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CALIBRATION AND VALIDATION OF THE FAO AQUACROP MODEL FOR TOMATO (*Solanum lycopersicon*) IN THE COASTAL SAVANNAH AGRO-ECOLOGICAL ZONE OF GHANA

BY

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Thesis submitted to the Department of Agricultural Engineering of the School of Agriculture, University of Cape Coast, in partial fulfillment of the requirements for the award of Master of Philosophy in Agricultural Engineering Irrigation Technology

MAY 2015

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DECLARATION

Candidate’s Declaration

I hereby declare that this study is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere

Signature……………………………………………………Date……………

Name: Amos Twehway Sawmadal

Supervisors’ Declaration

Wehereby declare that the preparation of this study was supervised in accordance with the guidelines on thesis laid down by the University of Cape Coast.

Principal Supervisor’s

Signature…………………………….........Date…………………………..

Name: Rev. Prof. Dr. Joshua Danso Owusu-Sekyere

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Signature ...…………………………………………Date...........................

Name: Prof. Dr. Livingstone Kobina Sam-Amoah

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ABSTRACT

Two field experiments were conducted to compare the growth and yield of tomatoes using experimentation and FAO AquaCrop model at the University of Cape Coast Teaching and Research Farm in the Cape Coast Metropolitan Assembly of the Central Region of Ghana. The Randomized Complete Block Design was used with four (4) treatments and four(4) replications for the two experiments. The treatments used for both experiments were T_1 – Full irrigation (100 %), T_2 – 90 % irrigation, T_3 – 80 % irrigation, T_4 – 70 % irrigation. Data was collected on water requirement, plant height, leaf area, stem diameter, internode length,number of harvested fruits, fruitsdiameter, weight of harvested fruits and yield for both experiments after which the results were compared to that generated by AquaCrop model.

At 100 % water application (full irrigation), crop coefficient for tomato was determined to be 0.62 - 0.63, 1.54 - 1.61, 1.23 - 1.34 and 0.92 –0.93 for the initial, development, mid-season and the late season stages respectively. The total amount of water applied for the 116 days ranged between 307 mm and 359.89 mm. Twenty percent deficit (irrigation) had no significant reduction on the yield of tomatoes. T_4 had adverse effect on the plant and yield as indicated, which recorded the lowest yield of 3.11 t/ha in the first experiment and 2.10 t/ha in the second experiment. The model did not accurately simulate the yield of tomatoes under deficit irrigation. In the case of $T_{4,}$ however, the level of accuracy was high at 18.09 %. The model was able to simulate the seasonal ETc for T_2 at 9.88 % in Experiment 1 but not for the others.

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DEDICATION

To my mother, Martha Glaygbomar Boda and my parents, Mr and Mrs Arthur

D. K. Sawmadal

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I wish to express my profound thanks to the West Africa Agricultural Productivity Program (WAAPP)-Liberia, Ministry of Agriculture government of the Republic of Liberia who sponsored me in diverse ways. I am so grateful to Rev. Prof. J. D. Owusu-Sekyere and Prof. L. K. Sam-Amoah my principal and co-supervisors respectively for their useful suggestions and comments. My sincere gratitude goes to Mr. Joseph Konduah and Mr. Joseph Dadzie, both Technicians at the Technology Village, University of Cape Coast, where the research was conducted for their immense support during the collection of the data.

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TABLE OF CONTENTS

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Digitized by Sam Jonah Library

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©University of Cape Coast

Digitized by Sam Jonah Library

©University of Cape Coast

LIST OF TABLES

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LIST OF FIGURES

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LIST OF PLATES

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LIST OF ACRONYMS

ANOVA	-	Analysis of variance
cm	-	centimetre
cm^2	-	squared centimetre
CWR	-	Crop water requirement
d	-	deviation
DAT	-	days after transplanting
ETc	-	Specific Crop Evapotranspiration
ETo	-	Reference crop evapotranspiration
FAO	-	Food and Agriculture Organization of The United Nations
g	-	grammes
ha	-	hectares
T	-	Treatment
t	-	tonnes
Prob.	-	Probability
Sed	-	Standard error of the difference of means
Lsd	-	Least significant difference
Kc	-	Crop Coefficient
USDA	-	United States Department of Agriculture
CC	-	Green canopy cover [percent or fraction]
CCx	-	Maximum green canopy cover [percent orfraction]
E	-	Soil evaporation [mm per unit time]

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ECe - Electrical conductivity of the saturated soilpaste extract [dS/m]

FC - Field Capacity

Kc - Crop coefficient

Kc,Tr x - Crop transpiration coefficient for when the canopy fullycovers the ground (CC = 1) and stresses are absent

Ksat - Saturated hydraulic conductivity [mm per unit time]

PWP - Permanent wilting point

TAW - Total available water

Θ - Water content

Tn, - cold Minimum air temperature at upper threshold for coldstress affecting pollination [°C]

Tr - Crop transpiration [mm per unit time]

Trx - Maximum crop transpiration (for a well watered crop) [mmper unit time]

Tx, - heat Maximum air temperature at lower threshold for heatstress affecting pollination [°C]

$WP_{B/ET}$ - WP as the ratio of biomass to ET [kg/m^3]

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CHAPTER ONE

INTRODUCTION

Background of the study

Tomato, *Solanum lycopersicon*is a popular vegetable with high per capita consumption in Ghana as it is used in almost all Ghanaian homes. Tomato is the second most valuable vegetable crop next to potato (FAO, 2011).It is very nutritious and a major source of vitamins A, C and riboflavin as well as carbohydrate, protein, calcium and carotene in diets (Purseglove, 1979; Bull, 1989). The edible part of the tomato represents about 94 % of the total weight of the fruit (De Lannoy, 2001). A 100 g tomato contains 93.8 g water, 1.2 g protein, 4.8 g carbohydrate, 7 mg calcium, 0.6 mg iron, 0.5 mg carotene, 0.06 mg thiamine, 0.04 mg riboflavin, 0.6 mg niacin and 23 mg vitamin C (De Lannoy, 2001).

Tomato production is a source of employment and income to both rural and urban dwellers. It contributes significantly to the economic growth of Ghana and is a source of foreign exchange. Tomato is used in a great variety of ways. It is used in soups and stews and also as sauces of various kinds, with a lot of juicy varieties preserved in sandwich or ketchup. It is a member of the family of Solanaceae. On the average, the fruit contains 8 % protein 34 % minerals (mainly K^+ Ca^+ and P) 48 % total soluble sugars, 9 % citric acid and 0.5 % vitamin (Grierson & Kader, 1986).

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Global population is increasing every year and is estimated to grow by 2.9 billion people over the next 50 years, of which 95 % will be in developing countries. This growth rate is high especially in rural communities where rain-fed agriculture forms the dominant basis for livelihood security. It is clear that the large dependence on rain-fed agriculture as a livelihood base will continue in the foreseeable future. The key answer to the threat seems to rest shoulder-high on the need to increase crop production to meet overwhelming demands. The indications are that the rainfall pattern is deteriorating over time leading to greater food insecurity. Even in areas where total seasonal rainfall is adequate on average, it may be poorly distributed during the year and variable from year to year (GIDA & JICA, 2004).

Research indicates that in developing countries, an estimated 95 % of agriculture is mainly rainfed, resulting in high yield losses every year, very low quality products being produced, high cost of production, etc. It might also result in crop failure when the rains fail since water is a major component for crop growth and development (FAO, 1999).

Currently the outlook for food security in many developing nations including Ghana is a cause for serious concern. Problem of food security is exacerbated by the rapid growth of population and the attendant increase in demand for food. Provided it is economically viable, increase in irrigation could become a key source of agricultural growth as well as poverty alleviation for farmers, who otherwise would unduly depend on low and erratic rainfall. This would help to increase the productivity of the land, although to a limited extent, the need for extending the cultivated area for feeding the rapidly growing population (GIDA & JICA, 2004)

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Statement of the problem

The use of tomato has continued to increase as a major food for human consumption and as an ingredient in feed for livestock production. Furthermore, the growing demand is putting tremendous pressure on tomato production, hence, competition for available water. At the same time, it increases the price of tomato which in turn has raised its price in general.

The demand for water has always been the main factor limiting crop production in much of the world where rainfall is not ample. The complexity of crop response to water deficits led to the use of empirical production functions as the most practical option to assess crop yield response to water. In the midst of empirical approaches, Doorenbos and Kassam (1979) presented an important equation to determine the yield response of field, vegetable and tree crops, to water as $\left(\frac{\mathrm{Y_X - Y_a}}{\mathrm{Y_X}}\right) = Ky\left(\frac{\mathrm{ET_X - ET_a}}{\mathrm{ET_X}}\right)$……………………….. **(1.1)**

Where, Y_x and Y_a are the maximum and actual yield, ET_x and ET_a are the maximum and actual evapotranspiration, k_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

Precise and accurate crop development models are important tools in evaluating the effects of water deficits on crop yield or productivity. FAO AquaCrop model predicts crop productivity, water requirement, and water use efficiency (WUE) under water-limiting conditions. Moreover, the ease of use of the AquaCrop model, the low requirement of input parameters, and its sufficient degree of simulation accuracy makes it a valuable tool for estimating crop productivity under rainfed conditions, supplementary and deficit irrigation, and on-farm water management strategies for improving the efficiency of water use in agriculture. For instance, models tested on maize

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include CERES - Maize model (Jones, Kiniry & Dyke,1986), Muchow - Sinclair-Bennett (MSB) model (Muchow & Carberry, 1990), the EPIC phase model (Cavero, Farré, Debaeke & Faci, 2000), Crop Syst (Stöckle, Donatelli & Nelson, 2003) and the Hybrid –maize model (Yang *et al*., 2004).

Majority of these models, however, are quite sophisticated, demanding advanced skills for their calibration and operation, and require a large number of parameters, some of which are also cultivar - specific and are not easily measured or accessible to end users. Hence the newly developed AquaCrop model (Raes, Steduto, Hsiao & Fereres2009; Steduto, Hsiao, Raes & Fereres, 2009) which is user-friendly and practitioner-oriented type of model maintains the most advantageous balance between accuracy, robustness and simplicity and requires a relatively small number of parameters will serve as an effective model to evaluate the growth and yield of tomatoes in Ghana. With the recent increase in the demand for tomatoes in the world, there was a need to investigate the response of tomatoes to water deficits and improve the efficiency of growth and yield in tomato production in Ghana.

Objectives of the Study

Main objective

The study aimed at calibrating and validating the AquaCrop Model for the tomato crop.

Specific objectives

- To investigate the growth and yield of tomato under different water deficits.
- To simulate the growth and yield of tomato under different levels of water deficits using AquaCrop.

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- To compare the growth and yield of tomato simulated by AquaCrop with those attained through experiments under four different irrigation regimes.

Justification

The tomato sector in Ghana has failed to reach its potential, in terms of attaining yields comparable to other countries, in terms of the ability to sustain processing plants, and in terms of improving the livelihoods of those households involved in tomato production and the tomato commodity chain. Average yields remain low, typically under 10 t/ha. Because of production seasonality, high perishability, poor market access, and competition from imports, some farmers are unable to sell their tomatoes, which are left to rot in their fields.

It necessitates the availability of an effective model that can easily evaluate the growth and yield of tomatoes so as to raise the level of production and yield. The model can be used as a planning tool or assisting in making management decisions, whether strategic, tactical or operational. The AquaCrop model represents an effort to incorporate current knowledge of crop physiological responses into a tool that can predict the attainable yield of a crop based on the water supply available. One important application of the AquaCrop would be to compare the attainable against actual yields in a field, farm, or a region, to identify the constraints limiting crop production and water productivity.

The particular features that distinguish AquaCrop from other crop models is its focus on water, the use of ground canopy cover instead of leaf

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area index, and the use of water productivity values normalised for atmospheric evaporative demand and of carbon dioxide concentration that confer on the model an extended extrapolation capacity to diverse locations and seasons, including future climate scenarios. Moreover, although the model is simple, it gives particular attention to the fundamental processes involved in crop productivity and in the responses to water, from a physiological and agronomic background perspective.

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CHAPTER TWO

LITERATURE REVIEW

AquaCrop Rationale

The tremendous complexity of crop responses to water deficits has led to the use of production functions as the most practical option to assess crop yield responses to water. Among the empirical functions approaches, Doorenbos and Kassam (1979) presented a highly significant source to determine the yield response to water of field, vegetable and tree crops, through the equation.

$$\left(\frac{\mathrm{Y_X - Y_a}}{\mathrm{Y_X}}\right) = Ky\left(\frac{\mathrm{ET_X - ET_a}}{\mathrm{ET_X}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(2.1)}$$

Where, Yx and Y are the maximum and actual yield, ETx and ET are the maximum and actual evapotranspiration, and ky is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

Scientific and experimental progresses in crop-water relations from 1979 to date, along with the strong demand for improving water productivity as one of the major features to cope with water scarcity, influenced FAO to revise its irrigation and drainage Paper 33. This was carried out through a consultative process with specialists from major scientific and academic institutions, and governmental organizations globally. The consultation led to a revision framework that treats separately field crops from tree crops. For the field crops, it was suggested to develop a model of proper structure and conceptualization that would evolve from Equation (2.1) and be designed for planning, management and scenario simulations. The result is the AquaCrop model which differs from most models for its balance between accuracy, simplicity and robustness. The conceptual framework, underlying principles, and distinctive components and features of AquaCrop are described by Steduto *et al*. (2009), while the structural detail sand algorithms are reported by Raes *et al*. (2009). Calibration and performance evaluation for several crops are presented by Farahani, Izzi, Steduto, and Oweis (2009); Garcia-Vila Fereres, Mateos, Orgaz and Steduto (2009); Geerts *et al.* (2009); Heng, Hsiao, Evett, Howel and Steduto (2009); Hsiao *et al.* (2009).

Model growth-engine

AquaCrop evolved from the previous Doorenbos and Kassam (1979) approach (Equation 2.1)by separating:

- The ET into soil evaporation (E) and crop transpiration (Tr) and
- The final yield (Y) into biomass (B) and harvest index (HI).

The separation of ET into E and Tr avoids the confounding effect of the non-productive consumptive use of water (E).This is important especially during incomplete ground cover. The separation of Y into Band HI allows the distinction of the basic functional relations between environment and B from those between environment and HI. These relations are in fact fundamentally different and their use avoids the confounding effects of water stress on B and on HI. The changes described led to the following equation at the core of the AquaCrop growth engine:

$B \quad = WP \quad \times \quad \epsilon Tr \ldots\ldots\ldots\ldots\ldots 2.2$

Where,

ϵ -Sumation

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Tr – the crop transpiration (in mm)

WP – water productivity parameter (kg of biomass per m^2 and per mm of cumulated water transpired over the time period in which the biomass is produced). Equation (2.2) has a fundamental implication for the robustness of the model due to the conservative behaviour of WP (Steduto, Hsiao & Fereres, 2007).

According to Steduto (2003) both equations (2.1 and 2.2) are different expressions of a water-driven growth-engine in terms of crop modelling design. AquaCrop is in the time scale used for each one.

AquaCrop has a structure that overarches the soil-plant-atmosphere continuum. It includes the soil, with its water balance; the plant, with its development, growth and yield processes; and the atmosphere, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration. Additionally, some management aspects are explicitly considered (e.g. irrigation, fertilization, etc.), as they affect the soil water balance, crop development and therefore final yield. Pests, diseases, and weeds are not considered.

