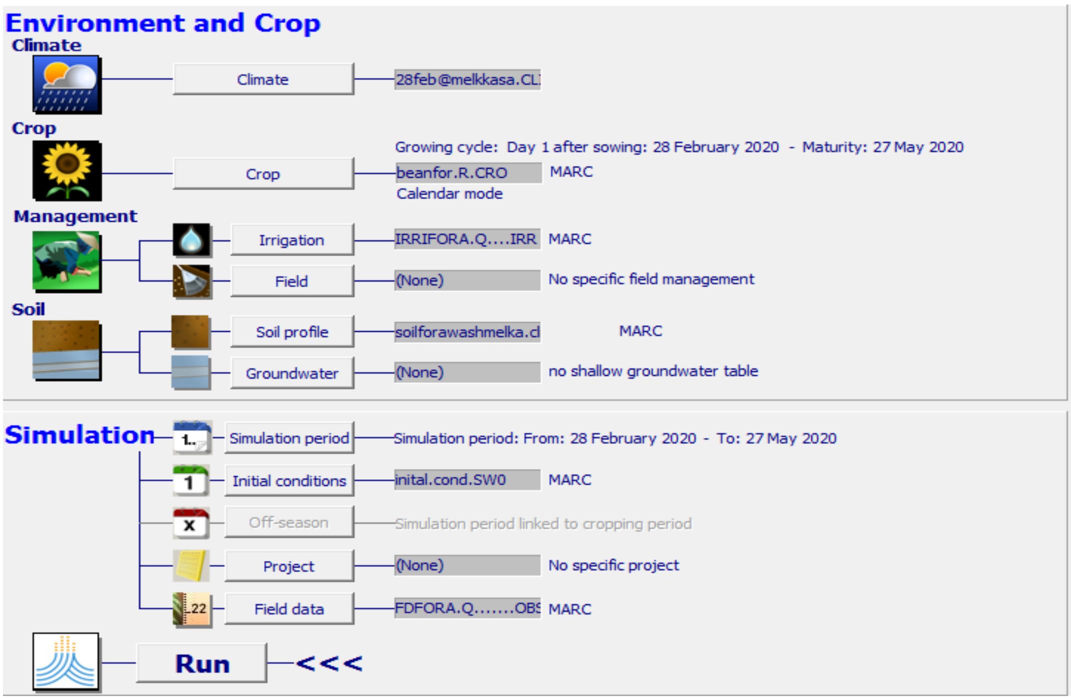

Figure 7: Required input data for AquaCrop

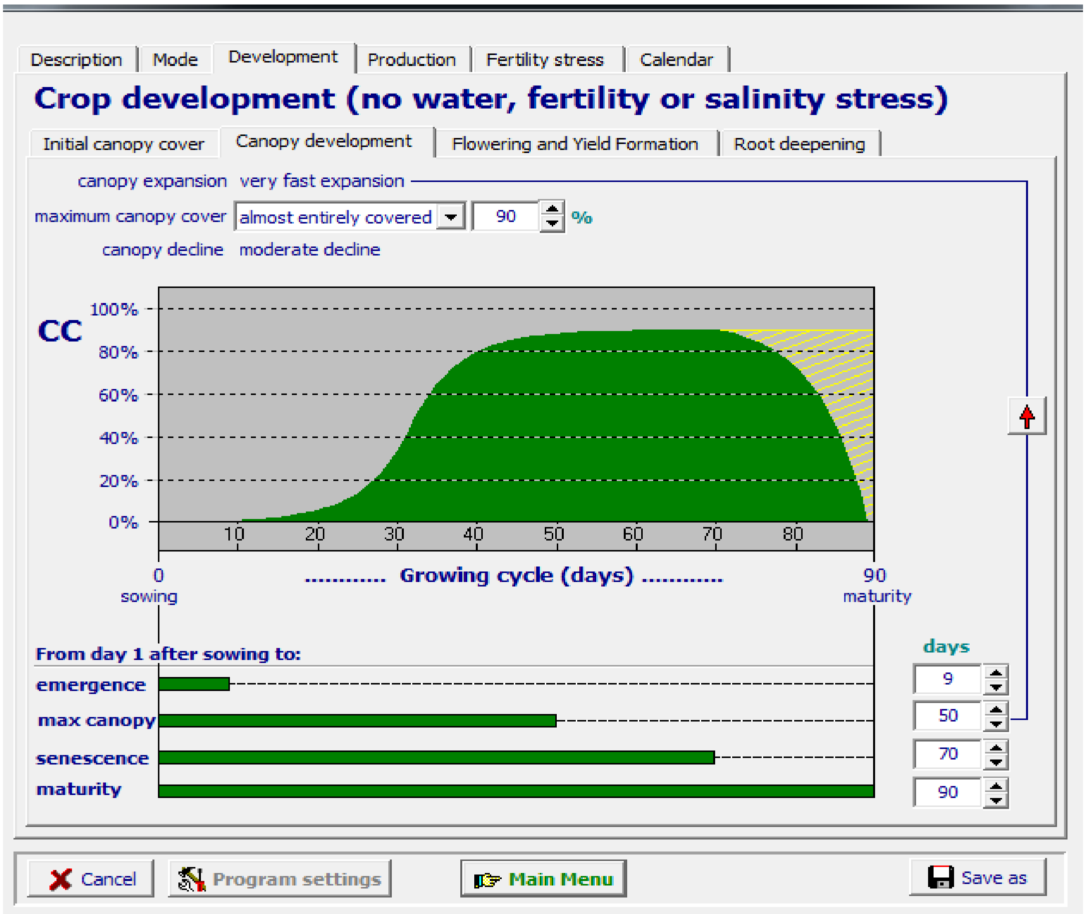

Figure 8:Crop development in acuacrop model