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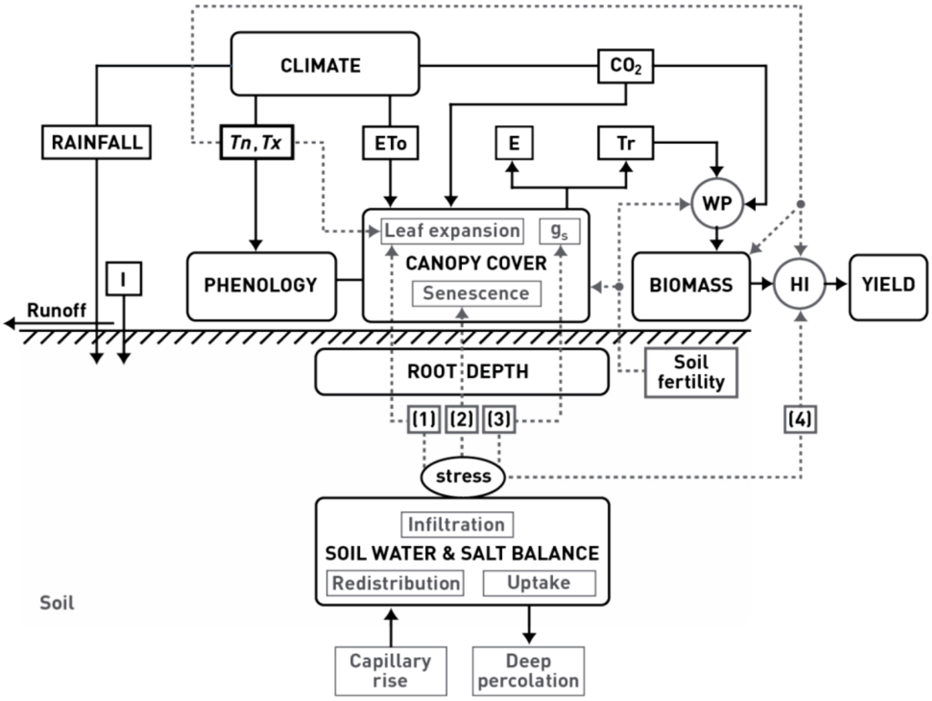

Fig-1: Flowchart of AquaCrop including the main components of soil-plant-atmosphere continuum (Raes *et al*., 2009; Steduto *et al*., 2009)

The atmosphere

The atmospheric environment of the crop is described in the climate component of AquaCrop and deals with key input meteorological variables. Five weather input variables are required to run AquaCrop: daily maximum and minimum air temperatures (T), daily rainfall, daily evaporative demand of the atmosphere expressed as reference evapotranspiration (ETo), and the mean annual carbon dioxide concentration in the bulk atmosphere. Reference evapotranspiration (ETo) is obtained following the procedures described in the FAO Irrigation and Drainage Paper 56 (Allen, Pereira, Raes & Smith, 1998). In situations where not all the required input variables for calculating ETo are available, Paper56 also describes the methods to derive them. AquaCrop does not include the routines for calculating ETo, but a separate software

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programme (ETo calculators) based on Paper 56 is provided to the user for such purpose. Temperature (in full), rainfall and ETo may be provided at different time scales, specifically daily, 10-day, and monthly records.

However, at run time, AquaCrop processes the 10-day and monthly records into daily values. This flexibility for different time scales of weather input variables is required to use AquaCrop in areas of limited weather records (Raes *et al*., 2009; Steduto *et al*., 2009). The temperature (T) plays a role in influencing the crop development (phenology); the rainfall and ETo are inputs for the water balance of the soil root zone; and the CO_2 concentration of the bulk atmosphere influences the crop growth rate and the water productivity.

The Crop

In AquaCrop, the crop system has five major components and associated dynamic responses: phenology, aerial canopy, rooting depth, biomass production and harvestable yield. The crop grows and develops over its cycle by expanding its canopy and deepening its rooting system while at the same time the main developmental stages are established. Crop responses to possible water stress, which can occur at any time during the crop cycle, occur through three major feedbacks, reduction of the canopy expansion rate (typically during initial growth), acceleration of senescence (typically during completed and late growth), and closure of stomata (typically during completed growth).

Water stress of particular relevance may also affect the water productivity parameter (WP) and the harvest index (HI). The canopy, thus, represents the source for actual transpiration that gets translated in a

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proportional amount of biomass produced through the water productivity parameter, WP (Equation 2.2). The harvestable portion of such biomass (yield) is then determined via the harvest index (H_1).

$Y = B.H_1$ …………………………………………….... (2.3)

Even though AquaCrop uses a HI parameter, it does not calculate the partitioning of biomass into various organs (e.g., leaves, roots, etc.), i.e. biomass production is decoupled from canopy expansion and root deepening. This choice avoids dealing with the complexity and uncertainties associated with the partitioning processes, which remain among the least understood and most difficult to model. The relationship between shoot and root is maintained through a functional balance between canopy development and root deepening.

The AquaCrop distinguishes four major crop types on the basis of their harvestable yields; fruit or grain producing crops, root and tuber producing crops, leafy vegetable producing crops and forage crops. Each of this crop type has its own corresponding developmental stages. The genetic variation among species and cultivars may be implemented in the model through the variation in timing and duration of the various developmental stages, as well as through the rate of canopy expansion, rate of root deepening, the water productivity parameter and other response factors to environmental conditions. The canopy is a crucial feature of AquaCrop through its expansion, ageing, conductance and senescence (Figure. 1), as it determines the amount of water transpired, which in turn determines the amount of biomass produced. The canopy expansion is expressed through the fraction of green canopy ground-cover (CC). For non-stressed conditions, the expansion from emergence to full

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canopy development follows the exponential growth during the first half of the full development and follows an exponential decay during the second half. After the full development, the canopy can have a variable duration period before entering the senescence phase.

Having canopy development expressed through CC and not via leaf area index (LAI) is one of the distinctive features of AquaCrop (Raes *et al.*, 2009; Steduto *et al.*, 2009). It introduces a significant simplification in the simulation, reducing the overall aboveground canopy expansion to a growth function and allowing the user to enter actual values of CC even estimated by eye. Moreover, CC may be easily obtained also from remote sensing. Beyond CC, where differences due to canopy architecture and height may influence other processes (e.g. aerodynamic conductance in determining evapotranspiration), corrections are introduced implicitly linked to the type of crop (e.g. maize will have a higher aerodynamic conductance than soybean due to expected difference in crop height).

In AquaCrop the root system is simulated through its effective rooting depth and its water extraction pattern. The effective rooting depth (Z) is defined as the soil depth where most of the root water uptake is taking place, even though some crops may have a few roots beyond that depth (Raes *et al.*, 2009; Steduto *et al.*, 2009). As previously indicated, the growth engine of AquaCrop is water driven (Equation 2.2). The model does not simulate lower hierarchical processes expressing the intermediary steps involved in the accumulation of biomass. The underlying processes are “summarized” and synthetically incorporated into one single coefficient defined biomass water productivity (WP). The basis for using Equation 2.2 as the core of the model

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growth engine lies on the conservative behaviour of water productivity, WP (Steduto & Albrizion, 2005; Steduto *et al.*, 2007).

The WP parameter of AquaCrop is normalized for ETo and the carbon dioxide (CO_2) concentration of the bulk atmosphere, it may vary moderately in response to the fertility regime, and remains constant under water deficits except when severe water stress is reached. The normalization of WP for climate makes the model applicable to diverse locations and seasons, including future climate scenarios. Once the biomass (B) is obtained (Equation 2.2), the crop yield is derived by multiplying B by the harvest index, HI (Equation 2.3). Starting from flowering, HI is simulated after a lag phase, by a linear increase with time for a given period during yield formation that depends on the crop species and cultivar. HI can be adjusted for water deficits depending on the timing and extent of the water stress during the crop cycle (Raes *et al.*, 2009; Steduto *et al.*, 2009).

The Soil

The soil component of AquaCrop is configured as a dispersed system of a variable depth allowing up to five horizons of different texture composition along the profile. As default, the model includes all the classical textural classes present in the USDA triangle but the user can input its own specific value. For each texture class, the model associates a few hydraulic characteristics which can be estimated from soil texture through pedotransfer functions. The hydraulic characteristics include the hydraulic conductivity at saturation and the volumetric water content at saturation, field capacity and wilting point (Raes *et al.*, 2009; Steduto *et al.*, 2009).

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As for the soil profile explored by the root system, the model performs a water balance that includes the processes of runoff (through the curve number), infiltration, redistribution or internal drainage, deep percolation, capillary rise, uptake, evaporation and transpiration. A daily step soil water balance keeps track of the incoming and outgoing water fluxes at the boundaries of the root zone and of the stored soil water retained in the root zone. A distinctive feature of the water balance in AquaCrop is the separation of soil evaporation (E) from crop transpiration (Tr) based on a modification of the Ritchie's approach (Ritchie, 1972). In the simulation of E, AquaCrop includes the effects of mulches, withered canopy cover, partial wetting by localized irrigation, and the shading of the ground by the crop canopy.

The Field Management

The field management considers options related to the fertility level or regime to be adopted during the crop simulation, and to field-surface practices such as mulching to reduce soil evaporation, or the use of soil bunds to control surface run-off and infiltration. Four fertility levels are considered: non-limiting, near-optimal, medium and poor fertility. These levels influence the water productivity (WP) parameter, the canopy growth development and its maximum canopy cover and the rate of decline in green canopy during senescence. Thus, AquaCrop does not compute nutrient balances, but offers the user some options to incorporate the anticipated fertility regime into the overall yield response (Raes *et al.*, 2009; Steduto *et al.*, 2009).

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The Irrigation Management

The water management considers options related to rainfed-agriculture (no irrigation), and irrigation where, after selecting the method (sprinkler, drip, or surface, either by furrow or flood irrigation), the user can define its own schedule on the basis of depth or timing criteria, or let the model to automatically generate the scheduling on the basis of fixed interval, fixed depth, or fixed percentage of soil water content criteria. The irrigation option is particularly suited for simulating the crop response under supplemental or deficit irrigation. (Raes *et al.*, 2009; Steduto *et al.*, 2009).

The Uses of the AquaCrop Model

The model can be used as a planning tool or assist in making management decisions, whether strategic, tactical or operational. The AquaCrop model represents an effort to incorporate current knowledge of crop physiological responses into a tool that can predict the attainable yield of a crop based on the water supply available. One important application of AquaCrop would be to compare the attainable against actual yields in a field, farm, or a region and to identify the constraints limiting crop production and water productivity. It can also be very useful for scenario simulations and for planning purposes for use by economists, water administrators and managers and invariably will help with land use capabilities of a country. It is suited for perspective studies such as those under future climate change scenarios. Overall, it is particularly suited to develop agricultural water management strategies for a variety of objectives and applications.

The particular features that distinguish AquaCrop from other crop models is its focus on water, the use of ground canopy cover instead of leaf

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area index, and the use of water productivity values normalised for atmospheric evaporation demand and of carbon dioxide concentration that confer on the model an extended extrapolation capacity to diverse locations and seasons, including future climate scenarios. Moreover, although the model is simple, it gives particular attention to the fundamental processes involved in crop productivity and in the responses to water, from a physiological and agronomic background perspective (Raes *et al*., 2009; Steduto *et al*., 2009).

Tomato

Origin and Distribution

Tomato (*Solanum lycopersicon*) originated from Central and South America. The tomato plant belongs to the family, Solanaceae and the genus-*Lycopersicon*. It is thought that the Portuguese introduced the crop into West Africa in the 16th and 17th centuries and it has since become the most popular vegetable crop (Norman, 1992). The crop is now widely grown throughout most tropical areas such as Ghana, Senegal and Nigeria.

Botany

The tomato plant is a perennial which is usually grown as an annual. It is prostrate in growth. Some cultivars, however, grow erect. The crop can have a very extensive root system. However, the primary root is usually damaged during transplanting. A dense lateral root system therefore develops. Most of the root system is located in the first 0.3 m of the soil. The crops have different types of habits of growth, namely, determinate and indeterminate (Norman, 1992).

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In the determinate plant, the terminal bud ends up in a flower, and growth of axillary shoots is suppressed due to flowering. Hence such types are dwarf or short. There are only one or two leaves between flowering trusses. Such do not require staking and are used for extensive field growing. Examples are Dwarf Gem, Harvester, Piacenza and Ronita. The terminal bud in an indeterminate plant continues to be vegetative and does not end in a flower. This is usually referred to as the standard. Indeterminate types are tall and a blossom truss (cluster) is produced at every third internode, being separated by three leaves. Examples are Ponderosa, Local strains, Supersonic and Improved *Zuarungu*. The tomato plant gives a strong characteristic odour smell. Tindall (1983) found that tomato varies in height ranging between 0.7 m and 2.0 m tall. Different cultivars have different growth habits (Cobley & Steel, 1976). The stem is hairy and round when young and become angular when old (Thompson & Kelly, 1957).Branching at the base of the tomato stem is often monopodial becoming sympodial higher up (Kochhar, 1986). It has a strong tap root system which may be damaged at transplanting. When this happen, a dense system of fibrous and adventitious roots are formed (Purseglove, 1988).The plant bears numerous alternate leaves which are also hairy and variable in shape. It has yellow flowers which are borne terminally opposite and sometimes between leaves in clusters of 4 – 12 per cluster (Tindall & Kunkel 1988).

Climatic Requirement

The tomato crop is a warm season crop which responds to thermoperiodism but is neutral to the day length. Tomato plant thrives best at day temperature of 23.9 °C to 29.4 °C and night temperatures of 15.6 °C to

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21.1 °C. Production is limited by day temperatures higher than 35.6 °C. Tomato production is highly successful in the southern and northern Guinea Savanna and Sudan Savanna zones during the dry season (Harmattan) with irrigation because night temperatures drop to 15 °C or lower.

The red colour of tomatoes is caused by a red pigment called lycopene. Lycopene is formed between 20 °C and 29.4 °C; its development is hindered by a daily temperature above 31.7 °C. Sinnadurai and Amuti (1970) demonstrated that although tomato is day neutral with regard to flowering and fruiting, it is influenced by long days in regard to soluble solids.

Soil Requirement

Tomato can be grown on many kinds of soils but the crop prefers a rich, well-drained sandy loam soil into which well-decomposed compost or green manure has been incorporated. The crop is able to offset nematode attack if the soil has high organic matter content. Usually a soil free from root knot nematode and Fusarium and Bacterial Wilt is desirable. The crop is tolerant to rather high acidity, so liming is only recommended at soil pH of 5.0 or lower. Tomato, however, grows best in a pH range of 6 to 7 (Norman, 1992).

Water Requirement

Total water requirement (ETc) of a tomato crop grown in the field lasting for 90 to 120 days is 400 to 600 mm, depending on the climate (FAOSTAT, 2001). Water requirements related to reference crop evapotranspiration (ETo) in mm/period are given by the crop factor (Kc) for

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different crop development stages or during the initial stage 0.4 – 0.5 (10 to 15 days), the development stage 0.7 – 0.8 (20 to 30 days), mid-season stage 1.05 – 1.25 (30 to 40 days), the late-season stage 0.8 – 0.9 (30 to 40 days) and at harvest 0.6 – 0.65 (FAOSTAT, 2001).

For an average growing period of 130 days, the net total amount of applied irrigation water ranged from about 300 mm to 400 mm for good fruits in central Brazil (Silva & Maroucelli, 1996). Doorenbos and Pruitt (1979) reported that total water requirement for tomato crop included the pre-transplanting watering. Depending on the climatic demands, the total water may vary for different locations. Karim, Wierzba and Al-Alousi (1996) carried out a field experiment to determine the optimum soil moisture regimes and water requirement of receiving the maximum yield potential of tomato on a clayey terrace in Bangladesh. A maximum yield of 37.0 Mg/ha was obtained when allowing 3 % depletion on soil available water (SAW). The total water used and water use efficiency (WUE) were found to be 193.6 mm and 0.0001911 kg/ha/m^3 respectively. It was concluded that at soil moisture depletions exceeding 40 % SAW, a severe water stress was imposed on growing tomatoes, hence yield was significantly reduced.

Qasem and Judah (1985) found that the water applied and its uptake by plants is decreased with increasing soil moisture tension. Crop coefficients increased rapidly to reach a maximum at flowering, after that the crop coefficient declined. It was also observed that the greatest stress (50 centibars at a depth of 30 cm) did not adversely affect the crop since yields were not significantly reduced.

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Methods of irrigating tomato

The unavailability of adequate rainfall to compensate for evaporation losses by a crop necessitates the need for the application of irrigation if any good yield is to be expected by the farmer. Surface irrigation by furrow is still commonly practised. Pressurised irrigation methods (sprinkler, mini-sprinkler and drip irrigation) are now common in many main cropping countries. In recent years, experiments with deficit irrigation have been directed at these objectives, with either the deficit maintained at a selected level over a long time (often referred to as DI), or with the irrigation being deficit only at selected stages of the crop's life cycle, referred to as regulated deficit irrigation (RDI) (Battilani *et al*., 2008). In more arid areas pre plant irrigation is practised when past rainfall is insufficient to replenish the soil profile. Frequently, if soil is well charged initially, one to two irrigations over a 2-4 week period are used for stand establishment after transplant or seeding.

During canopy development and much of the flowering period, irrigation needs to be sufficient to ensure fast canopy growth and yet not so much as to cause excessive leaf growth and the associated dropping of flowers and young fruit. Soon after fruit colour change, irrigation should be reduced, but the start of irrigation cutback depends on the water remaining in the root zone of the soil, and the ET rate for that period. These are readily simulated by AquaCrop. Donan and Kreutzwiser (2000) also recommended the use of drip irrigation by stating that apart from water use efficiency, drip irrigation has the capacity to deliver liquid fertilizers which makes its use more economical. In the year 1972, Peacock and Rauschlolb (1977) compared drip, sprinkler and

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surface irrigation, and found that drip used less water while achieving good plant vigour, fruit production and quality.

Time of irrigating tomato

Grimes and Dickens (1977) stated that both early and late irrigation no matter the method chosen lowered the tomato yield. They further added that the period at the beginning of flowering is most sensitive to water stress and soil water depletion in the root zone during this period should not exceed 25 %. As a result, controlled and timely irrigation is essential for higher yields. Huguez and Philippe (1998) indicated that the amount of water to be applied to fully satisfy the crop water requirement is not based on only the function of the crop evapotranspiration losses. But also, the moisture retention capacity of the soil, soil porosity, infiltration capacity of the soil to yield up water to plant roots, and the capacity of the crops to take up the water will determine the amount of water to apply and even the next date of irrigation.

Water uptake by tomato

Tomato has a tap root which is broken at the time of transplanting and a profusely branched lateral root system subsequently develops. Root depth can extend up to 1m but under irrigation, roots are concentrated mainly in the upper 0.3 m soil depth (Norman, 1992). Vaux and Pruitt (1983) reported that as long as soil moisture is maintained throughout the growing season these roots will be able to uphold an adequate flow of water through the plants to the leaves to maintain growth. According to Vaux and Pruitt (1983), normally 100 % of the water uptake by tomato roots occurs in the first 0.5 to 1.0 m soil depth.

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Qasem and Judah(1985) found that the water applied and its uptake by the crop is decreased with increasing soil moisture tension. Crop coefficients increased rapidly to reach a maximum at flowering, after that they declined. It was also observed that the greatest stress (50 centibars at a depth of 0.3 m) did not adversely affect the crop since yields were not significantly reduced.

Processes of water loss from tomato plant

There are two main components of crop water loss process: the first one due to evaporation losses from soil and the crop, usually called evapotranspiration (ET), and the other that includes all the losses resulting from the distribution of water to the (vaporization) and removal from the evaporating surface (vapour removal). The driving force to remove water vapour from the evaporating surface is the difference between the water vapour pressure at the evaporating surface and that of the surrounding atmosphere. As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and might stop if the wet air is not transferred to the atmosphere.

Transpiration consists of vaporization of liquid water contained in plant tissues and the vapour removal to the atmosphere. Crops predominantly lose their water through the stomata. These are small openings on the plant leaf through which gases and water vapour pass. The water, together with some nutrients, is taken up by the roots and transported through the plant. The vaporization occurs within the leaf, namely in the intercellular spaces, and the exchange with the atmosphere is controlled by the stomata aperture. Nearly all water taken up is lost by transpiration and only a tiny fraction is used within the plant.

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According to Berrie and Berrie (1990) transpiration, like direct evaporation, depends on the energy supply, vapour pressure gradient and wind. However, radiation, air temperature, air humidity and wind terms should be considered when assessing transpiration. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate; and are also influenced by crop characteristics, environmental aspects and cultivation practices.

Effects of water on tomato growth and development

Yayock, Lombin, Owonobi and Onazi (1988) reported that water required by tomato for growth and development by acting as a solvent for nutrient transport from the soils, into the roots and onto the sites of food synthesis in the plant. It is also a constituent of protoplasm of the plant systems and essential for movement of plant assimilates from their production sites. Water is also required for maintenance of turgidity which is important in the opening mechanism of the stomata of plant leaves.

Alvino *et al.* (2007) wrote that it is also involved in increasing important processes, like photosynthesis and hydrolysis of starch to sugar, and a better balance of energy as well as acting as a medium for the regulation of temperature in plants. Excessive water during the flowering period may cause an increase of flower drop and reduce fruit set as well as delay ripening due to excessive vegetative. The yield formation is also very sensitive to water and any heterogeneous distribution of irrigation leads to fruit cracking. Highest demand for water is during flowering (Doorenbos & Pruitt, 1979). Chlorophyll obliteration is quickened by moisture stress (Alberte, Thornber & Fiscus, 1997). Falcetti, Stringari, Bogoni and Sciencza (1995) reported that severe and

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prolonged water stress may result in poor flower-cluster development and reduced pistil and pollen viability and subsequent fruit set. Furthermore, fruit set, severe water stress may cause flower abortion and cluster abscission, probably associated with hormone changes (During, 1986).

Uncorrected water stress during tomato stage of development may result in reduced canopy development and, also consequently, inadequate leaf area to sufficiently support fruit development and maturation. Instantaneously after fruit set, water stress may also limit fruit cell and moreover enlargement, resulting in small fruit and low yield. According to Pill and Lambeth (1980), a reduction in fruit number and mean total fruit weight are due to water stress. Nadal and Arola (1995) reported insufficient canopy development during this time will limit the photosynthetic capacity of the leaves and furthermore may restrict fruit development and quantity.

Response of tomato to stresses

The vegetative or reproductive ratio of tomato depends on plant-water status, but to a less degree. As already mentioned, high water status stimulates vegetative growth and commonly leads to the dropping of flowers and newly set fruit early in the season. On the other hand, mild to moderate water stress early in the season, if lasting for many days, can result in a markedly smaller canopy, and hence, less biomass production resulting from reduced radiation capture. Photosynthesis per unit leaf area is moderately resistant to water stress. Thus, the crop is fairly resistant to moderate drought once good canopy cover is achieved. Over-irrigation cause’s excessive leaf growth and plants high in vegetative vigour tend to produce low quality fruit because of reduced

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content of soluble solids. Moreover, excess water near harvest can cause nitrate accumulation in the fruit.

For some cultivars, wide fluctuations in soil moisture levels during fruit maturation can cause fruit cracking, blotchy ripening, blossom-end rot and varied size and shape. The crop is sensitive to frost. Low temperatures, if persisting for more than a few days, reduces leaf and truss initiation rates, and the plant produces thicker leaves, so they intercept less light; fruit set is reduced as a result of poor pollination. Dropping of flowers and young fruit under cold temperatures has already been noted.

Exposure to high temperatures causes a reduction in the number of pollen grains and impairs their viability and germinability, markedly affecting fruit set. High day and night temperatures cause hastening in flowering and marked reduction in number of trusses, flowers per truss and an increase of blossom drop and fruit abortion. High humidity, combined with temperatures above about 27 °C, also affects pollen germination, resulting in reduced yield. Tomato, as with many other crops, can compensate for day and night temperatures, mitigating the stresses already suffered. Nevertheless, differences between day and night temperatures of less than about 12 °C adversely affect yield of many cultivars (Gent & Ma, 1998). Processing tomato cultivars bred for semi-arid warm climates, however, do not respond negatively to maximum temperatures in the range of 35-40 ºC.As is true for other crops, mineral nutrient requirement is high for high production.

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Irrigation management for tomato

It is essential to establish a clear set of goals and to determine where water may have an impact on the crop, when considering irrigation management as a tool. Possible objectives may include controlling plant vigour, preventing infrequent water deficit stress, the effort to manage fruit development or attempting to alter fruit quality by influencing soluble solids, pH, etc. The irrigation system must match soil type, depth, water holding capacity, infiltration rate and the effective rooting zone of the roots. Careful selection of the most appropriate irrigation system for tomato production is also of a high significant priority. This latter point may require detailed knowledge of the cultivar (Michael, 1978). The available water and its cost also determine or demand careful consideration. Tomato planted on hillside is not amenable to furrow or flood irrigation practices. Soil with low infiltration rates and significant slope also present runoff problems for overhead sprinkler systems with high delivery rates.

According to Michael (1978), drip irrigation can accommodate all of these situations, but has higher initial asset investment costs and generally require a higher level of management. In addition, factors that warrant consideration are water quality, filtration requirements, system automation, and local availability of equipment, supplies and support. Irrigation management increased plant height, height of canopy, fresh and dry weights of shoots and roots, stem diameters, number of leaves, fruit and whole plant dry weights.

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Benefits of irrigation to tomato

Irrigation of tomatoes can result in higher and more consistent yields, better quality, larger fruit, less blossom-end rot and less cracking. Research on processing tomatoes in Ontario has shown yield increases of up to 81 % on a range of soil types with the use of properly scheduled irrigation. Tomato yields increased with irrigation in both wet and dry years and on sandy soils as well as on clay loams. On light soils, with their low water-holding capacity, the tomato crop can be very responsive to irrigation, but correct scheduling will provide maximum benefit. Proper scheduling is critical when irrigating tomatoes on heavier soils. Research into deficit irrigation and early irrigation cut-off dates may result in the development of strategies to maximize fruit solids and water use efficiency under irrigated systems on both heavy and light soils. The maximum benefit from irrigation is achieved when the proper amount of water is applied at the right time, minimizing moisture stress while avoiding overwatering (LeBoeuf, Shortt, Tan & Verhallen, 2008).

Furthermore, irrigation is required when rainfall is insufficient, to compensate for the water lost through evapotranspiration. In addition, irrigation is done with the main aim of supplying water in the right quantity and time to a crop. Also, irrigation helps to solve the problem of plant water losses linked to the failure of rainfall to fully satisfy the water needs for tomato production all year round. Irrigation acts primarily as a crop indemnity against short duration drought. Irrigation is also known to delay and elongate growth stages especially the vegetative growth stage and which is capable of delaying bud formation in orchards (Michael, 1978). Uniform supply of moisture throughout the growing season promotes the plant leaves growth and

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also reduces scorching of plants by the sunlight (Pill & Lambeth, 1980). Moreover irrigation is also known to delay and elongate the vegetative growth stage, which is an advantage to the vegetable farmer interested in the vegetative fraction of the crop. Satch, Smith and Fork (1983) reported that irrigation can also be used as a mechanism to dilute the concentration of soluble salts that cause salinity problems within the soil.

Harvesting and Yield

Tomato fruit is tender and highly perishable; however, the stage of maturity at which tomatoes are harvested depends upon the purpose for which they are grown and the distance they are to be transported (Soitout, 1969). Although several stages of maturity are known for tomato harvesting, mature green, pink and red ripe are recognized. Fruits for processing are harvested when red in colour while those for immediate consumption are orange to red (Blay, 1978).

Harvesting of tomatoes in general starts 7 – 8 weeks after transplanting and they remain in crop for four to five weeks. The harvest period is generally longer in the northern savanna zones (6 – 9 months) than in the southern growing areas (3 – 4 months). Great care is needed in harvesting (which should be done daily) and also generally tomatoes should be handled with great care to avoid bruises.

Yield of tomato depends upon several factors including the cultivar planted, spacing and method of growing. Furthermore, it depends on whether the plants are pruned, staked, date of planting vegetational zone, amount of organic matter in soil and so forth.

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In general, the average yield on growers' farms is very low ranging from 7.5 to 15 t/ha. However, with improved horticultural practices including the use of improved introduced cultivars, yields ranging from 17.5 t/ha to 80 t/ha have been reported, depending on the zones, areas, seasons, temperatures and also adequate irrigation facilities (Soitout, 1969; Norman, 1974; Uzo, 1976; Adelana, 1977; Quinn, 1980).

Quality of irrigation water

Irrigated agriculture is dependent on an adequate water supply of usable quality. The water quality used for irrigation is essential for the yield and quantity of crops, maintenance of soil productivity and protection of the environment. For instance, the physical and mechanical properties of the soil, example soil structure (stability of aggregates) and permeability are very sensitive to the type of exchangeable ions present in irrigation waters. Gupta and Gupta (2000) reported that not all water is suitable for irrigation. The suitability of water for irrigation purposes depends upon the constituents of the soil to be irrigated. Particular water may be harmful for irrigation of a particular crop or soil, but the same water may be useful for irrigating another crop or soil. The following parameters are very important as they affect the quality of irrigation water:

i) pH;

ii) Total dissolved solids;

iii) Sediments;

iv) Bacterial contamination;

v) Proportion of sodium ions to other nutrients or minerals;

vi) Concentration of toxic elements; and

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vii) Concentration of bicarbonates.

Soil-Plant-Water relationships

The Soil-plant-water relationships contain and supplies water, oxygen, nutrients and mechanical support for plant growth and relate to the properties of the soil and plants that affect the movement, retention and use of water. Soil provides the room for water to be used by plants through the roots present in the same medium. Water, as such and also as a carrier of large amounts of nutrients, is required in a large measure for the successful growth of crops. The rate of entry of water into the soil and its retention, movement and availability to plant roots are all physical phenomena. Hence, it is important to know the physical properties of the soil in relation to water for efficient management of irrigated agriculture (Michael, 1978). Also the soil functions as a storehouse for plant nutrients, as habitat for soil organisms and plant roots and as a reservoir for water to meet the evapotranspiration demands of plants.

Soil physical properties influencing irrigation

The soil consists of mineral and organic materials that cover much of the earth’s surface. It contains living matter, air and water and can support vegetation. Moreover, the soil is classified into a three-phase system comprising the solid made up of minerals, organic matter and various chemical compounds, the liquid phase called the soil moisture and the gaseous phase described as the soil air. The components of the soil phase give rise to pore spaces of different geometrical components. These pore spaces are filled with water and air of varying proportions. The presence of the solid particles, liquid (soil solution) and gas (soil air) constitutes a complex polyphasic

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system. Soil physical properties have a significant influence on crop plant growth and development. Soil texture and structure are the most important of these properties. Soil texture is most important in the areas of water holding, nutrient supply and on ease of tillage. Soil structure has the greatest influence in the areas of soil aeration, water infiltration and soil temperature.

Evapotranspiration (ET) and Consumptive use (CU)

The process of combined "loss" of water vapour from within the leaves of plants ("transpiration") and evaporation of liquid water from water surfaces, bare soil and vegetative surfaces is called evapotranspiration. The most important atmospheric factors that affect transpiration are solar radiation, the humidity of the air surrounding the plant, temperature, and humidity of the air carried to the plant by wind and the net radiation availed to the plant. Also increasing humidity of the air surrounding the leaf, other things being constant, will decrease the vapour pressure difference between the leaf and the surrounding air and reduced rate of transpiration will result. As wind sweeps away any layer of water vapour accumulated around the leaf it either increases or decreases the rate of transpiration.

Radiation influences the rate of evapotranspiration in two different ways. Firstly, radiation raises leaf temperatures above that of its surrounding air. Secondly, the presence of light (shortwave radiation) activates the opening or closing of stomata. Evaporation (from leaf or vegetative surfaces, soil and water surfaces) and transpiration (from plants) occur simultaneously and there is no easy way of distinguishing between the two processes. Hence, the term evapotranspiration (ET). Evaporation is prominent during the juvenile stage of growth (when the crop is small, water is predominantely lost by soil

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evaporation, at sowing nearly 100 % of ET comes from evaporation) whereas transpiration takes over as the plant grows (once the crop is well developed and completely covers the soil, it becomes the main process, while at full crop cover more than 90 % of ET comes from transpiration) (Sam-Amoah, 1996).

Consumptive use (CU) includes the use of water in all of the plant's processes (rather than just transpiration) as well as the unavoidable evaporation of soil moisture, snow and intercepted precipitation associated with vegetal growth. Thus, CU exceeds ET by amount of water used for absorption, photosynthesis, structural support and development. Since this variation is usually less than 1 % of ET and CU are normally assumed to be equal (Sam-Amoah, 1996).

Determining evapotranspiration

Crop ET is determined by accurate direct measurement or calculation from climatic data and can also be determined by measuring the various components of the soil water balance. Moreover, direct measurement techniques involve separating a portion of the crop from its surroundings and determining ET by measurement. Many theoretical and empirical or semi-empirical equations have been developed for assessing crop or reference crop evapotranspiration from meteorological data (FAO, 1990).

Estimating ET from climatological data

Due to the difficulty of obtaining accurate direct measurement of pan evaporation under field conditions, ET is often predicted on the basis of climatological data. The approaches followed are to relate the magnitude and variation of ET to one or more climatic factors (temperature, day length,

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humidity, wind sunshine, etc.). Broadly, these approaches fall into two classes: purely empirical attempts to correlate ET with one or more climatic factors, or the application of a more theoretical approach. Most prediction formulae use a differentiation between climate and crop. Often such formulae have to be used under climatic and agronomic conditions different from those for which they were originally developed. The more commonly used formulae in estimating ET are the Blaney-Criddle method and the Penman-Monteith method.

Direct measurement of ET/CU

Various methods have been used to determine the quantity of water consumed by agricultural crops and natural vegetation. Regardless of the method, the problems encountered are numerous. The source of water used by plant life, whether from precipitation alone, irrigation plus rainfall or ground water plus precipitation is a factor in selecting a method. Principal methods are tank and lysimeter experiments, field experimental plots, soil moisture studies, integration, and inflow-outflow for large areas. As for lysimeter experiments, crops are often grown in buried soil-filled tanks called lysimeters. They differ in the way in which change in soil moisture within a control volume throughout the time interval being considered (ΔS) is determined. Firstly, lysimeters can be grouped into three categories:

- non-weighing type,
- non-weighing percolation type and
- weighing type.

Weighing lysimeters which provide the most accurate data for short time periods are constructed so that ΔS is determined by weighing. Various techniques for measuring or inferring changes in soil are used to determine ΔS in non-weighing lysimeters.

Also weighing lysimeters have a second tank that retains surrounding soil so that the inside container is free for weighing. In addition they usually have a means for removing and measuring deep percolation and leaching requirements. Non-weighing lysimeters, constant water-table type for use where a high water-table normally exists, may or may not have this capacity. Reliability of ET data collected with lysimeters depends on how well conditions within the lysimeters (i.e. soil structure and density, drainage characteristics, temperature and density, height, etc. of the crop) match conditions surrounding the lysimeters. Non-weighing percolation lysimeters are often used in areas of high precipitation. The lysimeters must be large enough to minimize boundary effects and to avoid restricting root growth. Owing to high installation cost and the immobility of lysimeters, their use as routine field instruments is excluded. They are used primarily as research tools for checking the accuracy of methods being used to determine ET.

Crop Water Needs/Crop Evapotranspiration (ETc)

Crops need water right from the time of sowing continuously. The rate of water use is not, however, the same for all the crops. Crop water requirement is the depth or total water (mm) needed to meet the water loss through ET of a crop, being disease-free, crop growing in a large field under non-restricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment (Doorenbos & Pruitt, 1979). The concept accommodates all processes affecting the water use

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by a crop but precludes the influences of local advection, water stress, poor soil and poor fertility management, or/and unsuitable farming conditions.

When irrigation was practiced for subsistence purposes the concept of crop water requirement did not exist but surely developed as evidence began to accumulate on the dependency of yields on water applications. Crop water need mainly depends on:

- The climate; crop grown in a sunny and hot climate needs per day more water than the same crop grown in a cloudy and cooler climate,
- The crop type; crops like maize or sugarcane need more water than crops like bean and tomato,
- The growth stage of the crop; fully grown crops need more water than crops that had just been planted.

The initial growth stage of the crop growth or under bare soil conditions, loss from a field is mostly through evaporation and it decreases to give way to transpiration, but once the crop is fully grown and completely covers the ground or the surface of the soil, transpiration becomes the dominant process (Allen *et al.*, 1998). The extent of evaporation gives an indication on how much water has been lost and thus needs to be added to compensate or replenish for the loss.

Reference Crop Evapotranspiration (ETo)

The reference crop evapotranspiration (ETo) is defined as the rate of evapotranspiration from a large area or field, covered by green grass, which grows actively, completely shades the ground and that which is not short of water (Allen *et al.*, 1998). In addition, the reference crop evapotranspiration (ETo), is a climate parameter expressing the evaporative power or influence of

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the atmosphere. Allen *et al.* (1998) reported that the reference surface is a hypothetical grass reference crop with specific characteristics that provide a reference to which ET from other surfaces can be related. This is needed to calculate the specific crop evapotranspiration (ETc), that is, an evapotranspiring surface not short of water, being disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. ETo is expressed in mm/day and does not consider crop and soil factors.

Crop Coefficient (Kc)

Crop coefficient (Kc), relates the actual rate at which the crop uses water (ETc) to ETo during its entire growth stages. The coefficient (Kc) for a crop is determined experimentally and reflects the physiology of the crop and the degree of crop cover. Tomato has four growth stages, that is: the initial stage which is the period from sowing or transplanting until the crop covers about 10 % of the ground; the crop development stage which starts at the end of the initial stage and lasts until the crop full ground cover has been reached (ground cover 70 – 80 %); the mid-season stage which starts at the end of the crop development stage and lasts until maturity stage. This includes flowering and fruit-setting; the late season stage which starts at the end of the mid-season stage and lasts until the last harvest day. Kc represents the fraction of the potential ET used by the crop and usually varies according to growth stages.

The Kcs are low in the beginning of the season due to small leaf area and hence low water use or apply, and advance as the canopy reaches full development. Computation of the crop factor, Kc, depends on factors such as

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crop type, the climatic conditions of the environment and the growth stages of the crop. Several Kc values for tomato at different growth stages have been estimated by researchers in some agro-climatic regions. Kc values for tomato at various growth stages are as follows: initial stage = 0.45 – 0.5, crop development stage = 0.7 – 0.75, mid-season stage = 1.15, and late season stage = 0.7 – 0.9 (FAO, 1999). In addition, Doorenbos and Kassam (1979); Doorenbos and Pruitt (1977); Wright (1981, 1982) through their own crop factor estimations for some crops gave Kcs for tomato at various growth stages as already listed. It implies that different crops at different growth stages have different Kc values. Figure 2 is a Kc graph representing the various stages of a crop's growth (FAO, 1999).

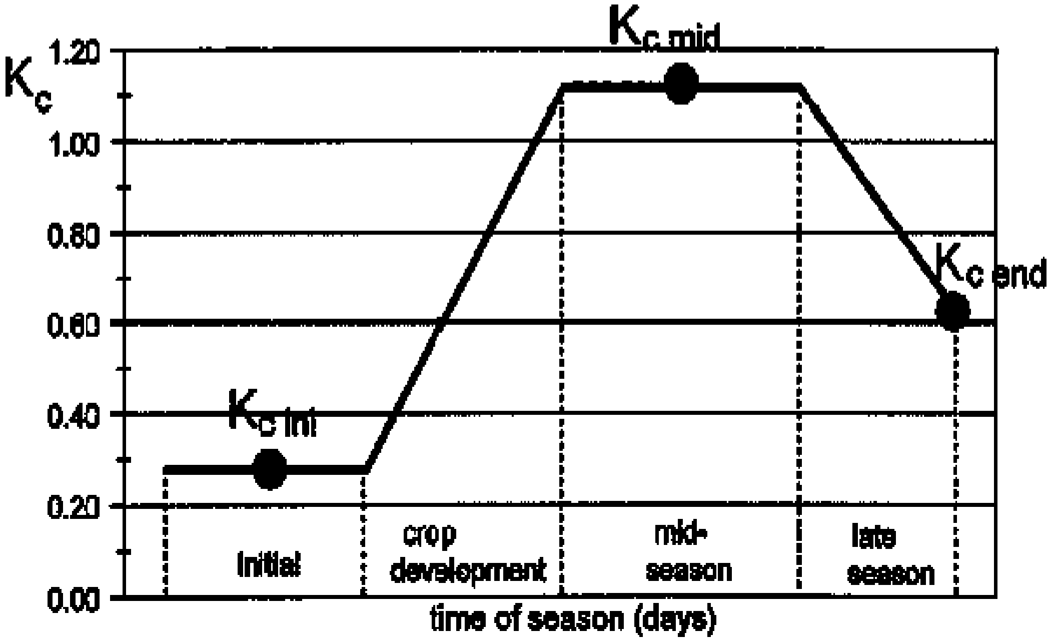

Fig 2: Kc graph representing the various stages of crop growth (FAO, 1999)

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Pan evaporation

The evaporation rate from pans filled with water is easily obtained. In the absence of rain, the amount of water evaporated during a period mm/day(s) corresponds with the decrease in water depth in that period. Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from an open water surface. Although the pan responds in a similar fashion to the same climatic factors affecting crop transpiration, several factors produce significant differences in loss of water from a water surface and from a cropped surface. Reflection of solar radiation from water in the shallow pan might be different from the assumed 23 % for the grass reference surface. Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the daytime.

There are also differences in turbulence, temperature and humidity of the air immediately above the respective surfaces. Heat transfer through the sides of the pan occurs and affects the energy balance. Notwithstanding the difference between pan-evaporation and the ET of cropped surfaces, the use of pans to predict ETo for periods of 10 days or longer may be warranted. The pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient (Allen *et al.*, 1998).

Pan coefficient (Kpan)

FAO (1977), when using the evaporation pan (Epan) to estimate or calculate the ETo, a comparison is made between both the evaporation from the water surface in the pan and evapotranspiration of the standard grass as the water in the pan and the grass do not reach in exactly or closely the same way

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to climate. Hence a special coefficient is used (Kpan) to relate one to the other. The pan coefficient, Kpan, depends on the following factors namely:

1. The type of pan used
2. The pan environment: if the pan is placed in a fallow or uncultivated or cropped area
3. The climate: the humidity and wind speed.

As for the Class A evaporation pan, the Kpan varies between 0.35 and 0.85. The Kpan is high if:

1. The pan is placed fallow or uncultivated area
2. The humidity is high and
3. The wind speed is low.

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CHAPTER THREE

WATER REQUIREMENT, DEFICIT IRRIGATION AND CROP COEFFICIENT OF TOMATO (*Solanum lycopersicon*) USING IRRIGATION INTERVAL OF TWO (2) DAYS

Introduction

Tomato, *Solanum lycopersicon*is a popular vegetable with high per capita consumption in Ghana as it is used in almost all Ghanaian homes. Tomato is the second most valuable vegetable crop next to potato (FAO, 2011). Tomato products make a significant contribution to human nutrition owing to the concentration and availability of several nutrients it contains and to their wide spread consumption. Water deficits and insufficient water are the main limiting factors affecting worldwide crop production (Nuruddin, 2001).

The complexity in the demand for water, changing climatic conditions and the need to overcome the challenge of food security of the ever growing global population are causing a tremendous problem in agriculture, particularly, in our part of the world. Research indicates that about 800 million people, mostly in Africa, sleep daily without food and fibre (FAO, 2003). The key solution is simply to increase crop production to meet the frightening demands. The indications are that the rainfall pattern is deteriorating, over time leading to food insecurity. Even in regions where total seasonal rainfall is sufficient on average, it may be inadequately distributed during the year and variable from time to time (GIDA & JICA, 2004).

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Water stress in tomato leads to the obliteration of plant organs sensitive to moisture stress. On the other hand, mild to moderate water stress early in the season, if lasting for many days, can result in a markedly smaller canopy, and hence, less biomass production resulting from reduced radiation capture. Photosynthesis per unit leaf area is moderately resistant to water stress. These organs include flowers, apical meristems and sprout or bud (Huguez & Philippe, 1998). Low moisture in the soil may, however, lead to problems of reduced growth rate, metabolic activities, development and yield of crops. Low moisture could also result in total loss of a crop or make the crop vulnerable to both biotic and abiotic complications (Ware & McCllum, 1975).

Research indicates that some growth periods of a plant such as germination and emergence, flowering and fruit set are the periods most critical to water stress conditions, resulting in tissue wilting and loss of entire plants (Norman, 1992). Water plays a crucial role in determining the yield of tomato. However, it is probable that a water scarcity period will have to be faced in the not distant future. The unpredictable rainfall, increasing competition for water resources and the inability of rainfall to compensate for evapotranspiration losses by a crop necessitate the adoption of irrigation if appreciable yield and growth is to be obtained by the producer.

Deficit irrigation is a strategy that allows a crop to sustain some degree of water deficit in order to reduce costs, maintain satisfactory yields and potentially augment income. Under this strategy, crops are deliberately allowed to sustain some degree of water stress and yield reduction and can help maintain farm profitability in times of limited and costly water supply.

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The study was thus intended to determine the water requirement (ETc) of tomato crop, with specific regard to growth and yield under four different irrigation regimes.

Materials and Methods

Study area

The study area was the School of Agriculture Teaching and Research Farm at the University of Cape Coast, Ghana. It lies around latitude 5° 06’ N and longitude 1° 15’ W at an altitude of 1.1m. This site lies within the coastal savannah agro-ecological zone of Ghana. The soil is described as sandy loam with characteristics as neutral to slightly acidic in reaction and with a pH of 5.7. The annual temperature is 23.2 – 33.2 °C with an annual mean of 27.6 °C and a relative humidity of 81.3 – 84.4 % (Owusu-Sekyere, Asante & Osei-Bonsu, 2010). The study area experiences two rainy seasons, namely the major season which starts from May and ends in July and a minor season that starts around September and ends around mid- November to give way to the dry Harmattan season that runs till the end of March in the subsequent year.

Experimental design and cultivation practices

Two field experiments were carried out. Experiment one involved the growing of tomato in plastic buckets filled with sandy loam soil using an irrigation interval of two days. The results obtained were used to calibrate the AquaCrop model. The experiment was carried out from June – September, 2014. Experiment two, similar to the first one, provided result used in validating the AquaCrop model and this was conducted from August – November, 2014.

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The Randomized Complete Block Design (RCBD) was used, with four irrigation treatments (T_1, T_2, T_3 and T_4) and four replications (R_1, R_2, R_3 and R_4). There were 5 plants per treatment under each replication with plant spacing of 1.0 m. The experiments were conducted under a rain shelter.

Water applications

The treatments were as follows:

T_1 = 100% ETc

T_2 = 90% ETc

T_3 = 80 % ETc

T_4 = 70% ETc

Planting

Tomato seeds (*Wosowoso*) variety was nursed on a seed bed about 25 cm deep in rows 10 – 15 cm apart and transplanted after 21 days for both experiments. A week before transplanting, reduction in water supply was administered at the nursery in order to harden the seedlings to lessen transplanting shock. The nursery was watered until near to soil saturation, prior to transplanting to enhance easy uprooting of seedlings and to prevent injury to roots of the seedlings. Transplanting was done two days after saturation. Each container had one seedling.

Cultivation practices

Weeds were removed by hand fork as soon as they appeared and spraying of insecticides was done once during each experimental phase and it was carried out one week before the flowering stage.

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Growth stages

In this research, the treatments were imposed on four growth stages, namely: the initial stage (excluding seedlings at the nursery), the development stage (period of rapid growth of the crop, also known as vegetative stage), the mid-season stage (flowering and fruiting stage), and the late season stage (full maturity and ripening of fruits). In the two experiments, the initial stage lasted for 15 days, the developmental stage lasted for 30 days, and the mid-season stage lasted for 50 days whilst the late season stage lasted for 21 days. The late season stage was later characterized by senescence and drying of leaves after the harvesting was over.

Irrigation regime

Two-day irrigation interval was adopted and the volume of water applied on each two-day interval was as a result of the computed loss in mass of each container with the plants of the treatment set up over the last two-days. The equivalent in volume basis was found and applied to the plants as the various treatments demanded. Irrigation days for both experiments were 58 days out of the total of 116 days of the trial period.

Soil analysis

Soil samples were taken from each bucket and were thoroughly mixed together. The samples were divided into four and two opposite quadrants were taken out. This was repeated and each time, another opposite quadrant was taken off until a substantial amount was obtained. The sample was then dried for four days after which it was ground and then analyzed for the amount of

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nitrogen, phosphorous and potassium. Soil at two growth stages (initial and late seasons) were considered for analysis.

Calculation of crop water requirement (ETc) and crop co-efficient (Kc)

Crop water requirement and crop coefficient were determined as follows:

a) $ET_C = ET_O \times K_c$ ……………………………………………….3-1

b) $K_c = \frac{ET_C}{ET_O}$……………………………………………………... 3-2

c) $ET_O = \text{Epan} \times \text{Kpan}$ ……………………………………………... 3-3

d) ET_C (2days) = Loss in weight of buckets. ………………………… 3-4

e) ET_C for a growth stage = Summation of ET_C for the number of irrigation days. ……………………………………………………………….. 3-5

WhereET_C = Crop evapotranspiration or Crop water requirement (mm/d)

K_c = Crop factor

ET_O = Reference evapotranspiration (mm/d)

Kpan = Pan co-efficient (0.80)

Epan = Pan Evapotranspiration (mm/d) …………………………………… 3-6

Plant growth parameters measured

Plant height

Plant height for each plant was determined by measuring the length of the plant from the base to the apex of the plant at the initial, developmental, mid-stage and the late-season stages using a metre rule. All five plants for each treatment per replication were selected and their heights at the various growth stages were measured at specific intervals after transplanting. The data obtained were summed up and their mean heights were obtained by dividing the sum by the number of plants chosen.

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Leaf area

The longest dimension along the petiole line of the leaf and the widest breadth across the leaf were measured as the length and width of the leaf by using a 30 cm metre rule. Five leaves from different parts of the plants were randomly selected on each of the plants. The leaf area was obtained by multiplying the product by a factor of 0.75 (Squire, 1990; Lal & Rao, 1951).

Mean stem diameter and internode length

An electrical calliper was used to measure the stem diameter and a 1.5 m tape rule was used to measure the internode length of each treatment.

Mean number of fruits per treatment

Number of fruits per treatment was determined by counting the number of harvested fruits on each of the plants from each treatment. The numbers obtained were then summed up and divided by twenty.

Mean fruit weight

An electronic balance (0.001g sensitivity) was used to weigh each fruit from the various treatment combinations. These were then summed up and divided by the number of plants.

Fruit Size

An electrical calliper was used to measure the major diameter of the fruit from each treatment for the size.

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Reference evapotranspiration rate and rainfall reading

Evaporation rate and amount of rainfall readings were obtained from a US Class A evaporation pan and a rain gauge, situated at the farm where the experiments were conducted. The first experimental period experienced six rainfall events whereas the second experimental period recorded three rainfall events. Daily reduction in the water level in the pan with reference to the initial level was recorded. Each of these readings was accumulated for each of the growth stages and was multiplied by the pan factor (0.8) to get the reference evapotranspiration (ETo). The pan factor of 0.8 was selected because it was placed in an area which has a modest wind speed of 2-3ms^{-1} and a high humidity.

Statistical analysis

The results were subjected to the analysis of variance (ANOVA) procedure using GenStat statistical soft-ware to investigate whether there were statistical differences in the parameters studied. Mean comparisons were done using Duncan’s Multiple Range Test at a probability level of 0.05 for separation of means (Russel, 1990)

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Results and Discussion

Table 1: Growth period, ETo, ETc and Kc for all the growth stages for Experiment-1

Growth Stage	Period (days)	ETo	ETc (100%)	ETc (90%)	ETc (80%)	ETc (70%)	Kc (100%)	Kc (90%)	Kc (80%)	Kc (70%)
Initial	15	49.3	31.1	27.70	23.9	22.3	0.63	0.56	0.48	0.45
Dev.	30	57.7	92.9	78.50	69.0	59.5	1.61	1.36	1.20	1.03
Mid.	50	114	152.5	130.50	118.5	110.5	1.34	1.14	1.04	0.97
Late	21	32.9	30.5	26.30	23.4	21.0	0.93	0.80	0.71	0.64
Sum(mm)	**116**		**307**	**263**	**234.8**	**213.3**				

Table 2: Growth period, ETo, ETc and Kc for all the growth stages for Experiment-2

Growth Stage	Period (days)	ETo	ETc (100%)	ETc (90%)	ETc (80%)	ETc (70%)	Kc (100%)	Kc (90%)	Kc (80%)	Kc (70%)
Initial	15	50	30.89	25.70	21.90	19.10	0.62	0.51	0.44	0.38
Dev.	30	64.6	99.8	80.50	71.00	61.50	1.54	1.25	1.10	0.95
Mid.	50	142	174.5	153.5	140.0	131.50	1.23	1.08	0.99	0.93
Late	21	59.2	54.7	40.0	39.08	35.00	0.92	0.68	0.66	0.59
Sum (mm)	**116**		**359.89**	**299.71**	**272.0**	**247.1**				

At the conclusion of both experiments, 307.00 mm and 359.89 mm were recorded as the water requirement for the 116 days growing period after transplanting whilst the Crop co-efficient (Kc) values for tomato grown in the coastal savannah Agro-ecological zone of Ghana were 0.63, 1.61, 1.34 and 0.93 for the initial, developmental, mid-season and the late season stages respectively for the first experiment (Table-1), and 0.62, 1.54, 1.23 and 0.92, respectively for the second experiment (Table-2). The values are quite different from the FAO mean crop coefficients for tomato (FAOSTAT, 2001).

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The water requirement according to FAOSTAT (2001) was 400 mm to 600 mm for tomato crop grown in the field lasting for 90 to 120 days, depending on the climate. The Kc values recorded in this work were not different from Kc values reported by Allen *et al*. (1998). Also the developmental stages had the highest Kc value of 1.61 and 1.54 for both experiments. According to Doorenbos and Kassam (1979), the Kc value for this stage is the highest as compared to the other stages. Also, the seasonal water requirement for tomato for both experiments were found to be within the range reported by Silva and Maroucelli (1996) which was 300 mm to 400 mm.

The differences in Kc values could be due to the shorter growth periods used in this work. Owusu-Sekyere, Sam-Amoah, Teye and Osei (2012) recorded Kc values of 0.62, 1.61, 1.23 and 0.92 for the initial, developmental, mid-season and the late season stage, respectively for tomato. These values compare quite well with those obtained in this work. The differences might again be due to differences in growth periods used.

Allen *et al.* (1998) reported that crop coefficients are low in the early season due to small leaf area and thus low water uptake and this approaches unity as the canopy reaches maximum development with corresponding increase in water use by the crop which proves the lower Kc value obtained at the initial stage of this research. Also Doorenbos and Pruitt (1979) noted that plant height and total growing season influence crop coefficient values. The higher the plant and the longer the growing season, the higher the crop coefficient values and vice versa. Environmental factors such as temperature, solar radiation, wind speed and relative humidity prevailing at the experimental site have influence on the crop water need of a plant (Pereira,

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1998). These could be the reason for the slight differences between crop coefficient values recorded by various researchers as well as in this research. Silva and Maroucelli (1996) indicated that the crop water requirements ranged between 300 mm to 400 mm depending on the climatic condition and the season of the crop and the location. Schwab, Fangmeier, Elliot and Frevert (1993) also asserted that the seasonal water requirement for tomato ranges between 450 – 600 mm depending on the season of planting and the climatic conditions prevailing in the area. The findings in this work are in agreement with the findings of Silva and Maroucelli (1996) and can be concluded that the water requirement of tomato for the Cape Coast area ranges between 307.00 mm and 359.89 mm. The range takes into account crop characteristics, time of planting and general climatic conditions.

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Table 3: Mean plant height (cm) for the treatments at the various stages of plant growth for both experiments

FIRST EXPERIMENT					SECOND EXPERIMENT			
Treatment	**Initial 15 DAT (cm)**	**Developmental 40 DAT (cm)**	**Mid-season 90DAT (cm)**	**Late season 116 DAT (cm)**	**Initial 15 DAT (cm)**	**Developmental 40 DAT (cm)**	**Mid-season 90 DAT (cm)**	**Late season 116 DAT (cm)**
T_1	23.35a	49.24a	62.86a	66.95a	22.77a	48.55a	62.47a	66.53a
T_2	21.01b	46.29a	57.58b	65.18ab	19.61b	44.02b	57.60b	61.42b
T_3	20.40b	44.43ab	57.23b	61.60b	19.54b	42.03bc	56.72b	61.13b
T_4	18.04c	40.50b	55.09c	59.55c	17.5c	40.43c	55.82b	58.11c
	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5
	Sed = 0.705	Sed = 2.057	Sed =1.547	Sed = 1.932	Sed = 0.346	Sed = 1.476	Sed = 1.307	Sed = 1.334

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Means followed by the same letter within a column indicate no significant differences in the treatments at 5 % probability level. From Table 3 it can be observed that in both experiments T_1 for all the growth stages of the crop development produced the highest mean plant height. In the first experiment, for all the growth stages of the crop development, the plant heights for T_2 and T_3 were not significantly different from each other as was also observed in experiment two.

At 40 DAT, T_1, T_2 and T_3 were not significantly different from each other but T_1 and T_2 were significantly different from T_4. T_3 and T_4 were not significantly different from each other with the exception of the initial, mid-season and late stages of this experiment. At 90 DAT, T_1 was significantly different from T_2, T_3 and T_4 but T_2, and T_3 were not significantly different while T_4 recorded a mean plant height that was significantly different from the other treatment. T_1 maintained the highest height of 66.95 cm at 116 DAT followed by T_2 with mean value of 65.18 cm and by T_3 with mean value 61.60 cm. T_4 recorded the lowest mean plant height of 59.55 cm which was significantly different from T_1, T_2 and T_3.

In the second experiment, for all the growth stages of the crop development T_2 and T_3 were not significantly different from each other. At 40 DAT, T_3 and T_4 were not significantly different from each other. However, the trend varied as T_4 was significantly different from T_1, T_2 and T_3 in the various stages of the crop growth. At 116 DAT, T_1 recorded mean plant height that was significantly different from T_2 and T_3, but T_2 and T_3 were not significantly

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different from each other. T_1 maintained the highest height of 66.53 cm followed by T_2 with mean value of 61.42 cm and by T_3 with mean value 61.13cm. T_4 recorded the lowest mean plant height of 58.11 cm which was significantly different from the other treatments.

According to Rahman, Nawata and Sakuratani (1999), water stress results in reduction in growth of most growth parameters in plants. Plants grow by cell expansion after the cell goes through division to increase the number and size of cell. Cells grow by water uptake. T_1 had the greatest mean height for all the growth stages followed by T_2, T_3 and T_4 in both experiments. The irrigation water applied was used to the advantage of the plants that were fully irrigated. Moreover T_1 attained the highest plant height at all the stages of the crop growth in both experiments due to frequent and consistent application of full crop water requirement in the rooting environment which in turn, provided good soil moisture regime in the crop root zone throughout thus favouring T_1. This is in accordance with Allen *et al*. (1998) who indicated that plants grow rapidly with increase in crop water use. Furthermore as water used by plants is optimum, growth is rapid since the plants will have enough water to be transpired by leaves to increase leaf area, plant height and root development.

Kramer (1983) noted that available water, when less than the crop water requirement would make the plant reduce its rate of metabolic activities such as photosynthesis, root respiration (Wilcox, 1987), transpiration and translocation (Craft, 1999). The research of Norman (1995); Berrie and Berrie (1990) indicates that if the availability of soil moisture becomes a limiting factor then the level of

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transpiration of the plant should be expected to decrease as the physiological mechanism to sustain the plant and subsequently the rate of growth and development will decrease. This further supports this work. This is evidenced by plants which received 70 % of the irrigation water applied recorded the lowest mean plant height for the growth stages of both experiments.

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Table 4: Mean leaf area (cm^2) for the treatments at the four growth stages of plant growth for both experiments

	FIRST EXPERIMENT				**SECOND EXPERIMENT**			
Treatment	**Initial 15 DAT (cm^2)**	**Developmental 40 DAT (cm^2)**	**Mid-season 90 DAT (cm^2)**	**Late Season 116 DAT (cm^2)**	**Initial Stage 15 DAT (cm^2)**	**Developmental 40 DAT (cm^2)**	**Mid-season 90 DAT (cm^2)**	**Late season 116 DAT (cm^2)**
T_1	7.02a	25.15a	48.45a	9.77a	6.78a	21.56a	48.82a	9.28a
T_2	6.83a	24.95a	44.01b	8.01b	6.46a	20.79ab	44.15ab	7.46b
T_3	6.71a	24.27b	43.40b	7.81b	6.58a	20.47bc	41.15b	7.58ab
T_4	6.69a	19.74c	33.10c	5.40c	6.44a	19.48c	33.11c	5.44c
	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5
	Sed = 0.517	Sed = 0.0903	Sed = 0.2756	Sed=0.2204	Sed=0.2657	Sed = 0.443	Sed = 2.104	Sed = 0.765

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Means within a column followed by same letter are not significantly different at 5 % probability level. From Table 4, the leaf area analysis of variance for the various treatments showed no significant differences at 5 % probability level between them at 15 DAT. At 40 DAT, there were significant differences between the various treatments applied. However, T_1 produced the largest mean leaf area of 48.45 and 48.82 cm^2 respectively at 90 DAT for both experiments while T_4 produced the least mean leaf area of 33.10 and 33.11 cm^2 for experiments 1 and 2 respectively.

At the late stage of crop development, significantly lower mean leaf areas were recorded for the various treatments but the trend remained the same. However, T_1 produced the highest mean leaf area for the four stages of growth (initial, development, mid-season and late season stage) at 90 DAT and 116 DAT and was significantly different from T_2. But at 15 DAT and 40 DAT, it was not significantly different from T_2 in Experiment 1 but was significantly different from the other treatments. The mean leaf areas, for the different treatments at the late stage were different from each other. This was not different from the observation made by Owusu-Sekyere *et al.* (2012); Owusu-Sekyere and Dadzie (2009). The results from both experiments, for all treatments growth stages are in agreement with Norman (1995) that this could be due to water stress and could be said that reduction of moisture reduces the rate of leaf expansion as a mechanism to obviate the effect of moisture stress and that leaf area increased with water application. Flower and Ludlow (1986) recorded that relative water in leaf is considered an alternative measure of plant water status reflecting the metabolic

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activity in plant tissues. T_2, T_3 and T_4 showed that water stress decreases leaf area relative to water content leading to reduced leaf area compared to the full crop water requirement. As the plant undergoes water stress, the water pressure inside the leaves decreases and the plant wilts.

The results indicate lower mean leaf area values were recorded for the late season stages of the crop development. These values were recorded 15 days after irrigation ceased for all treatments. Still T_1 recorded the highest leaf area. The lower values could be ascribed to the drying up and wilting of leaves at this stage. The decrease could be ascribed to root systems which are not able to compensate for water lost by transpiration through a reduction of the absorbing surface (Leung, 2001). These differences could also be due to the plant’s response to reduced water levels by reducing the surface area of the leaf as a mechanism to avert the effect of moisture stress (Berrie & Berrie, 1990); Norman (1995).

Furthermore, this reduction in leaf growth is associated with a reduction in photosynthetic capacity as a result of water application and stage of tomato. This suggests that deficit irrigation has significant effect on tomato leaf area and therefore confirms the assertion of Kozlowski (1964) that moisture stresses reduce plant leaf area by restricting cell expansion in the leaf. Continuous flow of nutrients from the soil into the plant’s system is reduced when transpiration is reduced (Berrie & Berrie, 1990). The main consequence of moisture stress is decreased growth and development caused by reduced photosynthesis, a process in which plants combine water, carbon dioxide and light to make carbohydrates for energy. Chemical limitations due to reductions in critical photosynthetic components such as water can negatively impact plant growth. The ability to recognize early symptoms of water stress is crucial to maintaining the growth of plants; the most common symptom is wilting. According to El Jaafari (2000), water deficit exerts a negative effect on relative water content. Thus the ability of the plant to survive severe water deficits depends on its ability to restrict water loss through the leaf epidermis after the stomata have attained minimum aperture.

Table 5: Mean stem diameter and internode length of tomato as influenced by soil moisture levels for the treatments for both experiments

	First experiment		**Second experiment**	
Treatment	**Stem Diameter 90 DAT (mm)**	**Internode Length 90 DAT (cm)**	**Stem Diameter 90DAT (mm)**	**Internode Length 90 DAT (cm)**
T_1	10.03a	19.36a	9.78a	19.30a
T_2	9.75ab	19.01a	9.43a	18.97ab
T_3	9.50b	18.57a	9.00a	18.20b
T_4	7.62c	16.57b	7.17b	16.57c
	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5
	Sed = 0.169	Sed = 0.362	Sed = 0.358	Sed = 0.376

Means within a column followed by same letter are not significantly different at 5 % probability level. From Table 5, changes in the plant stem diameter and internode length were used to study the effects of water deficit on the growth of tomato plants. The data were pooled for each treatment for both experiments.

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There was no significant difference between T_1 and T_2. T_2 and T_3 were not significantly different but T_1 was significantly different from T_3 and T_4 while T_4 was significantly different from all the other treatments at 90 DAT. The trend changed as compared to the results from the second experiment. However, T_1, T_2 and T_3 were not significantly different from each other but were significantly different from T_4. For the internode length, plants that received 100 %-ETc, 90 %-ETc and 80 %-ETc had longer internodes compared to that of the plants that received 70 %-ETc. In this research, there was a significant reduction in stem diameter and internode length of plants subjected to high water stress. Results from this study are similar to those made by Kirnak, Kaya, Tasand Higgs (2001) where stem diameter of water stressed plants were smaller than the equivalent component in the plants receiving their full crop water requirement. Similar effects of water stress were also observed by Bradford and Hsiao (1982) and other researchers that stem and plant growth may be inhibited at low water potential despite complete maintenance of turgor in the growing regions as a result of osmotic adjustment.

Klepper, Browning and Taylor (1971) indicate that the stem diameter changes reflect changes in stem tissue hydration. On the other hand, T_1, T_2 and T_3 had an increase in internode length compared to T_4, for it is well known that as soil water availability becomes limited, plant growth is usually decreased. It had been reported that when tomato plants are subjected to different levels of water stress under field conditions, vegetative growth is inhibited (Nyabundi & Hsiao, 1989) thus affecting tomato stem and internode. This is evidenced by plants

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which received 70 % of irrigation water applied as they recorded the lowest diameter and length for the growth stage for both experiments.

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Table 6: Mean yield component (Number of fruits, Fruit diameter, Fruit mass & t/ha) for the treatments for both experiments

	First experiment				**Second experiment**			
Treatment	**Mean number of fruits per treatment**	**Mean fruit diameter per treatment (mm)**	**Mean fruit weight (kg)**	**Mean yield (t/ha)**	**Mean number of fruits per treatment**	**Mean fruit diameter per treatment (mm)**	**Mean fruit weight (kg)**	**Mean yield (t/ha)**
1	62.45a	44.77a	0.53a	5.30a	52.45a	42.80a	0.45a	4.50a
2	58.52a	42.30b	0.47b	4.70b	48.52a	41.76ab	0.38ab	3.80ab
3	57.12ab	41.22b	0.45b	4.50b	41.12ab	40.72b	0.32b	3.20b
4	49.41b	23.40c	0.31c	3.11c	26.41b	22.90c	0.21c	2.10c
	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5	Prob = 0.5
	Sed = 3.742	Sed =0.990	Sed = 0.0318	Sed = 0.318	Sed = 7.741	Sed = 0.876	Sed = 0.0323	Sed = 0.323

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Treatment means followed by the same letter are not significantly different at 5% probability level but means with different letters are significantly different from the rest. From Table 6, for the mean number of fruits, treatment T_1 recorded the highest and it was significantly different from T_4 though not significantly different from T_2 and T_3 at probability level of 5 %. T_3 and T_4 were, however, not significantly different from each other in the first experiment. However, the trend remained the same as T_1 in the second experiment which had mean number of fruits that was not significantly different from T_2 and T_3 but significantly different from T_4. In the first Experiment, T_1 produced the highest mean number of fruits (62.45) which was closely followed by T_2 producing 58.52 fruits against 52.45 for T_1 and 48.52 for T_2 in the second Experiment. T_3 also recorded 57.52 fruits in the first Experiment against 41.12 for Experiment two.

T_4 which was significantly different from T_1 and T_2 but not significantly different from T_3 recorded the lowest mean number of fruits 49.41 and 26.41 respectively in both experiments. It could therefore be said that a slight reduction of water requirement of tomato does not significantly affect the number of fruits obtained from both experiments. However, water stress above 10 % affects number of fruit. Satch *et al*. (1983); Norman (1995) stated that the number of fruits decreases under water stress which is in agreement with this study. It is also in agreement with Pill and Lambeth (1980) who observed a reduction in fruit numbers with decreasing soil water, explaining that the lower soil moisture could result in pollen and stigma dehydration as well as unnecessary elongation of flower style which could result in up to 50 % reduction in fruit setting and final fruit yield. Furthermore,

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the result illustrate a direct relationship between water applied and the mean number of fruits per treatment and corresponds with Pellitero, Pardo, Simon, Suso and Cerrolaza (1993) who noted that the number of fruits per treatment decreased as soil water deficit increased. Factors that could be responsible for low fruit numbers include blossom drop, whereby all cells and tissues at the distal and blossom ends of the plant stems fail to receive enough moisture to uphold their growth and development thus leading to cell failure, flower abortion and its subsequent drop (Smart & Simmons, 1995).

In terms of fruit size, T_1 (44.77 mm) was significantly different from T_2 (42.30 mm) and T_3, while T_2 and T_3 were not significantly different from each other but were all significantly different from T_4 in Experiment 1. However, T_1 produced the highest mean fruit size and it was not significantly different from T_2, while T_2 and T_3 were not significantly different at probability level of 5 %, but T_4 was significantly different from the other treatments in Experiment 2.

This is attributed to Pill and Lambeth (1980) who indicated that water had an effect on plants and thus concluded that water scarcity is capable of limiting plant growth and making it impossible for plants to attain their full genetic potential. Furthermore a mixture of factors, quantity of water applied, nutrient uptake levels might have contributed to obtain these results.

Hence T_1 produced the heaviest fruits in both experiments weighing 0.53 kg and 0.45 kg respectively. This was followed by T_2, T_3 and T_4 in both experiments. T_1 was significantly different from T_2, T_3 and T_4 while T_2 and T_3 were not significantly different but T_4 was significantly different from all of them in Experiment 1. However, in the second experiment, T_1 was

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significantly different from T_3 and T_4 though not significantly different from T_2, while T_4 was significantly different from the rest of the other treatments.

The mean fruit per weight treatment was also significantly affected by different water application. In experiment one, T_1 produced the heaviest fruits weighing 0.53 kg. This was followed by T_2 weighing 0.47 kg while T_3 recorded a mean weight of 0.45 kg and T_4 recorded the lowest fruit weight of 0.31 kg. Significant difference was observed in Experiment two between T_1 (0.45 kg) and T_4 (0.21 kg) while there was no significant difference between T_1 (0.45 kg) and T_2 (0.38 kg). T_2 (0.38 kg) and T_3 (0.32 kg) were not significantly different but T_4 (0.21 kg) was significantly different from all the other treatments. This order suggests that availability of the right amount of water enhances the development and final yield of tomato as reduction imposes stress thus making the plants unable to efficiently make use of available nutrients for growth and yield.

This accounted for the highest mean fruit weight recorded by T_1 which received the highest amount of water application. Fruits are made up of carbohydrates in the form of simple sugars which are produced by the plant green chlorophyll pigments in combination with sunlight, water, carbon dioxide in the process of photosynthesis. When this process is reduced due to reduced water requirement, the sensitive phytochrome pigments (chlorophyll pigmentation) that intercept sunlight for the process which is affected tend to reduce leaf area as well as leaf size subsequently leading to reduced fruit weight (Pill & Lamberth, 1980). T_1 in return produced the highest yield in tonnes per hectare recording 5.30 t/ha in experiment one against 4.5 t/ha in the second experiment while T_4 produced the least yield of 3.11 t/ha in the first

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experiment and 2.10 t/ha in Experiment two. However, the total yield obtained from the various treatments for Experiment one was 17.61 t/ha against 13.60 t/ha recorded for Experiment two.

The average yields obtained from open tomato fields in Ghana is between 7.5 – 15 t/ha (Norman, 1992), in 2012 the average yield of tomatoes in Ghana stood at 7.2 t/ha and the world average was 33.7 t/ha (FAOSTAT, 2013). Comparing the output yields of this research work in tonnes per ha, which was produced during both experiments, they fell within the range observed by Norman (1992) but this was relatively low as compared to the world average yield of 33.7 t/ha (FAOSTAT, 2013).

NPK Levels

The NPK levels in the soil before the experiment and after the experiment for the four treatments imposed are shown in Figure 3 to 5. The chemical analysis of the soil indicates that the essential nutrients in the soil were optimum to support the growth and development of the crop. It was generally observed that NPK levels declined over the experimental period. The uptake of nutrients such as nitrogen, phosphorous and potassium by plants was influenced by the amount of water available in the soil. At the end of the experiment, nitrogen reduced as the amount of water decreased from 100 % to 90 %, then 80 % and 70 %. Also, it was seen that T_4 and T_3 utilized more phosphorus and potassium than T_1 and T_2. This is in agreement with work done by Owusu-Sekyere *et al.* (2012) who recorded an increase in the uptake of potassium as the amount of water applied decreased.

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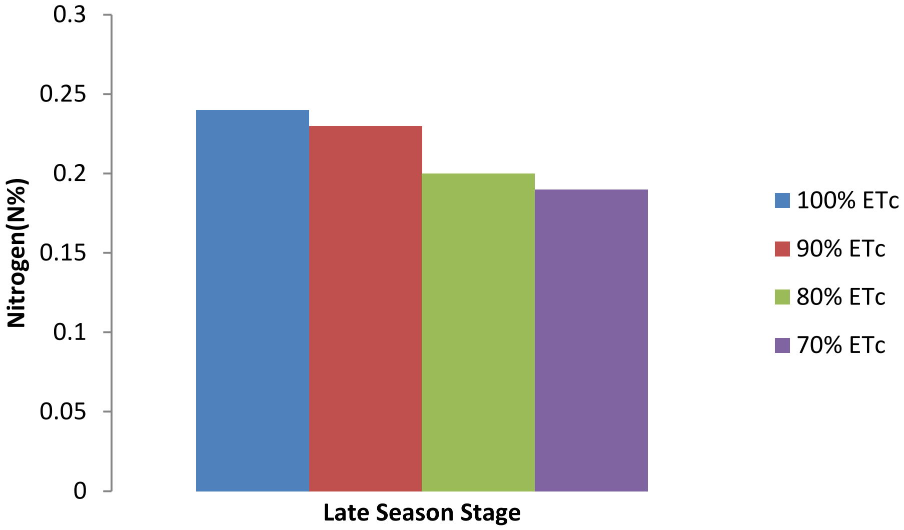

Figure 3:Levels of Nitrogen in the soil at the late stage

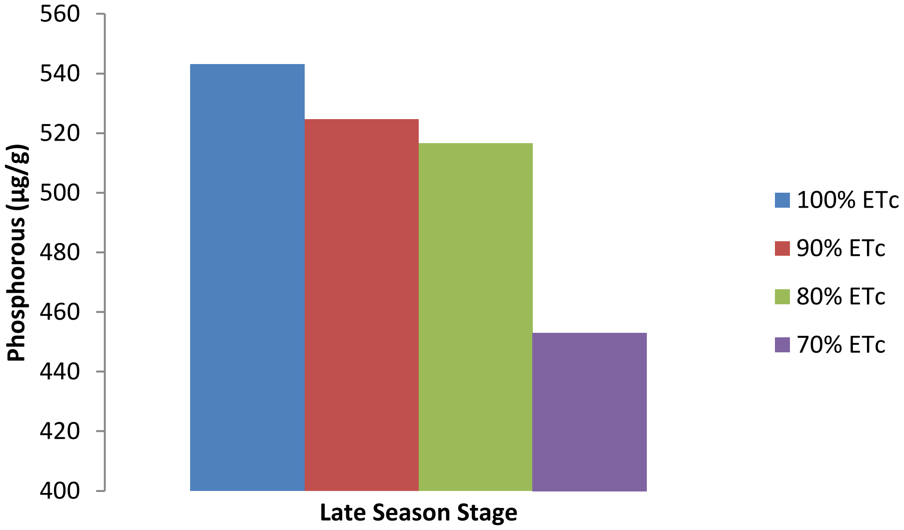

Figure 4: Levels of Phosphorous in the soil at the late stage

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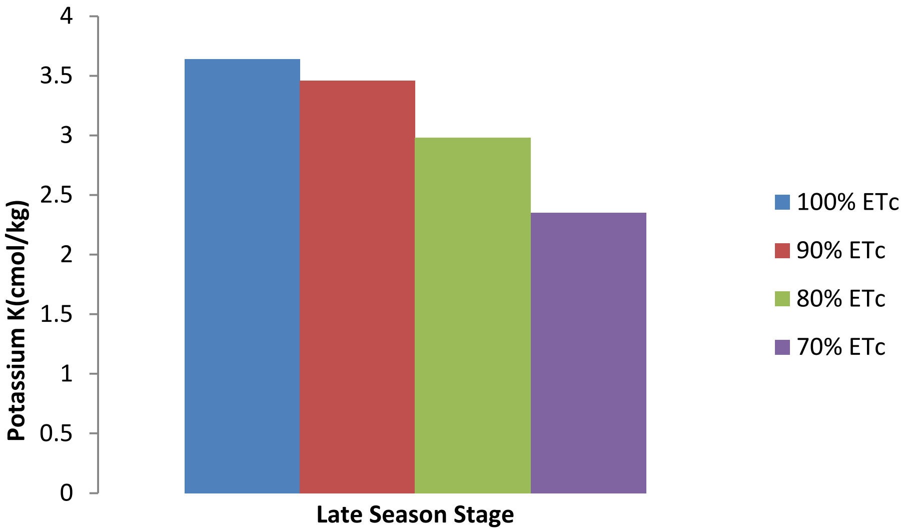

Figure 5: Levels of Potassium in the soil at the late stage

Conclusions

The response of tomato crop to different water stress levels can be used for optimization and sustainability of tomato production as it influences its growth and yield in the coastal savannah agro-ecological zone of Ghana. The results show that deficit irrigation is feasible. However, to a large extent when water given is below 20 % deficit irrigation, it negatively affects growth, development and total yield or profitability of tomato production increasing negative effect on the crop survival. A two-day irrigation interval was used to determine the ETc and crop coefficient for the various growth stages of tomato in the two field experiments. At 100 % ETc (full irrigation),for the initial, developmental, mid-season and the late season stages respectively, the crop coefficients for tomato were determined to be in the ranges: 0.62 – 0.63, 1.54 – 1.61, 1.23 – 1.34 and 0.92 – 0.93 and the total quantity of water applied for the 116 days ranged between 307.00 mm and 359.89 mm. From the experiments, it can be concluded that 20 % deficit irrigation has no significant

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reduction on the yield of tomato but above this threshold, there is an adverse effect on the plant and yield as indicated by T_4 which recorded the lowest yield.

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CHAPTER FOUR

CALIBRATION AND VALIDATION OF AQUACROP FOR FULL AND DEFICIT IRRIGATION OF TOMATO

Introduction

The strain on global water resources continues to be more acute as a result of increase in population and economic growth. It is estimated that by 2050, food demand will roughly double (IWMI, 2007). Rockström *et al.* (2009) projected that between 16950 and 118600 km³ of water is used in worldwide food production. As the current rate of agricultural water use efficiency is constant, an estimated amount of 5700km³ of fresh water will be required to meet the estimated food and fibre demand by 2050. This demand will manifest at a number of levels. Restrictions on water availability and use will affect the cost and supply of water-sensitive commodities and other agricultural inputs.

Simulation models are increasingly being used in problem solving and in decision making. The developers and users of these models, the decision makers using information derived from the results of these models, and the individuals affected by decisions based on such models are all rightly concerned with whether a model and its results are "correct". AquaCrop is one of the newly developed decision support tools useful in modelling and devising strategies for efficient management of crop water productivity at the farm level. To make AquaCrop applicable worldwide, it must be tested in

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different areas with different soil conditions, crops, agronomic practices and climatic conditions. Calibration and performance evaluation has been done for cotton (Farahanin, Izzi, Steduto & Oweis, 2009); (Gracia-Vila *et al*., 2009) and for maize (Heng *et al*., 2009); (Hsiao *et al*., 2009) and for hot pepper (Sam-Amoah, Darko & Owusu-Sekyere, 2013).

Considering the economic value of tomato in Ghana and the world at large, the model could be used to study the crop's response to various levels of water application. Eventually, this will lead to a better knowledge of how to improve the yield of tomato through the adoption of optimal water management. The main aim of this research was thus to calibrate and test the model for tomato grown under full and deficit irrigation in the coastal savannah agro-ecological zone of Ghana (Cape Coast).

Materials and Methods

Study area

The study area was the School of Agriculture Teaching and Research Farm at the University of Cape Coast, Ghana. It lies on latitude 5° 06' N and longitude 1° 15' W at an altitude of 1.1m. This site lies within the coastal savannah agro-ecological zone of Ghana. The soil is described as sandy loam with characteristics as neutral to slightly acidic in reaction and with a pH of 5.7. The annual temperature is 23.2 – 33.2 ºC with an annual mean of 27.6 ºC and a relative humidity of 81.3 – 84.4 % (Owusu-Sekyere *et al*., 2010). The study area experiences two rainy seasons, namely the major season which starts from May and ends in July and a minor season that starts around September and ends around mid- November to give way to the dry Harmattan season that runs till the end of March in the subsequent year.

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Field Experiments

Two field experiments were conducted (June – September, 2014 and August – November, 2014). The two experiments were carried out under a rain shelter and involved the growing of tomato in plastic containers filled with sandy loam soil administering an irrigation interval of two days with different irrigation treatments. The results obtained from experiment one was used to calibrate the model and the data obtained from the second was used to validate the model.

Short description of the AquaCrop Model

The conceptual framework, underlying principles, and distinctive components and features of the model have been described by Steduto *et al.* (2009). Also Raes *et al.* (2009) has reported the structural details and algorithms of the model. The model is a menu-driven programme with a well-developed and friendly user interface. The menus (windows) are the interconnection between the user and the programme, while the multiple graphs and their schematic displays in the menus assist the user to detect the courses of input changes and to analyze the simulation results. The main menu gives the user access to all sets of menus where input data is displayed and can be modified. Input data constitute climatic data, crop, management and soil characteristics that describe or define the environment in which the crop will develop. Prior to simulation, the simulation phase and the initial conditions at the beginning of the simulation must be entered.

The user can track changes in the soil water and corresponding changes in the crop development, soil evaporation, transpiration, ET rate, biomass production and yield, when running a simulation.

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Results of simulation are stored in output files. However, the data can be retrieved in spread sheet format for further processing and analysis. Furthermore, programme settings permit the user to change default settings and reset to individual’s default values once more.

Creating input files of the AquaCrop Model

Creating a Climate File

To create a climate file, the following files must be selected or created: Temperature file, ETo file, Rain file and CO_2 file. The user has to specify the type of data (daily, 10-daily or monthly data) and the time range. Existing climatic data can also be inserted in an ETo, rain, or temperature file as long as the structure of the file is maintained.

Data covering the experimental periods such as, temperature was obtained from the nearby meteorological station in Cape Coast. The US Class A evaporation pan was used to estimate the daily reference evapotranspiration (ETo) over the trial period by using the equation:

$ETo = Kp \times Epan$

Where, Kp = Pan co-efficient

Epan = Pan evaporation (mm/d)

Since the experiments were carried out under a rain shelter, the rain file contained zero values although there were rainfall occurrences over the periods. The default CO_2 file provided with AquaCrop was utilised.

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Creating a crop file

In creating a crop file, the user selects the type of crop (Fruit/Grain producing crops, Leafy vegetable crops, Roots and tubers, or Forage crops) and specifies a few parameters. With the assistance of this information, AquaCrop generates the complete set of required crop parameters. The parameters are displayed and the values can be adjusted in the Crop characteristics menu.

The four growth stages were taken into account namely: the initial stage (exclusive of seedlings at the nursery), the development stage (stage of rapid growth of the crop, also known as vegetative stage), the mid-season stage (flowering and fruiting stage), and the late season stage (full maturity and ripening of fruits) were considered for both experiments carried out.

Table 7: Duration and dates for the various growth stages for the two experiments

Growth Stage	Duration (Days)	1st Experiment	2nd Experiment
Initial	15	02/06/14/ - 16/06/14	02/08/14 - 16/08/14
Development	30	17/06/14 - 16/07/14	17/08/14 - 16/09/14
Mid-Season	50	17/07/14 - 04/09/14	17/09/14 - 05/11/14
Late Season	21	05/09/14 - 25/09/14	06/11/14 -26/11/14

Creating irrigation schedule

In creating an irrigation schedule, the user specifies the time and application depth of the irrigation events. In all experiments, a two day irrigation interval was employed. The volume of water applied to each treatment was obtained by the computation of mass loss by each container with the plants of the treatment. Irrigation days for the two experiments were summed to 58 days out of 116 days of the entire growing period. Also irrigation files were created for each of the treatments in both experiments.

Creating a soil file

In creating a soil file, the user has to specify only a few characteristics namely: soil type, depth of soil, etc. With the assistance of this information, AquaCrop generates the complete set of soil parameters. The parameters are displayed and the values can be adjusted or modified in the Soil profile characteristics menu. The soil texture used was sandy loam.

AquaCrop Model Parameterization

A few crop parameters were approximated to be conservative (that is their values cannot be changed or modified) whilst the user-specific parameters were taken from Experiment One (Tables 8 and 9).

Table 8: Conservative Parameters of AquaCrop used in Simulation

Description	Units/Meaning	Value
Base temperature	°C	10
Upper temperature	°C	30
Soil H_2O depletion factor, canopy expansion	Upper threshold (p-exp)	0.25
Soil H_2O depletion factor, canopy expansion	Lower threshold (p-exp)	0.25
Coefficient of positive impact on HI	Vegetative growth	10
Coefficient of negative impact on HI	Stomatal closure	8
Allowable maximum increase of specified HI	%	15
H_2O productivity normalized for ETo & CO_2	g/m^2 (WP*)	17
H_2O productivity normalized for ETo & CO_2 during yield formation	g/m^2 (WP*)	100

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Parameters	Unit	Measured/Calibrated
Soil surface covered by an individual seedling at (90%) recover	(cm²/plant)	5
Number of plants per hectare	ha⁻¹	80000
Time from transplanting to recover	Days	7
Maximum canopy cover, CCx	%	65
Time from transplanting to start senescence	Days	90
Time from transplanting to maturity, i.e. length of crop cycle	Days	116
Time from transplanting to flowering	Days	15
Maximum effective rooting depth	(m)	0.80
Time from sowing to maximum rooting depth	Days	50
Reference Harvest Index (HIO)	%	50
Water productivity (WP*)	g/m²	17
Soil texture		Sandy loam

Statistical analysis used in validating the AquaCrop Model

The performance of the model was evaluated by using the following statistical parameters: the normalized-root mean square error (N-RMSE) calculated as RMSE= $\sqrt{\sum_{i=1}^{n}\frac{(O_i - S_i)^2}{n}}$ and N-RMSE = $\sqrt{\sum_{i=1}^{n}\frac{(O_i - S_i)^2}{n}}\,X\,\frac{100}{M}$

Where, S_i and O_i are the simulated and observed (measured) values as samples taken along the season (e.g. biomass and CC), or at the end of the season (e.g., grain yield), *n* is the number of observations, and M is the mean value of O_i.

The RMSE represents a measure of the overall, or mean 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

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being simulated, and therefore the closer the value is to zero, the better the model simulation performance.

The N-RMSE expresses how much the overall deviation between observed and simulated values departs from the overall deviation between observed values (O_i) and their mean value (M). The added value of this statistical indicator (N-RMSE) as compared to RMSE, is in its ability to capture how well the model performs over the whole simulation period, for instance, along the season. In other words, while RMSE does not distinguish between large deviations occurring in some part of the season and small deviations in other part of the season, N-RMSE accounts for the different deviations, as they depart from (O_i– M) along the season and expresses an efficiency of the model performance, which is expressed in percentage. Also normalized RMSE gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent with a normalized RMSE less than 10 %, good if the normalized RMSE is greater than 10 % and less than 20 %, fair if normalized RMSE is greater than 20 % and less than 30 %, and poor if the normalized RMSE is greater than 30 %

Results and discussion

The calibrated AquaCrop model concentrated on its performance to forecast crop yields and seasonal ETc. Summary of the outcome of the simulations that is, the simulated fruit yield and the seasonal ETc of the different ETc treatments have been compared to the measured values for the first and second experiments as shown in Tables 9 and 10.The results show that the model performed both well in simulating the water dynamics whilst the yield was not accurately simulated.

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Table 9: Comparison between simulated and measured value of yield and seasonal ETc of tomato for various treatments (Experiment 1 - Calibration)

	Yield (t/ha)				Seasonal ETc (mm)			
Treatment	**Measured**	**Simulated**	**RMSE**	**N-RMSE (%)**	**Measured**	**Simulated**	**RMSE**	**N-RMSE (%)**
T_1	5.30	4.57	0.73	13.77	307.00	320.00	6.50	8.46
T_2	4.70	2.98	1.72	36.59	263.00	250.00	6.50	9.88
T_3	4.50	2.13	2.37	52.66	234.80	210.00	12.40	21.12
T_4	3.11	1.72	1.39	44.69	213.30	180.00	16.65	31.22

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Table 10: Comparison between simulated and measured value of yield and seasonal ETc of tomato for various treatments (Experiment 2 - Validation)

	Yield (t/ha)				Seasonal ETc (mm)			
Treatment	**Measured**	**Simulated**	**RMSE**	**N-RMSE (%)**	**Measured**	**Simulated**	**RMSE**	**N-RMSE (%)**
T_1	4.50	4.57	0.07	1.55	359.89	320.00	19.94	22.16
T_2	3.80	2.98	0.82	21.57	299.71	250.00	24.85	33.17
T_3	3.20	2.13	1.07	33.43	272.00	210.00	31.00	45.58
T_4	2.10	1.72	0.38	18.09	247.10	180.00	33.55	54.30

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From the results, the AquaCrop model can be used to evaluate water use efficiency, as well as to assess yield from scenarios for alternative water management strategies for tomato. However, there seems to be no universal model, thus the applicability of key calibrated variables must be tested under different conditions (Farahani *et al*., 2009).

Hsiao *et al.* (2009) indicated that further comprehensive refinements (calibration) may be important in order to include more characteristics of the crop in response to the diverse climate, cultivar, soil and agronomic (such as macro and micronutrients interactions with water, variety, planting density and other environmental factors) conditions.

Table 9 illustrates a poor prediction of the yield for the deficit irrigated (90 %-ETc – 70 %-ETc) with normalized RMSEs of the simulated from the measured yield approximately ranging from 36.59 % to 52.66 %. The N-RMSE for yield under full irrigation is 13.77 % and it was found to be in close agreement between the simulated and observed. This is in line with Araya, Keesstra and Stroosnijder (2010) who indicated that the simulated grain yield was in close agreement with the observed. The result also agreed quite well with Jin *et al.* (2014) that the AquaCrop model predicted canopy cover, biomass yield and grain yield with acceptable accuracy. The finding confirms that the AquaCrop model can be considered as a valid model. The statistical evaluations for yield also confirm the model's validity. Also the model was capable of simulating yields under full irrigation. This is in accordance with Steduto, Hsiao, Evett, Heng and Howell (2009a); Steduto, Hsiao, Raes and Fereres (2009c) that several herbaceous crops as a function of water consumed

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under any of the four conditions, which are rainfed, supplemental, deficit and full irrigation.

In view of the calibrated results, the N-RMSE ranged from 9.88 % to 31.22 % for the seasonal ETc for the mild stress condition treatment T_2 and 8.46 % for the under non-water-stress treatment, thus indicating that the model was capable of simulating the seasonal water requirement accurately for T_2 but did not accurately simulate T_3 and T_4. In addition, the model was noted to simulate satisfactorily crop water use (ET) under non-water-stress and mild stress treatment, T_2. This was not different from the observation made by Steduto *et al*. (2009a). Furthermore, the results show that the model performed very well for simulating water dynamics of the seasonal water requirement (Table 9). The calculated normalized RMSE, were 8.46 % for full irrigation and 9.88 % for water deficit irrigation T_2, respectively. This is in agreement with work done by Andarzian *et al.* (2011) who reported that the model predicted very well in simulating the water requirement for both full and deficit irrigation. The results also conform to those of Araya *et al.* (2010) who found that the soil water simulated by the model agreed well with the observed data. The seasonal ETc obtained (Table 9) also agree with Bitri, Grazhdani and Ahmeti (2014) who reported that the model performed very well for simulating water dynamics for full and deficit irrigation.

With regard to the validation trial, Table 10 indicates that the yield of T_1 was accurately simulated by the model and was followed by the deficit irrigated treatments $T_{4,}$ T_2 and T_3. Over all, the AquaCrop model predicted tomato yield with acceptable accuracy under variable irrigation levels. This is in agreement with the report by Abedinpour *et al.* (2012).The simulated yields

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showed a good agreement with measured tomato yields (Table 10). The simulated tomato yield varied from 1.72 to 4.57 t/ha, while the measured yield varied from 2.10 t/ha to 4.5 t/ha for deficit irrigation treatments T_4, T_2 T_3 and full irrigation in the second experiment of the cropping seasons. The calculated model evaluation criteria between simulated and measured yield were normalized RMSE = 18.09 % and 1.55 % respectively. Bannayan (2011) also asserted that the AquaCrop model estimated very well in simulating the grain yield under both full and deficit irrigation. Bitri *et al.* (2014) recorded that the model predicted very well in simulating the grain yield accurately under both full and deficit irrigation. This is in agreement with this study. The model accurately simulated the water requirement for T_2 in the calibrated experiment. However, the model did not accurately simulate the water requirement for the validation experiment even though the model under-estimated the water requirement of T_1. The N-RMSEs of simulated seasonal ETc from measured values were 22.16 %, 33.17 %, 45.58 % and 54.30 % for T_1, T_2, T_3 and T_4, respectively.

The yield from the experimental period and the model yield indicate some significant variation for both deficit irrigated treatments T_2 and T_3. The yield obtained were 3.80 and 3.20 t/ha for the experimental treatments and 2.98 and 2.13 t/ha for the simulated, suggesting that the model under-estimated the yield by 21.57 % and 33.43 %. Given the fact that the grain yields are derived directly as a factor from the total biomass yields, there is likely to be a compromise between over prediction or under-prediction of either grain yields or total ETc depending on the objective of simulation exercise. In this study, the focus was more on yields and seasonal ETc given

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its importance especially as a food and cash crop in the region. As observed by Todorovic, Albrizio and Zivotic (2009), careful parameterization of crop growth parameters during the season might be particularly important in different agro climatic scenarios of varying water stress conditions that should be examined for their peculiarity not only through a simple stress response function, based on the fractional soil water depletion, but also through the plant physiological responses that may vary during the crop development and growth. In turn, the intensity and duration of water stress could have different impacts on growth and its partitioning into yield during each phase of the growing season (Todorovic *et al.*, 2009). The fact that the yield of the model was similar to that of the validated experiment for both full irrigation and deficit irrigated treatment T_4, suggests that AquaCrop model can be used by water officers for water allocation purposes in which the research practices must be implemented.

With respect to tomato, as per this study, the model has been reported to quite accurately and satisfactorily simulate seasonal ETc under full irrigation and 10 % deficit irrigation but at higher deficit irrigation, the model was less accurate. While yields of full irrigation and 30 % deficit irrigated treatment of the experimental periods were within acceptable ranges. These are in agreement with Izzi, Farahani and Oweis (2009) who found out that the AquaCrop model was able to accurately simulate the canopy cover, evapotranspiration, biomass and yield within acceptable ranges. Also, the evaluation of the AquaCrop model illustrated that the model was able to simulate crop water use (ET) and yield accurately. This agrees with the assertion of Heng *et al.* (2009) that the model can simulate the crop water use

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and the model performed satisfactorily for the growth of aboveground biomass, grain yield, and canopy cover (CC) in the non-water-stress treatments and mild stress conditions.

Conclusions

It can be concluded that generally, AquaCrop can be a useful tool to simulate or predict the yield and water requirement of crops. The model was able to simulate more accurately the yield of tomato under full irrigation than the deficit irrigated treatments for the calibrated experiment. However, it simulated accurately the water requirement for T_2 in experiment one. It also simulated quite accurately the yield of T_4 but did not accurately simulate the water requirement for the validated experiment.

It can be pointed out that the calibration of the model was affected by a lack of data on the progress of crop canopy architecture which is an essential parameter used in developing the AquaCrop model.

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CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

From the study it can be concluded that:

(a) Tomato responds to water stress when deficit irrigation is reduced below 20 %, above this threshold there is an adverse effect on the plant.

(b) Water applied at different levels to tomato, significantly affected the growth, development and fruiting of tomato.

(c) The model simulated accurately the yield of tomato response to full irrigation but it was less satisfactory in simulating the yield of tomato to deficit irrigation. Among the deficit irrigation treatments, T_4 gave 18.09 % of tomato yield respectively.

(d) AquaCrop simulated the seasonal ETc to an appreciable degree for T_2 in the first experiment but did not accurately simulate the seasonal ETc for the second experiment.

Recommendations

(a) 20 % deficit irrigation is feasible since it does not significantly affect growth, development and total yield of tomato and thus leads to a profitable savings of water utilised.

(b) The research should be repeated in different agro-ecological zones.

(c) Progress data on canopy architecture should be obtained and utilised since it is an essential parameter used in developing AquaCrop.

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APPENDICES

APPENDIX I

(A) RESULTS OF ANALYSES OF VARIANCEFOR EXPERIMENT ONE

```
***** Analysis of variance *****

Variate: PLANT_HEIGHT_INITIAL_STAGE
Source of variation          d.f.        s.s.         m.s.      v.r.    F pr.
WATER_LEVEL                     3     57.2429      19.0810     19.20    <.001
Residual                        9      8.9450       0.9939
Total                          15     76.8908

***** Tables of means *****
Variate: INITIAL_STAGE
Grand mean  20.70
WATER_LEVEL   0.7        0.8        0.9        1.0
            18.04      20.40      21.01      23.35
***** Standard errors of differences of means *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.               0.705

***** Least significant differences of means (5% level) *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.               1.595

                ***** Analysis of variance *****
Variate: PLANT_HEIGHT_DEVELOPMENTAL_STAGE
Source of variation          d.f.        s.s.         m.s.      v.r.    F pr.
WATER_LEVEL                     3     160.875       53.625      6.33    0.013
Residual                        9      76.198        8.466
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Total                          15      253.361
***** Tables of means *****
Variate: DEVELOPMENTAL_STAGE
Grand mean 45.12

WATER_LEVEL   0.7         0.8         0.9         1.0
            40.50       44.43       46.29       49.24
***** Standard errors of differences of means *****
Table            WATER_LEVEL
rep.                       4
d.f.                       9
s.e.d.                 2.057

***** Least significant differences of means (5% level) *****
Table            WATER_LEVEL
rep.                       4
d.f.                       9
l.s.d.                 4.654

                    ***** Analysis of variance *****
                 Variate: PLANT_HEIGHT_MID_SEASON
Source of variation            d.f.         s.s.         m.s.       v.r.    F pr.
WATER_LEVEL                       3      128.316       42.772       8.93    0.005
Residual                          9       43.103        4.789
Total                            15      186.171
                     ***** Tables of means *****
Variate: MID_SEASON
Grand mean 58.22
WATER_LEVEL   0.7         0.8         0.9         1.0
            55.09       57.23       57.58       62.86
***** Standard errors of differences of means *****
Table            WATER_LEVEL
rep.                       4
d.f.                       9
```

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s.e.d.                    1.547

     ***** Least significant differences of means (5% level) *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.               3.501

               ***** Analysis of variance ****
Variate: PLANT_HEIGHT_LATE_SEASON
Source of variation          d.f.       s.s.       m.s.     v.r.   F pr.
WATER_LEVEL                     3    132.103     44.034     5.90   0.016
Residual                        9     67.174      7.464
Total                          15    221.466

***** Tables of means *****
Variate: LATE_SEASON
Grand mean 63.34
WATER_LEVEL   0.7       0.8       0.9       1.0
            59.55     61.60     65.18     66.95
***** Standard errors of differences of means *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.               1.932

     ***** Least significant differences of means (5% level) *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.               4.370
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```
                          ***** Analysis of variance *****

Variate: LEAF_AREA_INITIAL_STAGE

Source of variation          d.f.        s.s.        m.s.      v.r.    F pr.

WATER_LEVEL                     3      0.2836      0.0945      0.18    0.909

Residual                        9      4.8108      0.5345

Total                          15      6.0755


                           ***** Tables of means *****

Variate: INITIAL_STAGE

Grand mean 6.81

WATER_LEVEL   0.7        0.8        0.9        1.0

             6.69       6.71       6.83       7.02

               ***** Standard errors of differences of means *****

Table          WATER_LEVEL

rep.                     4

d.f.                     9

s.e.d.               0.517

            ***** Least significant differences of means (5% level) *****

Table          WATER_LEVEL

rep.                     4

d.f.                     9

l.s.d.               1.169



                          ***** Analysis of variance *****

Variate: LEAF_AREA_DEVELOPMENTAL_STAGE

Source of variation          d.f.        s.s.        m.s.      v.r.    F pr.

WATER_LEVEL                     3    78.08277    26.02759   1596.48    <.001

Residual                        9     0.14673     0.01630

Total                          15    78.33562

                           ***** Tables of means *****

Variate: DEVELOPMENTAL_STAGE

Grand mean 23.527
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```
WATER_LEVEL   0.7        0.8        0.9        1.0
           19.742     24.270     24.947     25.148

        ***** Standard errors of differences of means *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.              0.0903

      ***** Least significant differences of means (5% level) *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.              0.2042


                  ***** Analysis of variance *****

Variate: LEAF_AREA_MID_SEASON

Source of variation          d.f.        s.s.        m.s.      v.r.   F pr.
WATER_LEVEL                     3    505.9100    168.6367   1110.10   <.001
Residual                        9      1.3672      0.1519
Total                          15    508.5335

                   ***** Tables of means *****

Variate: MID_STAGE

Grand mean 42.239

WATER_LEVEL   0.7        0.8        0.9        1.0
           33.103     43.398     44.013     48.445

        ***** Standard errors of differences of means *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.              0.2756

      ***** Least significant differences of means (5% level) *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.              0.6235
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                    ***** Analysis of variance *****
Variate: LEAF_AREA_LATE_STAGE
Source of variation          d.f.        s.s.        m.s.      v.r.   F pr.
WATER_LEVEL                     3    38.68982    12.89661    132.70   <.001
Residual                        9     0.87468     0.09719
Total                          15    39.85977
***** Tables of means *****
Variate: LATE_STAGE
Grand mean 7.749
WATER_LEVEL   0.7       0.8       0.9       1.0
            5.403     7.810     8.010     9.773
             ***** Standard errors of differences of means *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.              0.2204

          ***** Least significant differences of means (5% level) *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.              0.4987

                    ***** Analysis of variance *****
Variate: STEM_MID_STAGE
Source of variation          d.f.        s.s.        m.s.      v.r.   F pr.
WATER_LEVEL                     3    14.26912     4.75637     83.60   <.001
Residual                        9     0.51206     0.05690
Total                          15    14.92039

                     ***** Tables of means *****
Variate: MID_STAGE
Grand mean 9.23
```

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```
WATER_LEVEL   0.7       0.8       0.9       1.0
             7.62      9.50      9.75     10.03

          ***** Standard errors of differences of means *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.               0.169


        ***** Least significant differences of means (5% level) *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.               0.382


                ***** Analysis of variance *****

Variate:  INTERNODE_MID_STAGE

Source of variation        d.f.        s.s.        m.s.     v.r.   F pr.
WATER_LEVEL                   3     18.6456      6.2152    23.76   <.001
Residual                      9      2.3542      0.2616
Total                        15     21.1668


                  ***** Tables of means *****

Variate: MID_STAGE

Grand mean 18.38

WATER_LEVEL   0.7       0.8       0.9       1.0
            16.57     18.57     19.01     19.36


          ***** Standard errors of differences of means *****

Table        T WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.               0.362
```

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```
          ***** Least significant differences of means (5% level) *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.               0.818

                    ***** Analysis of variance *****

Variate: TOTAL_NO_OF_FRUITS

Source of variation        d.f.       s.s.       m.s.     v.r.   F pr.
WATER_LEVEL                   3     358.03     119.34     4.26   0.039
Residual                      9     252.09      28.01
Total                        15     793.37

                     ***** Tables of means *****

Variate: TOTAL_NO_OF_FRUITS

Grand mean 56.87

WATER_LEVEL   0.7       0.8       0.9       1.0
            49.41     57.12     58.52     62.45

         ***** Standard errors of differences of means *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.               3.742

          ***** Least significant differences of means (5% level) *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.               8.466
```

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```
                    ***** Analysis of variance *****
Variate:TOTAL_FRUITS_DIAMETER
Source of variation        d.f.        s.s.        m.s.     v.r.   F pr.
WATER_LEVEL                   3    1151.347     383.782   195.88   <.001
Residual                      9      17.634       1.959
Total                        15    1198.792

                     ***** Tables of means *****
Variate: FRUITS_DIAMETER
Grand mean 37.92
WATER_LEVEL   0.7       0.8       0.9       1.0
            23.40     41.22     42.30     44.77

            ***** Standard errors of differences of means*****
Table            WATER_LEVEL
rep.                       4
d.f.                       9
s.e.d.                 0.990

       ***** Least significant differences of means (5% level) *****
Table            WATER_LEVEL
rep.                       4
d.f.                       9
l.s.d.                     2.239

                    ***** Analysis of variance *****
Variate: TOTAL_FRUIT_WEIGHT
Source of variation        d.f.        s.s.        m.s.     v.r.   F pr.
WATER_LEVEL                   3    0.098030    0.032677    16.16   <.001
Residual                      9    0.018198    0.002022
Total                        15    0.130055
```

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```
                    ***** Tables of means *****

Variate: FRUIT_WT


Grand mean 0.422

WATER_LEVEL    0.7       0.8       0.9       1.0
             0.311     0.450     0.467     0.532


          ***** Standard errors of differences of means *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.              0.0318


       ***** Least significant differences of means (5% level) *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.              0.0719


                 ***** Analysis of variance *****

Variate: TOTAL_YIELD

Source of variation       d.f.        s.s.        m.s.     v.r.   F pr.
WATER_LEVEL                  3      9.8030      3.2677    16.16   <.001
Residual                     9      1.8198      0.2022
Total                       15     13.0055


                    ***** Tables of means *****

Variate: YIELD_t/ha

Grand mean 4.22

WATER_LEVEL    0.7       0.8       0.9       1.0
              3.11      4.49      4.67      5.32
```

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```
          ***** Standard errors of differences of means *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.               0.318

       ***** Least significant differences of means (5% level) *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.               0.719
```

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APPENDICES II

(B) RESULTS OF ANALYSES OF VARIANCE FOR EXPERIMENT TWO

```
                 ***** Analysis of variance *****

Variate: PLANT_HEIGHT_INITIALT_STAGE

Source of variation        d.f.        s.s.        m.s.     v.r.   F pr.

WATER_LEVEL                   3     56.9281     18.9760    79.23   <.001

Residual                      9      2.1556      0.2395

Total                        15     64.1394


                   ***** Tables of means *****

Variate: INITIALT_STAGE

Grand mean 19.86

WATER_LEVEL 0.7  0.8        0.9           1.0

            17.50      19.54      19.61      22.77
                              *
        **** Standard errors of differences of means *****

Table          WATER_LEVEL

rep.                     4

d.f.                     9

s.e.d.               0.346
                              *
     **** Least significant differences of means (5% level) *****

Table          WATER_LEVEL

rep.                     4

d.f.                     9

l.s.d.             3.338


                 ***** Analysis of variance *****

Variate: PLANT_HEIGHT_DEVELOPMENTAL_STAGE

Source of variation        d.f.        s.s.        m.s.     v.r.   F pr.

WATER_LEVEL                   3     148.552      49.517    11.37   0.002

Residual                      9      39.204       4.356

Total                        15     196.274
```

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```
                         ***** Tables of means *****

Variate: DEVELOPMENTAL_STAGE

Grand mean 43.76

WATER_LEVEL   0.7       0.8       0.9       1.0
             40.43     42.03     44.02     48.55


                ***** Standard errors of differences of means *****

Table          WATER_LEVEL

rep.                     4

d.f.                     9

s.e.d.               1.476


          ***** Least significant differences of means (5% level) *****

Table          WATER_LEVEL

rep.                     4

d.f.                     9

l.s.d.                 3.338


                        ***** Analysis of variance *****

Variate: PLANT_HEIGHT_MID_SEASON

Source of variation          d.f.        s.s.        m.s.     v.r.   F pr.

WATER_LEVEL                     3      15.837       5.279     1.55

Treatment                       3     105.777      35.259    10.33   0.003

Residual                        9      30.726       3.414

Total                          15     152.339


                         ***** Tables of means *****

Variate: MID_SEASON

Grand mean 58.16

WATER_LEVEL   0.7       0.8       0.9       1.0
            55.82     56.72     57.60     62.47
```

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```
           ***** Standard errors of differences of means *****

Table            WATER_LEVEL
rep.                       4
d.f.                       9
s.e.d.                 1.307

        ***** Least significant differences of means (5% level) *****

Table            WATER_LEVEL
rep.                       4
d.f.                       9
l.s.d.                 2.956

                   ***** Analysis of variance *****

Variate: PLANT_HEIGHT_LATE_SEASON

Source of variation          d.f.        s.s.        m.s.     v.r.   F pr.
WATER_LEVEL                     3     118.091      39.364    11.05   0.002
Residual                        9      32.052       3.561
Total                          15     156.577

                    ***** Tables of means *****

Variate: LATE_SEASON

Grand mean 62.06

WATER_LEVEL   0.7        0.8        0.9        1.0
            58.11      61.13      61.42      66.53

           ***** Standard errors of differences of means *****

Table            WATER_LEVEL
rep.                       4
d.f.                       9
s.e.d.                 1.334
```

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```
        ***** Least significant differences of means (5% level) *****

Table            WATER_LEVEL
rep.                       4
d.f.                       9
l.s.d.                 3.019



                    ***** Analysis of variance *****

Variate: LEAF_AREA_INITIAL_STAGE

Source of variation          d.f.        s.s.        m.s.      v.r.    F pr.
WATER_LEVEL                     3      0.2836      0.0945      0.67    0.592
Residual                        9      1.2708      0.1412
Total                          15      1.7805

                      ***** Tables of means *****

Variate: INITIAL_STAGE

Grand mean 6.563

WATER_LEVEL   0.7        0.8        0.9        1.0
            6.440      6.578      6.460      6.775

           ***** Standard errors of differences of means *****

Table            WATER_LEVEL
rep.                       4
d.f.                       9
s.e.d.                0.2657



        ***** Least significant differences of means (5% level) *****

Table            WATER_LEVEL
rep.                       4
d.f.                       9
l.s.d.                0.6011
```

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```
                         ***** Analysis of variance *****

Variate: LEAF_AREA_DEVELOPMENTAL_STAGE

Source of variation          d.f.        s.s.        m.s.      v.r.    F pr.

WATER_LEVEL                     3     21.7357      7.2452     18.44    <.001

Residual                        9      3.5360      0.3929

Total                          15     26.2921


                          ***** Tables of means *****

Variate: DEVELOPMENTAL_STAGE

Grand mean 20.31

WATER_LEVEL   0.7       0.8       0.9       1.0

            19.48     20.47     20.79     21.56


              ***** Standard errors of differences of means *****

Table        WATER_LEVEL

rep.                   4

d.f.                   9

s.e.d.             0.443


          ***** Least significant differences of means (5% level) *****

Table        WATER_LEVEL

rep.                   4

d.f.                   9

l.s.d.             1.003


                         ***** Analysis of variance *****

Variate: LEAF_AREA_MID_SEASON

Source of variation          d.f.        s.s.        m.s.      v.r.    F pr.

WATER_LEVEL                     3     522.991     174.330     19.70    <.001

Residual                        9      79.648       8.850

Total                          15     679.410
```

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***** Tables of means *****

Variate: MID_STAGE

Grand mean 41.81

WATER_LEVEL	0.7	0.8	0.9	1.0
	33.11	41.15	44.15	48.82

***** Standard errors of differences of means *****

Table	WATER_LEVEL
rep.	4
d.f.	9
s.e.d.	2.104

***** Least significant differences of means (5% level) *****

Table	WATER_LEVEL
rep.	4
d.f.	9
l.s.d.	4.759

***** Analysis of variance *****

Variate: LEAF_AREA_LATE_STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
WATER_LEVEL	3	29.546	9.849	8.41	0.006
Residual	9	10.538	1.171		
Total	15	46.383			

***** Tables of means *****

Variate: LATE_STAGE

Grand mean 7.44

WATER_LEVEL	0.7	0.8	0.9	1.0
	5.44	7.58	7.46	9.28

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```
          ***** Standard errors of differences of means *****

Table            WATER_LEVEL
rep.                       4
d.f.                       9
s.e.d.                 0.765

        ***** Least significant differences of means (5% level) *****

Table            WATER_LEVEL
rep.                       4
d.f.                       9
l.s.d.                 1.731


                   ***** Analysis of variance *****

Variate: STEM_MID_STAGE
 Source of variation   d.f.    s.s.    m.s.    v.r.    F pr.
WATER_LEVEL                   3     16.0903      5.3634     20.98   <.001
Residual                      9      2.3011      0.2557
Total                        15     18.7247

                    ***** Tables of means *****

Variate: MID_STAGE
Grand mean 8.84
WATER_LEVEL   0.7        0.8        0.9        1.0
             7.17       9.00       9.42       9.77

          ***** Standard errors of differences of means *****

Table            WATER_LEVEL
rep.                       4
d.f.                       9
s.e.d.                 0.358
```

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            ***** Least significant differences of means (5% level) *****

Table              WATER_LEVEL
rep.                         4
d.f.                         9
l.s.d.                     0.809


                        ***** Analysis of variance *****

Variate:  INTERNODE_MID_STAGE

Source of variation           d.f.         s.s.        m.s.      v.r.    F pr.
WATER_LEVEL                      3      17.7425      5.9142     20.94    <.001
Residual                         9       2.5418      0.2824
Total                           15      20.4229


                          ***** Tables of means *****

Variate: MID_STAGE

Grand mean 18.26

WATER_LEVEL   0.7        0.8        0.9        1.0
            16.57      18.20      18.97      19.30

               ***** Standard errors of differences of means *****

Table              WATER_LEVEL
rep.                         4
d.f.                         9
s.e.d.                   0.376

            ***** Least significant differences of means (5% level) *****

Table              WATER_LEVEL
rep.                         4
d.f.                         9
l.s.d.                     0.850
```

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***** Analysis of variance *****

Variate: TOTAL_NO_OF_FRUITS

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	3	1581.4	527.1	4.40	0.036
WATER_LEVEL	9	1078.6	119.8		
Total	15	2782.6			

***** Tables of means *****

Variate: TOTAL_NO_OF_FRUITS

Grand mean 42.12

WATER_LEVEL	0.7	0.8	0.9	1.0
	26.41	41.12	48.52	52.45

***** Standard errors of differences of means *****

Table	WATER_LEVEL
rep.	4
d.f.	9
s.e.d.	7.741

***** Least significant differences of means (5% level) *****

Table	WATER_LEVEL
rep.	4
d.f.	9
l.s.d.	17.511

***** Analysis of variance *****

Variate: TOTAL_FRUITS_DIAMETER

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
WATER_LEVEL	3	1075.982	358.661	233.59	<.001
Residual	9	13.819	1.535		
Total	15	1095.468			

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```
                    ***** Tables of means *****

Variate: FRUITS_DIAMETER

Grand mean 37.05

WATER_LEVEL   0.7       0.8       0.9       1.0
            22.90     40.72     41.76     42.80


        ***** Standard errors of differences of means *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.               0.876


      ***** Least significant differences of means (5% level) *****

Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.               1.982


                   ***** Analysis of variance *****

Variate: TOTAL_FRUIT_WEIGHT

Source of variation        d.f.  s.s.     m.s.v.r.F pr.
WATER_LEVEL                  3   0.119742   0.039914    19.17   <.001
Residual                     9   0.018735   0.002082
Total                       15   0.159628

                    ***** Tables of means *****

Variate: FRUIT_WT

Grand mean 0.339

WATER_LEVEL   0.7       0.8       0.9       1.0
            0.211     0.319     0.377     0.447


        ***** Standard errors of differences of means *****
```

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```
Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.              0.0323

     ***** Least significant differences of means (5% level) *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
l.s.d.              0.0730


               ***** Analysis of variance *****
Variate: TOTAL_YIELD
Source of variation          d.f.       s.s.       m.s.     v.r.   F pr.
WATER_LEVEL                     3    11.9742     3.9914    19.17   <.001
Residual                        9     1.8735     0.2082
Total                          15    15.9628

                 ***** Tables of means *****
Variate: YIELD_t/ha
Grand mean 3.39
WATER_LEVEL   0.7      0.8      0.9      1.0
             2.11     3.20     3.77     4.47

***** Standard errors of differences of means *****
Table          WATER_LEVEL
rep.                     4
d.f.                     9
s.e.d.               0.323



***** Least significant differences of means (5% level) *****
```

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Table	WATER_LEVEL
rep.	4
d.f.	9
l.s.d.	0.730

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PLATES

Plate 1: Researcher collecting data on water losses.

Source: School of Agriculture teaching and research farm – U. C.C (2014)

Plate 2: Researcher collecting data on tomato plant height

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Plate 3: Researcher collecting data on tomato leaf area

Plate 4: Weighing of tomato fruits per treatments.

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